Evaluating the Biomechanical, Functional, and Clinical Outcomes of Bicruciate Stabilized Total Knee Arthroplasty

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Medical Biophysics

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Abstract

Total knee arthroplasty (TKA) is the only solution for treating arthritis of the knee joint. Although it is successful at reducing pain and returning function to affected joints, one in five patients still report dissatisfaction following their operation. Bicruciate stabilized (BCS) TKA was developed to improve outcomes by replicating normal knee structure and function. The biomechanical, functional, and clinical outcomes for the BCS design were investigated in this thesis through radiographic imaging techniques, wearable sensor systems, and questionnaires in a cohort of TKA patients.

A stereo x-ray technique, called radiostereometric analysis (RSA), assesses implant fixation by tracking micromotion of TKA devices relative to the bone. Risk of implant loosening can be predicted based on the magnitude of these micromotions. This thesis found micromotion of the BCS TKA was within safe thresholds for both the gap balancing and measured resection techniques, indicating sufficient fixation to the bone occurs and the BCS TKA is not expected to have elevated revision risks due to implant loosening.

The exact cause of patient dissatisfaction after TKA is unknown. This thesis sought to find any differences in objective data between satisfied and dissatisfied patients with a BCS TKA. RSA was used to measure implant micromotion and tibiofemoral contact kinematics. A sensor system tracked measures of patient function during a timed-up-and-go functional test, and patient-reported outcomes were collected. We found no difference in implant micromotions or patient function between satisfied and dissatisfied patients. However, dissatisfied patients had more anterior contact on the lateral condyle of the knee in early flexion, and more pain and unmet expectations.

Finally, correlations were found between implant micromotion and tibiofemoral contact kinematics. Contact patterns indicating reduced posterior femoral rollback in the lateral compartment correlated with greater implant micromotion. Since BCS TKA aims to replicate normal knee kinematics and guide posterior rollback, it was concluded that undesired kinematics resulted in greater micromotions, and a greater risk of implant loosening.
Overall, the restoration of kinematics—particularly in the lateral compartment—in BCS TKA appears to be important for reducing implant migrations, improving pain and feeling in the knee, and ultimately, enhancing patient satisfaction.

Keywords

Total knee arthroplasty; bieruciate stabilized; radiostereometric analysis; implant migration; contact kinematics; patient function.
Summary for Lay Audience

One in five Canadians live with arthritis, a disease of the joints that causes pain, limits mobility, and reduces quality of life. The knee is the most common joint affected, and with no cure available, many patients choose to undergo knee replacement to improve their symptoms. Knee replacements remove damaged bone and cartilage and replace them with metal and plastic implants. Although knee replacement is a very successful procedure, 20% of patients are dissatisfied after the operation. A relatively new type of knee replacement, called a bicruciate stabilized (BCS) implant, was designed to look and function like the normal knee to improve patient outcomes. In this thesis, the effectiveness of the BCS implant was studied.

The first step was to determine the fixation of BCS implants. Fixation is how securely the implants are attached to the bones and is measured by tracking how much the implant shifts, or migrates, after surgery. Implant migrations are very small, often less than a millimetre, and require special x-ray imaging, called radiostereometric analysis (RSA), to measure. Two surgical techniques were also compared; however, both techniques were determined to be equally effective options for long-term fixation of BCS implants.

Next, patients were divided into satisfied and dissatisfied groups to find any potential factors that cause patients to be dissatisfied with their knee replacement. RSA was used to study implant migration, and to assess kinematics (aka how the knee replacement moves) when bending the knee. Patient function was also measured during a walking and sitting test using sensors worn on each leg. Patients also answered questions about pain, expectations, and satisfaction. Dissatisfied patients were found to have different kinematics in the early stages of a knee bend, and reported more pain and unmet expectations.

Lastly, the implant migrations were compared with the kinematics to see if there were any relationships between the two for BCS implants. Abnormal kinematic patterns were related to greater implant migrations. This means that implants that do not move properly during knee bending are more likely to have worse fixation and may be at a greater risk of coming loose.
Co-Authorship Statement


JB: Conceptualization; data curation; formal analysis; investigation; project administration; visualization; writing – original draft preparation; writing – review and editing; manuscript submission.

EV: Investigation; resources; writing – review and editing.

BL: Investigation; resources; writing – review and editing.

JH: Investigation; resources; writing – review and editing.

MT: Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing.

DN: Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing – review and editing.

A version of this chapter has been published in the Journal of Arthroplasty.


JB: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; visualization; writing – original draft preparation; writing – review and editing; manuscript submission.

DN: Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing – review and editing.

BL: Investigation; resources; writing – review and editing.
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DN: Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing – review and editing.

JH: Investigation; resources; writing – review and editing.

BL: Investigation; resources; writing – review and editing.

EV: Investigation; resources; writing – review and editing.

MT: Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing.

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Dedication

To Gramma and Grampa,

thanks for everything
Acknowledgments

The work in the pages to follow would not have been remotely possible without the amazing support I have received during my graduate studies.

To my supervisor, Dr. Matt Teeter, thanks for taking a chance on a nervous 3rd year undergraduate student. I always tell everyone how fortunate I am to have landed in the perfect environment for me to be successful. You have this blend of trusting your students to be independent scientists while still being available at a moment’s notice when we need guidance. I hope to strike a similar balance one day. I will miss all your ideas for new side projects, papers, and collaborations. The opportunities you gave me have set me up for a successful future. I was unsure what that future held when I first joined your lab; however, your drive and passion has inspired me to pursue a career in research. Thank you for giving me the confidence and direction I needed.

To my advisory committee, Dr. Douglas Naudie and Dr. Emily Lalone, thank you for keeping me on track. Your mentorship has been essential, especially regarding the contents of this document, and I can’t imagine where I’d be without your guidance. Dr. Naudie, I have greatly appreciated all the reference letters you have written me. Thank you for your enthusiasm towards these projects and for sharing them with The Knee Society. Dr. Lalone, I still remember you asking me what I wanted for my future when I reclassified to a PhD. I didn’t have a good answer then, but I do now! Thank you for helping me think about the bigger picture.

I also owe a huge thank you to the clinical team at the Rorabeck Bourne Joint Replacement Clinic, in particular Dr. Brent Lanting, Dr. James Howard, Dr. Edward Vasarhelyi, and of course, Dr. Naudie. Firstly, thanks for agreeing to be a part of my studies. It would have been very difficult (read: impossible) to write a thesis on in vivo imaging and biomechanics of knee replacements without you. Thank you all for also taking the time to answer any of my clinical questions. I know how little spare time you all have, but you never made it feel that way. Brenda and Erika, thank you for always making me feel welcome in the clinic, even when us researchers tend to disrupt things.
Thank you, Abby, Bryn, and Anna, and everyone else up in the Kirkley Centre who helped me along the way. Abby and Bryn, thank you for teaching me how to run a clinical study, and for trivia nights at Molly Blooms. Anna, I always knew I could go to you to find my missing questionnaires. Thank you for all the free toques.

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To Max and Harley, the adjustment to graduate school would have been way more challenging if not for your friendship. I greatly appreciated all of the times you both helped me out on busy days in the Ortho Clinic, and I cherish all the memories we made together attending conferences, playing sports, and helping Max tie the knot. I never ended up posting the picture of the three of us outside 3 Brasseurs in Montreal, so I’m immortalizing the caption here: “An MD, DMD, and PhD walk into a bar…”

Thank you, TianDuo and Matt, for being the best roommates and friends I could’ve asked for. I miss the nights we would spend around the TV watching whatever NBA, NFL, or NHL game was on. Nathan, thank you for helping me pad my assist stats in intramural hockey. One day I
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To my fiancée Natasha, there are no adjectives that can describe just how grateful I am to have you in my life. Your unwavering love has meant the world to me, and I am so proud to be earning this PhD alongside you. Forming our little family of four with Winnie and Bucky has given me so much joy. Not even a global pandemic could prevent these past four years from being the best of my life. I always know that no matter where life takes us, I’ll be okay as long as I’m with you.

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<tbody>
<tr>
<td>3D</td>
<td>three-dimensional</td>
</tr>
<tr>
<td>ACL</td>
<td>anterior cruciate ligament</td>
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<tr>
<td>AL</td>
<td>anterolateral</td>
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<tr>
<td>AM</td>
<td>anteromedial</td>
</tr>
<tr>
<td>AP</td>
<td>anteroposterior</td>
</tr>
<tr>
<td>BCR</td>
<td>bicruciate retaining</td>
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<tr>
<td>BCS</td>
<td>bicruciate stabilized</td>
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<tr>
<td>BMI</td>
<td>body mass index</td>
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<tr>
<td>CAD</td>
<td>computer-aided design</td>
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<tr>
<td>CN</td>
<td>condition number</td>
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<tr>
<td>CONSORT</td>
<td>Consolidated Standards of Reporting Trials</td>
</tr>
<tr>
<td>COVID-19</td>
<td>coronavirus disease of 2019</td>
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<tr>
<td>eV</td>
<td>electron volt</td>
</tr>
<tr>
<td>F</td>
<td>female</td>
</tr>
<tr>
<td>F-MTPM</td>
<td>femoral maximum total point motion</td>
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<tr>
<td>GB</td>
<td>gap balancing</td>
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<tr>
<td>IMUs</td>
<td>inertial measurement units</td>
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<tr>
<td>keV</td>
<td>kiloelectron volt</td>
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<tr>
<td>KSS</td>
<td>Knee Society Score</td>
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<tr>
<td>L</td>
<td>lateral</td>
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<tr>
<td>LCL</td>
<td>lateral collateral ligament</td>
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<td>m</td>
<td>metre</td>
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<tr>
<td>M</td>
<td>male</td>
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<tr>
<td>M-As</td>
<td>milliamper-second</td>
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<td>MBRSA</td>
<td>model-based radiostereometric analysis</td>
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<td>MCL</td>
<td>medial collateral ligament</td>
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<td>ME</td>
<td>mean error</td>
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<tr>
<td>MR</td>
<td>measured resection</td>
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<td>MTPM</td>
<td>maximum total point motion</td>
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<tr>
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<td>osteoarthritis</td>
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<tr>
<td>OARSI</td>
<td>Osteoarthritis Research Society International</td>
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<tr>
<td>PCA</td>
<td>posterior condylar axis</td>
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<td>RCT</td>
<td>randomized controlled trial</td>
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<td>TKA</td>
<td>total knee arthroplasty</td>
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<td>T-MTPM</td>
<td>tibial maximum total point motion</td>
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<td>TUG</td>
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<td>WOMAC</td>
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Chapter 1

1 Introduction

1.1 Osteoarthritis

1.1.1 Etiology

Osteoarthritis (OA) is a common and disabling chronic joint disease that poses a considerable health burden on affected individuals, health care systems, and society as a whole.\textsuperscript{1–5} It is considered a whole joint disease, resulting in anatomic and physiological alterations of multiple joint tissues including cartilage, bone, ligaments, capsule, synovium, and muscle. Once thought to be a result of “wear-and-tear”, new insights into the pathogenesis of OA have proven there is more to learn about what causes the disease.\textsuperscript{2} Many risk factors for developing OA have been identified such as advanced age, female sex, obesity, genetics, socioeconomic status, joint injury, malalignment, and deformity.\textsuperscript{2} Mechanical, inflammatory, and metabolic factors are all thought to provide multiple overlapping pathways leading to the eventual imbalance between joint tissue repair and destruction.\textsuperscript{2} As a result of this imbalance, cartilage loses its integrity and begins to degrade, bone remodeling leads to development of osteophytes and bone marrow lesions, and proinflammatory mediators cause tissue hypertrophy and increased vascularity.\textsuperscript{2}

The anatomic and physiological changes in the joint manifest as several symptoms in people with OA. Pain is the most disabling among a host of symptoms including stiffness, crepitus, instability, swelling, muscle weakness, fatigue, and psychological distress.\textsuperscript{2,6} The result is a significant reduction in quality of life for those affected. The diagnosis of OA is often made based on symptoms alone, but plain radiography can be used to validate deterioration of the joint.\textsuperscript{2,7,8} However, since many patients do not seek medical attention until symptoms become unbearable, the diagnosis of OA is often made in later stages of the disease.
1.1.2 Epidemiology and Burden

OA is the most common musculoskeletal disease in the world, ranking 17th highest among the 369 diseases and injuries included in the Global Burden of Disease Study 2019 with 527.81 million prevalent cases, a 113.25% increase from 1990. Females are more commonly affected than males, as are older individuals. An expanding and aging population, combined with the obesity epidemic, suggests the global prevalence of OA will continue to rise. A 2010 report from the Arthritis Alliance projected that in Canada, the prevalence of OA will rise to 10.4 million individuals, or 25.6% of the total population by 2040, up from the 13% reported in 2010. The knee is the most frequent site of OA accounting for 60.6% of global prevalent cases, followed by the hand (23.7%) and the hip (10.2%).

The individual burden of OA is immense with symptoms of OA, mainly pain, resulting in limited activity and reduced quality of life in individuals. Over 15 million quality-adjusted life years are lost annually in the USA, comparable to those experienced by patients with highly morbid conditions such as cardiovascular disease and cancer. Many OA patients have some degree of movement limitation, with 25% being unable to perform activities of daily living. Knee OA in particular can be devastating to affected individuals, accounting for 83% of the total burden of OA. Among knee OA patients, 11% and 14% need assistance with personal care and routine needs, respectively.

The socioeconomic burden of OA is significant, due to both direct costs to health care systems and indirect costs attributed mainly to a loss in work productivity. The total cost of OA to high income countries such as Canada was estimated to account for 1%–2.5% of the gross national product. The total economic burden in Canada is projected to reach $1,455.5 billion by 2040 (amount in Canadian Dollars). Direct costs in Canada are projected to rise to $546.4 billion by year 2040, up from $10.2 billion in 2010, with indirect costs projected to rise from $17.3 billion in 2010 to $909.1 billion in 2040. In the US, individuals with knee OA had more physician and non-physician visits per year and had more hospital stays. Pharmaceutical costs only account for approximately 10% of direct OA costs, since there are currently no disease-modifying OA drugs. Most direct costs are associated with total knee and hip replacements, owing to hospital stays, operating room
time, and the implants themselves. Indirect costs are primarily due to productivity losses that include absenteeism (time lost from work), presenteeism (loss of productivity due to disease while at work), premature death, and early retirement.

There is reason to believe that treatments such as weight loss, pain medication, and joint replacements can have a positive impact on the total cost of OA. The Arthritis Alliance estimated that if every severe OA patient in Canada who was willing and able were given a total hip or knee replacement starting in 2011, $1.2 billion could be saved in direct health care costs over 30 years, and $14.3 billion in indirect costs could be saved from productivity losses as more workers could avoid severe OA. A 50% reduction in obesity rate was estimated to have an even greater effect, with $48.3 billion and $163.7 billion in direct and indirect costs, respectively, saved over 30 years. The Arthritis Alliance also hypothesized that $40.8 billion and $447.2 billion in direct and indirect costs, respectively, could be saved over 30 years if a pain management intervention was available that could reduce painful symptomatic OA by 33%.

1.1.3 Treatment Options

As mentioned, there are currently no disease-modifying OA drugs to reverse or cure the disease. Treatments focus on managing symptoms of OA, and the first line includes non-surgical conservative options such as education, exercise, weight loss if obese, walking aids, bracing, and pain management. Although counterintuitive to the classic view of OA as a wear-and-tear disease, strength and aerobic exercises help decrease pain and improve joint motion. Obesity is the greatest modifiable risk factor of knee OA, and it has been shown that weight reduction through exercise and diet modifications not only reduces the prevalence of OA, but can improve symptomology as well. The benefits of bracing are controversial, as there have been reports suggesting improvement in pain but there is a lack of strong evidence to support these findings. Pharmacological methods are key in the pain management of OA patients. Non-steroidal anti-inflammatory drugs, both topical and oral, have been shown to be effective for improving pain and function. In cases where topical and oral drugs are not effective, intra-articular corticosteroid injections are recommended, however there is controversy regarding their
Unfortunately, the benefits of conservative management are usually short-term.

Surgical intervention is often used to treat the symptoms of OA when conservative options fail. In cases of knee OA, arthroscopic knee surgery, osteotomy, and arthroplasty are common surgical solutions. Arthroscopic knee surgery continues to be widely used for management of knee OA despite contrary guidelines from the American Academy of Orthopaedic Surgeons. Osteotomy is reserved for younger active patients with moderately severe cases of OA in a single compartment. It can be an alternative to unicompartmental knee arthroplasty, which is more advisable for older patients. However, in severe cases of OA where other treatment options have failed, total joint arthroplasty remains the gold standard.

1.2 Total Knee Arthroplasty

1.2.1 Knee Anatomy

An understanding of basic knee anatomy (Figure 1.1) is required to appreciate the goals and principles of total knee arthroplasty (TKA). The knee is the largest synovial joint in the body and is comprised of bone, cartilage, meniscus, ligaments, tendons, muscle, synovium, joint capsule, and synovial fluid. There are two articulations in the knee joint, a tibiofemoral joint and a patellofemoral joint. The tibiofemoral joint is an articulation between the femoral condyles of the distal femur and the tibial plateau on the proximal tibia. The patellofemoral joint is an articulation between the posterior surface of the patella and the femoral sulcus on the anterior femur. Both joints combine to allow the knee to act as a modified hinge joint that allows for flexion and extension, translation, and axial rotation. In a normally aligned knee, the mechanical axis of the lower limb will run from the femoral head through the middle of the knee joint to the centre of the ankle (Figure 1.2). The anatomical axis of the femur will be approximately 5° valgus to the mechanical axis, whereas the anatomical axis of the tibia is collinear with the mechanical axis. The normal joint line of the knee is 2° to 3° of varus relative to the mechanical axis perpendicular.
Figure 1.1: Anatomy of the knee. Created with Biorender.com.

Figure 1.2: Normal alignment of the knee. Created in part with Biorender.com.
The tibiofemoral joint is the primary joint in the knee and allows for weight transfer from the upper leg to the lower leg. Stability of the tibiofemoral joint is provided by a complex combination of soft tissues and bony structures.\textsuperscript{25} The medial femoral condyle and medial tibial plateau are elliptical and the articulating surface is concave, whereas the lateral compartment is less elongated and has a convex articulating surface. These differences in medial and lateral structure allow for internal rotation of the femur relative to the tibia when the knee approaches full extension, known as the screw-home mechanism.\textsuperscript{25} Menisci are soft tissues on the articulating surfaces responsible for load bearing and facilitating articular movement.\textsuperscript{24,25}

Four main ligaments are responsible for stabilizing the knee. The anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) are located within the knee capsule.\textsuperscript{24,25} The ACL runs distally and anteriorly from the posterolateral surface of the intercondylar notch on the femur to the intercondylar eminence on the anterior tibia.\textsuperscript{24,25} It is thought to consist of an anteromedial and posterolateral bundle, which wrap upon themselves to increase tension as the tibia internally rotates.\textsuperscript{25} The ACL has many important functions to provide stability, preventing both hyperextension and anterior translation of the tibia relative to the femur, and guiding rotation for the screw-home mechanism during knee extension.\textsuperscript{24,25} The PCL runs distally and posteriorly from the medial surface of the intercondylar notch on the femur to the fovea centralis on the posterior tibia.\textsuperscript{24,25} Like the ACL it has two bundles, a posteromedial and anterolateral bundle.\textsuperscript{25} The two bundles also wrap upon themselves in internal rotation.\textsuperscript{25} In extension, the PCL resists varus and valgus rotation, and as the knee flexes it prevents anterior translation of the femur relative to the tibia.\textsuperscript{25} The other two ligaments reinforcing the knee capsule are the extracapsular medial collateral ligament (MCL) and the lateral collateral ligament (LCL). The collateral ligaments also provide stability by resisting varus and valgus rotation.\textsuperscript{24,25} The MCL is composed of a deep component responsible for providing rotational stability in extension and early flexion, and a superficial component that restricts anterior translation of the medial tibia.\textsuperscript{24,25} In addition to limiting varus forces, the LCL also resists anterior-posterior translation of the tibia.\textsuperscript{24,25} All four capsular ligaments work to lock the knee in full extension to provide stability when standing.\textsuperscript{24}
Finally, muscles act on the joint to provide motion. The quadriceps is located on the anterior side of the upper leg and acts to extend the knee.\textsuperscript{24,25} Antagonistic to the quadriceps are the hamstrings, located on the posterior side of the upper leg and function to flex the knee.\textsuperscript{24,25}

Each structure in the knee is vital for the proper functioning of the joint. Injury or disease to one structure can compromise the whole complex system and limit its ability to bear load or facilitate the wide variety of movement required by the joint. This delicate interaction between multiple structures makes the knee a very difficult joint to artificially recreate.

### 1.2.2 Principles of Total Knee Arthroplasty

The ultimate goals of TKA, also commonly referred to as total knee replacement, are to relieve pain, restore joint function, and to improve quality of life for the patient.\textsuperscript{28} It is a complicated and involved procedure reserved for severe knee OA cases where conservative treatment options have failed, and involves the removal of diseased tissue and reconstruction of the joint with artificial components.\textsuperscript{2,14}

There are many nuances and varying approaches to TKA, however they all share a set of common objectives. First, an incision is required for adequate visualization of the entire joint space. While there are minimally invasive incisional methods such as the mini-subvastus approach that have quicker post-operative recovery times, the medial parapatellar approach remains the most popular incisional method due to the excellent exposure provided to all three joint compartments.\textsuperscript{29,30}

Another key objective of TKA is to achieve proper alignment of the lower limb.\textsuperscript{31} In many cases of knee OA there is a deformity, where the lower limb is in either a varus or valgus alignment (Figure 1.3).\textsuperscript{26} There is debate amongst arthroplasty surgeons regarding the optimal alignment, however most aim to realign the mechanical axis of the lower limb to a neutral position and resect the distal femur and proximal tibia perpendicular to the mechanical axis for a joint line parallel to the floor.\textsuperscript{27,31,32} A neutral alignment allows load to be evenly distributed to both the lateral and medial articulating surfaces and prevents
condylar liftoff—a loss of tibiofemoral contact on the either the medial or lateral side of the knee.\textsuperscript{26,33} Malalignment following TKA is associated with numerous negative outcomes including increased implant wear rates, decreased function, joint instability, and early implant failure.\textsuperscript{34–39}

![Figure 1.3: Normal, varus, and valgus alignment of the lower limb. Black dashed line depicts the mechanical axis of the lower limb. Created with Biorender.com.](image)

There is dispute regarding the optimal surgical technique for achieving proper lower limb alignment and implant component positioning, however all techniques involve both bone resection and soft tissue release.\textsuperscript{40,41} Intramedullary or extramedullary guides have traditionally been used to manually position the cutting blocks that guide the resection of the distal femur and proximal tibia; however, computer navigation and robotic-assisted systems have been developed to improve the precision of component positioning.\textsuperscript{26,28,42,43} Another source of controversy amongst arthroplasty surgeons is the decision to resect the posterior patella.\textsuperscript{44} Further resections to the anterior and posterior aspects of the distal femur are performed after rotational positioning of the femoral component is
determined. Soft tissue releases work in tandem with bone resections to create balanced gaps within the joint space in both flexion and extension. Balanced flexion and extension gaps are achieved through symmetrical spacing between the resected distal femur and proximal tibia in both the lateral and medial compartments. Computer navigation and robotic-assisted systems capable of controlling soft tissue balancing have again been shown to improve surgical precision. The order of bone resection and soft tissue release can vary between techniques and is often up to personal preference of the surgeon or individual patient factors. However, the end goal is to have a properly aligned lower limb with symmetrical flexion and extension gaps.

Finally, after proper alignment of the lower limb is achieved through bone resections and soft tissue releases, the artificial components can be implanted (Figure 1.4). While there are a vast number of different TKA designs, the main components often include a metal femoral component, a metal tibial component, and a plastic insert. The metal femoral component, often made from cobalt-chromium, has two spheroidal condylar surfaces replicating the natural anatomy of the lateral and medial femoral condyles. The tibial component, often referred to as the tibial baseplate or tray, is typically made from titanium or cobalt-chromium and consists of a flat tibial platform on the superior surface and structures on the inferior bone-facing surface to improve fixation, such as a stem, keel, or pegs. Depending on the TKA design, the ultra-high molecular weight polyethylene insert is either mobile and free to move, or is fixed to the flat tibial platform. The shape of the articulating surface can also vary depending on the TKA design, but all modern polyethylene inserts have a lateral and medial condyle for smooth, low friction articulation with the lateral and medial aspects of the metal femoral component. Occasionally, the posterior surface of the patella is replaced with a dome-shaped polyethylene component. The components are impacted into the bone, often after application of bone cement, until they are flush with the resected bone for sufficient fixation.
It is then, after the removal of diseased tissues, realignment of the lower limb, and implantation of the artificial components, that the incision can be closed and the procedure is complete.

1.3 Surgical Technique

1.3.1 Implant Alignment and Soft Tissue Balance

As previously mentioned, a successful TKA procedure will improve stability, function, and pain in knees with OA. Two important factors that play a major role in the effectiveness of TKA are implant alignment and soft tissue balance. However, there is controversy regarding the best way to achieve optimal implant alignment and soft tissue balance. Two techniques, measured resection (MR) and gap balancing (GB), were established in the 1980’s that take differing approaches to set femoral component rotation. In brief, MR replaces bony resections with similar thickness implant components to restore the joint line and sets femoral component rotation using anatomical landmarks, while GB involves
balancing ligament tensions on a perpendicular tibial resection to create equal flexion and extension gaps. The next two subsections will elaborate on the details of both techniques, as well as the advantages and disadvantages of each. However, neither technique has been proven to be superior to the other, and the decision between using a GB or MR approach currently depends on surgeon preference and individual patient factors.41,51

1.3.2 Measured Resection

The two main goals of measured resection are to replace the resected bone with implant components of similar thickness and to determine the femoral component rotation using anatomical landmarks (Figure 1.5).41 The three landmarks that are used include the transepicondylar axis (TEA), the anteroposterior (AP) axis, and the posterior condylar axis (PCA).40,41 The TEA connects the prominence of the lateral epicondyle and the sulcus of the medial epicondyle, which correspond to the origins of the LCL and MCL, respectively. The TEA determines the neutral rotation orientation of the femur and approximates the flexion-extension axis of the knee. A rectangular flexion gap can be created by placing the femoral component parallel to the TEA, improving patellofemoral tracking, tibiofemoral kinematics, and coronal stability. The AP axis of the femur, or Whiteside line, often runs perpendicular to the TEA. It is the line that runs anterior to posterior from the centre of the trochlear sulcus to the midpoint of the intercondylar notch. The PCA is the most used landmark because it is easily identifiable. It is the line connecting the posterior aspects of the lateral and medial femoral condyles. In patients with normal posterior condylar anatomy, the femoral component can be placed in a neutral rotation orientation by rotating externally by 3° with respect to the PCA.
Figure 1.5: Frontal view of the knee in flexion showing the three anatomical landmarks used in measured resection: the transepicondylar axis, the anteroposterior (AP) axis, and the posterior condylar axis. Created in part with Biorender.com.

Since the tibial and femoral resections are independent of each other, the order of resection does not matter. If done first, the tibial resection is made perpendicular to the tibial anatomic axis. Distal femoral resection will then aim for neutral limb alignment with the mechanical axis, typically requiring 5° to 7° of anatomic valgus. The anatomic landmarks will then be used to make the appropriate AP and chamfer femoral resections for proper femoral component rotation. Osteophytes are then removed from the femur and tibia and knee stability is tested using trial components. Although the MR technique prioritizes anatomical positioning of implant components, soft tissue releases can be performed afterwards to achieve flexion and extension gap balance.
It has been suggested that MR is the optimal technique in cases with easily identifiable landmarks, large posterior osteophytes, or nonreducible coronal deformities with contracted ligaments.\textsuperscript{41} Supporters of MR have suggested one of its main advantages is preservation of the joint line. Other advantages include the technique’s respect for the native knee anatomy and the numerous methods to assess femoral component rotation afforded by the multiple anatomical landmarks.\textsuperscript{41} However, the substantial variation in femoral anatomy between patients results in variability in femoral component rotation between patients.\textsuperscript{41,52,53} Using all three landmarks can help minimize errors associated with MR, however these landmarks can be difficult to identify in some cases. Compounding the issue is that the PCA, the most easily identifiable landmark, is considered the least reliable and not appropriate for all patients, whereas the TEA, often considered the most reliable landmark, can be difficult to properly identify.\textsuperscript{40,41,53} Another limitation is that it is difficult to balance gaps through soft tissue releases after setting the gaps based on anatomical landmarks.\textsuperscript{41} It is suggested that the MR technique has an increased incidence of coronal instability in the form of condylar separation, which results in unequal loading and potential early implant loosening, although studies of implant migration have shown no differences between MR and GB techniques.\textsuperscript{54–56}

1.3.3 Gap Balancing

The main goal of the GB technique is to create symmetrical flexion and extension gaps, relying on ligamentous releases performed prior to bone resections (Figure 1.6).\textsuperscript{40,41} These soft tissue releases correct deformities and realign the limb before femoral rotation is set. Balancing the extension gap first is the more commonly used technique, however it is also possible to balance the flexion gap prior to the extension gap.\textsuperscript{40,41} As with MR, the order of distal femur and proximal tibia resections is up to surgeon discretion.\textsuperscript{41} If done first, the tibial resection is made perpendicular to the tibial anatomic axis. Osteophytes must then be removed before any soft tissue releases can be performed. Laminar spreaders assist with opening the flexion gap for removal of posterior osteophytes. After removal of osteophytes, the next step in the extension first GB technique is to release tight ligamentous structures to realign the lower limb to a neutral position relative to the mechanical axis and create a symmetric, rectangular extension gap. The next objective is to create a flexion gap that is
the same dimension as the extension gap. The knee is positioned to 90° of flexion and tensioners or laminar spreaders are used to adjust the collateral ligaments until a rectangular flexion gap of equal size as the extension gap is created. Posterior femoral condyles are resected once flexion-extension gap balancing has occurred, followed by anterior and chamfer resections.

Figure 1.6: Frontal view of the knee in A) extension and B) flexion. Symmetrical, rectangular gaps are created by balancing the medial and lateral sides in extension and flexion. Created in part with Biorender.com.

It is believed by GB proponents that balanced gaps are the most important determinate of TKA outcomes and that GB provides greater coronal stability.40,56 The greater coronal stability provided by equivalent flexion and extension gaps results in greater proprioception and less condylar separation that may prevent increased polyethylene wear and uneven implant loading.56,57 It has been recommended that GB is optimal in patients with minimal osteophytes, healthy collateral ligaments, or abnormalities that make the identification of
anatomical landmarks needed for MR more difficult. However, a disadvantage with the GB technique is that it often results in an elevated joint line, as mismatched gaps are corrected for by resecting additional bone from the distal femur and using a thicker polyethylene insert. The joint line elevation and additional distal and posterior femur resections can increase instability in midflexion, abnormal patellofemoral mechanics, insufficient posterior condylar offset, and knee impingement with reduced knee flexion. The GB technique can also result in nonanatomic femoral rotation, a result of residual osteophytes or improperly balanced ligaments that can jeopardize patellar tracking.

1.4 Implant Design

1.4.1 History of Knee Replacement

The first knee replacement was performed in 1890 by Dr. Themistocles Gluck, who introduced a hinged design made from ivory and fixed with an early version of bone cement. However, the knee arthroplasties performed by Gluck failed due to infection and he abandoned this work. Renewed interest in knee replacements occurred after Dr. John Charnley performed the first modern hip replacement in the early 1960’s. Two major advancements helped spur the development of the original total knee replacements that have inspired many of the designs still in use today. These were the development of high density polyethylene plastic as a bearing surface in 1963 and the popularization of a methylmethacrylate bone cement in 1960, which was later approved by the Federal Drug Administration in the United States in 1971. The challenge remained to design a knee replacement that could withstand the high load transfer demands and complex kinematics of the knee joint, reproducibly deliver good patient outcomes, and provide long-term implant survival. Two distinct design approaches simultaneously emerged, an anatomical approach and a functional approach. The anatomical approach aimed to preserve most or all of the soft tissue constraints and designed fixed components that avoided conflict with those constraints. The functional approach sought to simplify knee mechanics by resecting the cruciate ligaments and maximizing contact area between femoral and tibial components to reduce stress on the polyethylene. Table 1.1 summarizes the key philosophies and
innovations that originated from both design approaches. The following subsections will elaborate on both design philosophies.

Table 1.1: Summary of the Ideas Originating from the Functional and Anatomical Approaches to TKA Implant Design.

<table>
<thead>
<tr>
<th>Functional Approach</th>
<th>Anatomical Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Ligament resection</td>
<td>• Ligament retention</td>
</tr>
<tr>
<td>• Conforming femoral and tibial shapes</td>
<td>• Anterior flange for patella tracking</td>
</tr>
<tr>
<td>• Flat, neutral bone resections</td>
<td>• Multi-radii femoral components</td>
</tr>
<tr>
<td>• Equal flexion and extension gaps</td>
<td>• Nonconforming implant shapes</td>
</tr>
<tr>
<td>• Cam and post system</td>
<td>• Multiple implant sizes</td>
</tr>
<tr>
<td>• Metal-backed tibial components</td>
<td>• Asymmetric condyles</td>
</tr>
<tr>
<td>• Mobile-bearing polyethylene inserts</td>
<td>• Positioning using bony landmarks</td>
</tr>
</tbody>
</table>

1.4.2 Functional Approach to TKA Design

The functional design approach was first implemented by Drs. Freeman and Swanson, who developed the first cemented condylar total knee between 1966 and 1968. They adhered to three concepts to address the issues of polyethylene wear and knee deformities that proved to be influential for future functional designs. First, the approach required the resection of both cruciate ligaments to allow for the correction of deformities and broaden the contact areas of the femoral and tibial components. Second, the approach would simplify kinematics by reducing posterior femoral rollback and enabling a “roller-in-trough” design, which would also help to maximize contact area. Third, the bone surfaces in contact with implants would be flat to preserve bone and simplify the surgical technique. Freeman also introduced the concept of equal flexion and extension spaces, later coined as “flexion gap” and “extension gap” by Dr. Insall, which were an important aspect of functional designs and later became the principal tenet for the gap balancing surgical technique.

The Freeman-Swanson design influenced later designs by Drs. Insall, Walker, and Ranawat, including the Total Condylar knee, which was the first widely successful cruciate-sacrificing design. It had partially conforming femoral and tibial components with double-dished shapes, a troughed anterior flange and polyethylene patellar button, and a central tibial eminence to provide mediolateral stability. Despite its
success, the Total Condylar knee would suffer from anterior translation of the femoral component, especially in flexion. This would lead to deformation of the tibial polyethylene, tibial component loosening, anterior dislocation, and a limited range of knee flexion. Drs. Insall and Burstein further advanced the functional approach by introducing an oval intercondylar femoral cam that would engage a wedge-shaped tibial post at approximately 70° of knee flexion and resulted in progressive posterior displacement of the femur as flexion increased. These would be the first posterior-stabilized (PS) designs, which would influence many future PS designs that are still widely used today.

Another design concept to originate from the functional branch of TKA design was metal tibial baseplates with modular polyethylene inserts of various thicknesses, designed by Dr. Eftekhar. Previously, tibial components and liners were combined in one all-polyethylene tibial component. Eftekhar also designed the first tibial component stem to assist implant fixation. Mobile bearing and rotating platform knee designs, first created by Drs. Buechel and Pappas, also sprung from the functional approach as a method for minimizing contact stresses.

1.4.3 Anatomical Approach to TKA Design

The first anatomical TKA design was implanted in 1968, the same year as the Freeman-Swanson functional design. It was designed by Drs. Yamamoto and Kodama, and consisted of a femoral component with an anterior flange and a tibial component with two cutouts for retention of the cruciate ligaments. Dr. Townley further developed the anatomical design approach by proposing component shapes that mimicked natural anatomy. Femoral components had 3 separate radii of curvature in the sagittal plane and greater mediolateral radii than anteroposterior radii to broaden contact area. Tibial components were non-conforming to allow rotational freedom, and cruciate ligaments were preserved to provide rollback and joint stability. He also recognized the need for multiple implant sizes. His original design also had asymmetrical femoral condyles and an asymmetrical patellar flange, and while these had to be abandoned due to manufacturing limitations, many modern implants now incorporate these design features. Dr. Townley described multiple principles for anatomical TKA design and surgery, including (1) inserting the thinnest possible implant, (2) there should be normal knee kinematics, (3)
there should be a normal polycentric femoral surface contour, (4) accurate implant sizing, (5) preservation of all ligaments, and (6) implant positioning using anatomical landmarks to assure mechanical alignment.\textsuperscript{46} Another concept that originated from the anatomical design approach was the retention of the PCL only. The first posterior cruciate-retaining (PCR) replacement, the Duopatella knee, was developed by Drs. Walker, Ranawat, and Inglis as an anatomical alternative to the functional TC knee developed by Insall.\textsuperscript{71} It was first implanted in 1974, and it would later inspire many more PCR designs that are still popular today.\textsuperscript{46}

1.4.4 Bicruciate Stabilized TKA Design

The two most popular TKA designs used today are the PS and PCR replacements, which still trace their origins to the original functional and anatomical design approaches of the 1970s, respectively.\textsuperscript{45,46} However, both designs lack the ACL or structures to replicate ACL function. The ACL, as previously mentioned, is an important joint stabilizer and helps to drive knee kinematics, particularly preventing anterior translation of the tibia relative to the femur and the screw-home mechanism that occurs at full knee extension.\textsuperscript{24,25} While the original anatomical approach retained both cruciate ligaments, the early designs suffered from unacceptable failure rates and were not as widely successful as their functional design competitors.\textsuperscript{46,69,70} Advances in surgical technique and manufacturing processes have resulted in modern bicruciate retaining (BCR) designs that preserve both cruciate ligaments, like the original anatomical knee replacement designs, however the surgery is still technically difficult and requires both cruciate ligaments to be intact.\textsuperscript{72,73}

Another modern knee replacement that aims to provide ACL and PCL function is the bicruciate stabilized (BCS) design. The first BCS design, the Journey I (Smith & Nephew, Memphis, TN), was introduced in the early 2000s and implemented ideas from both the functional and anatomical design approaches.\textsuperscript{74–78} The Journey I BCS design, inspired by past functional designs, required resection of the ACL and PCL and replicated their function using a dual cam-post mechanism. As with the functional PS designs, the Journey I had a posterior femoral cam that interacted with the tibial post in deeper flexion to promote rollback, external rotation of the femur relative to tibia, and increase flexion range. However, unlike PS designs, the Journey I also had an anterior femoral cam that interacted
with the tibial post at full extension and early flexion to drive the screw-home mechanism, with internal rotation of the femur relative to the tibia as the knee approaches full extension. While the Journey I took a functional approach to dealing with cruciate ligaments, the shape of the implant components were reminiscent of the anatomical approach. The femoral component had asymmetrical condyles, multiple radii of curvature in the sagittal plane, and an asymmetrical anterior flange. The tibial polyethylene surface was designed to replicate tibial plateau surface geometry, with a concave medial condyle and a slightly convex lateral condyle. The Journey I components were also shaped to restore the natural 3° tibial varus joint line. These design features helped the Journey I achieve kinematic patterns more closely approximating normal knees. However, the kinematic constraints were suspected to cause symptoms similar to iliotibial band friction syndrome, leading to soft tissue stretching and knee pain. There was also a concern with tibiofemoral dislocation due to the height of the post and position of the cam presenting a short jump distance for the implant. Femoral component loosening was also a main cause of device failure. It was suggested that design modifications to reduce posterior rollback on the lateral condyle were necessary, and eventually, a recall of the Journey I was issued due to revision rates over 1.5 times greater than other standard TKA implants.

A second-generation design, the Journey II BCS (Smith & Nephew), was introduced in 2013 and is currently the only available BCS design (Figure 1.7). It is an altered version of the original Journey I, relaxing the constraints found in the first-generation device. Kinematic analyses have shown the Journey II still provides knee kinematics approximating the natural knee, but without the extreme posterior rollback laterally and external femoral rotation that resulted in the failure of its predecessor. Recent survivorship studies have shown improved early complication and revision rates of the Journey II, suggesting the design modifications have been effective, however, there is a need for more evidence. One of the objectives of this thesis is to use advanced imaging to predict the long-term fixation of the Journey II BCS design.
Figure 1.7: Bicruciate stabilized (BCS) TKA implant design. A) Frontal view of the BCS TKA implant, depicting bone resections perpendicular to the mechanical axis and femoral and tibial polyethylene geometry recreating the 3° physiological joint line. B) Sagittal view and C) axial view of BCS TKA depicting dual cam-post system.

1.5 Radiostereometric Analysis

1.5.1 X-ray Imaging

X-rays are a high-energy form of electromagnetic radiation, with wavelengths ranging from 0.01 to 10 nanometers and energy ranging from 100 electron volts (eV) to 100 keV. X-rays can be produced and controlled for imaging with x-ray tubes and x-ray generators. X-ray tubes provide the environment needed to produce the x-rays, whereas the generator provides the source of electrical voltage and user controls to energize the x-ray tube. Negative and positive voltage cables run from the x-ray generator to a cathode and anode in the x-ray tube, respectively. A separate circuit connects the cathode to a low-energy voltage source, which when activated, causes heating of the cathode filament and the release of electrons through thermionic emission. Electrons accumulate at the surface of the cathode filament to create a buildup of negative charge. The x-ray generator then applies a high voltage to the cathode and anode, resulting in the acceleration of electrons from the cathode to the positively charged anode. Each electron attains kinetic energy equal to the applied voltage, which can be selected by the operator and typically ranges from 50 to 150 keV. The tube current and exposure time are also adjustable imaging parameters.
that determine the total number of electrons that travel from cathode to anode during the exposure, and are often expressed as a single unit, milliampere-seconds (mAs). X-ray production occurs when accelerated electrons collide with the metal anode, usually made of tungsten, resulting in a process called Bremsstrahlung, where kinetic energy is converted to electromagnetic radiation of equivalent energy, in this case an x-ray photon (Figure 1.8).86

Figure 1.8: X-ray production from conversion of energy into electromagnetic radiation. Electrons that accelerate toward the metal anode interact with metal (usually Tungsten) atoms. Incident electron A demonstrates the production of characteristic x-ray radiation, where a K shell electron is ejected. An outer shell electron will transition to the inner shell, emitting an x-ray with equivalent energy to the difference in binding energies between the outer shell and K shell. Incident electrons B, C, and D demonstrate Bremsstrahlung, the process where kinetic energy is converted to electromagnetic radiation of equivalent energy. Electron B collides with the nucleus of the metal anode atom, and all kinetic energy is converted to an x-ray, representing the maximum energy of x-rays produced. Electron C has a close interaction with the nucleus resulting in a significant deceleration and the production of moderate energy x-rays, whereas Electron D has a distant interaction with the nucleus resulting in a smaller deceleration and the production of lower energy x-rays. Created with Biorender.com.
The first instance of x-ray being applied to imaging occurred in 1895, when Wilhelm Roentgen took the famous x-ray of his wife’s hand and wedding band. The ability to image metal and bone would prove useful for the assessment of another innovation introduced earlier that same decade, the knee replacement. Today, x-ray is still commonly used since it is a quick and comparatively cheap medical imaging technique. The simplest application of x-ray is projectional, or conventional, radiography, where the area to be imaged is placed between the x-ray tube and a detector. The body part, or implant components, of interest, will attenuate x-ray photons and prevent them from reaching the detector, resulting in brighter spots in locations on the image where less x-rays hit the detector. X-ray attenuation is proportional to the electron density (atomic number) and the thickness of the objects of interest. Bones, which are high in calcium (atomic number 20), and implant components—often made of metals such as titanium (atomic number 22), cobalt (atomic number 27), and chromium (atomic number 24)—attenuate more x-rays than soft tissues, which are composed of mostly hydrogen (atomic number 1) and carbon (atomic number 12). Therefore, bone and implants appear bright on radiographs and are clearly visible due to the low attenuation of the surrounding soft tissues.

1.5.2 Marker-Based Radiostereometric Analysis

Radiostereometric analysis (RSA), otherwise known as Roentgen stereophotogrammetric analysis, was developed for studying kinematics of the musculoskeletal system in 1972 by Göran Selvik. As the name suggests, it is a technique for determining the three-dimensional (3D) pose of a rigid body using a calibration object and simultaneous exposure of the rigid body from two different x-ray sources.

Both the object of interest and the calibration object, known as the calibration cage, are placed within the x-ray image field of view, and are exposed together. Calibration cages come in multiple configurations, most commonly in a uniplanar configuration where x-ray detectors are positioned side-by-side or in a biplanar configuration where x-ray detectors are positioned perpendicular to one another (Figure 1.9). Regardless of configuration, the calibration cage, made from a radiolucent material, is marked with a known distribution of
radiopaque beads in two planes—the fiducial plane and the control plane (Figure 1.10A). These fiducial and control beads can be detected on x-ray images and are used to define the laboratory, or global, coordinate system (Figure 1.10B). The first step is to use the position of the fiducial beads in the image coordinate system and the known position of the fiducial beads in the global coordinate system to create a transformation matrix bringing the x-ray image into the fiducial plane (Figure 1.10A–B). Then, the known location of the control beads and their position on the transformed x-ray image can be used to generate a line that can be extended beyond the control plane towards the x-ray source (Figure 1.10C). The intersection of the lines generated for each control point determines the location of the x-ray source, or focus. This process is repeated for the second x-ray image, with the position of the second x-ray source determined and the global coordinate system defined.

Figure 1.9: A) Biplanar and B) uniplanar calibration cages (RSA Biomedical, Umea, Sweden) for radiostereometric analysis.
Figure 1.10: Radiostereometric analysis calibration. A) Radiograph is transformed to the fiducial plane using the fiducial markers in known locations on the calibration object. B) Transformed radiograph in the laboratory coordinate system. C) Control markers on the transformed radiograph are back-projected through their corresponding control markers in the control plane to find the x-ray focus. Steps A–C are repeated for a second view. D) The intersection of the two lines from the object marker on the radiographs to their respective x-ray sources will determine the three-dimensional location of the object marker.

In marker-based RSA, tantalum marker beads are inserted into the bone and are attached or inserted into the implant components, and these object markers can be viewed on the x-ray images (Figure 1.11). These beads typically range from 0.8–1.0 mm in diameter and are often made of tantalum, a radiopaque, bioinert, and biocompatible metal. Lines can be generated by back-projecting from the object marker positions on the transformed x-ray images and the respective x-ray foci. The intersection of the two generated lines determines the 3D coordinates of the object marker in the global coordinate system (Figure 1.10D). Repeating this for each object marker allows rigid bodies to be constructed for the various objects of interest (i.e., bone and implant components), and the 3D position and orientation of the rigid bodies can be calculated.
The main advantage of the marker-based RSA technique is its exceptional accuracy and precision, which are on the order of tens to hundreds of microns.\textsuperscript{89,91} The superior accuracy and precision allow for relatively small clinical studies of implant kinematics, meaning new devices or surgical techniques can be assessed on a limited group of patients before being widely adopted.\textsuperscript{92,93} However, marker-based RSA relies on marked implants, which can be difficult, expensive, and may even jeopardize the strength of the implant or its fixation. Implant markers are also often obscured by the implant itself and are not visible on the x-ray images.\textsuperscript{94}

### 1.5.3 Model-Based Radiostereometric Analysis

In 2001, Valstar et al. proposed model-based RSA (MBRSA) to overcome the limitations of traditional marker-based methods (Figure 1.12).\textsuperscript{94} MBRSA takes advantage of the improved computational power of the 21\textsuperscript{st} century, using triangulated surface models, such as computer-aided design (CAD) models from the manufacturer, as the implant rigid body geometry. This removed the need to mark implants with tantalum beads and allows any implant design to be studied so long as a surface model is available. Now, the contour of the implant on both radiographic images is detected rather than markers. In a properly calibrated setup, a virtual projection of the surface models onto the images can be
generated. The contours of the “shadow” generated from the virtual projection can then be fit to the detected contours on both images by iteratively adjusting the poses of the surface model, minimizing the distance between projected and detected contours. The optimized fitting of contours on both images will result in the real 3D pose of the implant.\textsuperscript{94} There is a sacrifice made to precision when using MBRSA, however it is still precise enough for most clinical applications.\textsuperscript{95}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.12.png}
\caption{Model-based radiostereometric analysis software for A) a biplanar and B) a uniplanar setup. Shadows of the computer-aided models are fit to the implant outline on the radiograph to obtain three-dimensional pose. Tantalum markers are used to generate rigid bodies of the adjacent bones. Images acquired within Model-based RSA (RSAcore, Leiden, Netherlands).}
\end{figure}

While markers are no longer required on the implants, markers are still needed to generate rigid bodies of the adjacent bones. A set of guidelines for RSA published in 2005 provides recommendations for a pair of parameters that define the quality of the bone markers.\textsuperscript{92} The first, condition number (CN), describes the distribution of the markers within the bone, and is a function of the number of markers and the distance of each marker to an arbitrary straight line running through the cluster of markers.\textsuperscript{96} An upper limit of 150 for the CN has been suggested.\textsuperscript{92} The CN can be minimized by increasing the distance of each marker from the arbitrary line, reducing the collinearity of the distribution. A minimum of three markers are required, however inserting more markers decreases the likelihood of having a collinear distribution, so it is recommended that between six and nine markers are used.\textsuperscript{92} The second parameter is mean error (ME) of rigid body fitting, the “mean difference
between the relative distances of markers in a rigid body in one examination compared to that in another examination”. The ME reports whether the markers have shifted slightly within the bone between examinations. Markers that are deemed to have shifted over a set threshold can be excluded from the rigid body. The guidelines suggest using an upper threshold of 0.35 mm for ME of rigid body fitting.  

1.5.4 Applications of Radiostereometric Analysis

Goran Selvik introduced RSA as “a method for the study of the kinematics of the skeletal system”. Knee replacements, being radiopaque treatments for musculoskeletal disease, make for perfect objects to study using RSA. Kinematics simply refers to the branch of mechanics concerned with the motion of objects without reference to the forces which cause the motion. There are multiple kinematic measurements that can be made for knee replacements, including implant migration, inducible displacement, and tibiofemoral contact kinematics.

RSA is the gold standard technique for measuring longitudinal implant migration, or the shifting position of an implant relative to its host bone over time. These shifts in implant position are often submillimeter in nature, requiring a highly accurate technique like RSA to detect. Elevated early implant migrations are an indication that insufficient fixation has occurred, and can be used to predict future aseptic loosening, a major reason for long term revision of knee replacements. Implant migration is often reported as maximum total point motion (MTPM), the 3D translation at the point on the implant that moves the most between two examinations. MTPM can be located at any point on the implant, and the location of this point is not necessarily consistent for each follow-up examination of the same implant. Fictive points, or imaginary points of interest, can be positioned on the implant model in the software to measure migration at consistently defined points on the implant, simulating traditional marker-based methods (Figure 1.13). Migration can also be reported as translations and rotations about the medial-lateral (x axis), superior-inferior (y axis), and anterior-posterior (z axis) axes.
Figure 1.13: Inferior view of tibial component depicting location of fictive points. AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; ST, stem tip.

Thresholds for acceptable implant migration have been established comparing RSA data to the eventual fate of the studied implants. Pijls et al. established that early MTPM within the first six months post-operation under 0.5 mm was acceptable, meaning implants under the threshold are expected to have revision rates equal or superior to the industry standard 3% revision rate. An MTPM at six months over 1.6 mm is deemed unacceptable, meaning the implant is expected to have revision risks greater than the industry standard. Implants with MTPM measurements in between 0.5 and 1.6 mm are determined to be at risk and may or may not have elevated revision risks. MTPM values at six months can be subtracted from the MTPM measured at one year to determine the first stage of stability for the implant, with differences in the MTPM less than 0.2 mm indicating stable implants. Stability of the implant from one to two years post-operation can be determined in a similar manner, with a similar threshold of 0.2 mm for stable and unstable implants. Guidelines for RSA suggest performing the initial baseline measurement within two weeks post-operation, with follow-up examinations at six weeks, three months, six months, one year, and two years post-operation. Patients should be in a supine, non-weightbearing position when imaged (Figure 1.14).
Figure 1.14: Biplanar radiostereometric analysis setup with patient in a supine position. Yellow arrows depict x-ray beams.

RSA is also capable of measuring the inducible displacement of implant components to assess component fixation.\textsuperscript{91,92} Inducible displacements are similar to implant migration, however rather than measuring the micromotion of implants over time, they report the amount of micromotion that occurs when a force is applied to the implant to induce a displacement, as the name suggests. The inducible displacement will be the difference in pose of the implant component relative to the bone between a baseline, supine examination where no force is applied, and an examination taken at the same time point where a force is applied to the knee. Inducible displacement of knee replacements can be generated through many different force applications to the knee joint, including neutral standing positions, single leg stances, squatting or lunging positions, stepping activities, or applied axial or rotational forces (Figure 1.15).\textsuperscript{102–109} Unlike with implant migration, no threshold exists for detection of loose implant components using inducible displacement, however displacements up to 1.7 mm have been reported for stable components.\textsuperscript{109}
The ability of RSA to determine the 3D poses of implant components allows the contact between femoral and tibial components to be calculated, known as tibiofemoral contact kinematics. There are dynamic RSA techniques that allow for the monitoring of different dynamic activities, such as deep knee bends, walking, and stair climbing. However, traditional MBRSA can be used in a quasi-static manner and still produce tibiofemoral contact kinematics similar to dynamic methods for simple activities. In the quasi-static method, patients will be imaged in multiple static positions of an activity. For example, a deep knee bend can be recreated quasi-statically by imaging the patient while they are squatting at increasing intervals of knee flexion. Contact areas can be generated for each imaged position by finding points between the femoral and tibial components that are within a set distance of each other. Tibiofemoral contact kinematics can be calculated using these contact areas, with interpolation used for estimating the contact locations between the imaged flexion angles. Since the tibiofemoral joint has two points of contact, these points will be monitored to determine the contact kinematics.
contact, contact kinematics are reported for both the lateral and medial condyle. Contact kinematic patterns of natural knees have been well studied, and many modern knee replacement designs, such as the BCS TKA design, aim to approximate these patterns.84,115

![Figure 1.16](image)

Figure 1.16: Tibiofemoral contact areas (in purple) for increasing flexion angles of a deep knee bend.

1.6 Patient-Reported Outcomes

1.6.1 Role of Patient-Reported Outcome Measures

While there are specific surgical objectives for TKA, the ultimate end goal is to improve the quality of life for the patient. Therefore, patient-reported outcome measures (PROMs) are an important evaluation tool for determining the success of any TKA, especially given the increasing focus on patient-centered care in modern health care systems. PROMs, in the form of surveys or questionnaires, can be administered before and after TKA surgery to obtain qualitative feedback from the patient. There are many validated surveys and questionnaires used in the setting of TKA. The Short Form 12 (SF-12) is commonly used to assess general physical and mental health.116 The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) is a questionnaire specific for assessing osteoarthritis and joint replacement and assesses pain, stiffness, and function.117 The University of California, Los Angeles (UCLA) Activity Score is a simple 1 to 10 scale assessing a patient’s self-reported activity level.118 The Knee Society Score (KSS) is specific to TKA, with different versions for pre- and post-operation that both assess symptoms, satisfaction, expectations, and functionality, as well as a section to be
completed by a nurse practitioner or clinician on objective knee indicators. Implementing multiple PROMs can provide valuable information on the effectiveness of different TKA treatments, techniques, and devices across populations of different sexes, ages, body sizes, and activity levels.

While PROMs are a time efficient and cost effective tool for assessing TKA, there are several limitations to consider. The categorical nature of many PROMs can make it difficult to detect minor difference in outcomes, as patients who have very different levels of outcomes may be grouped together. Ceiling and floor effects can also occur when patients report the highest or lowest score available. This can make it very difficult to detect subtle differences between outcomes at the extremes, such as differentiating good and excellent outcomes. Discrepancies also exist between self-reported levels of activity and function versus objective measurements evaluated during instrumented sessions. The validity of questionnaires can also be negatively affected by pain, which can greatly influence the result of many PROMs.

1.6.2 Patient Satisfaction

Patient satisfaction following TKA is an elusive target, with many studies continuing to report approximately 20% of knee replacement recipients remain dissatisfied after the procedure. Joint registries, which have recently begun reporting PROMs, convey fairly similar findings, with the Australian Orthopaedic Association National Joint Replacement Registry reporting an 83.7% satisfaction rate and the Swedish Arthroplasty Register reporting an 81% satisfaction rate. The Canadian Joint Replacement Registry found better rates of satisfaction, reporting that 87.9% of patients felt satisfied. It is not fully understood why the rate of dissatisfaction persists despite advancements in surgical technique and implant design, but it is thought to be because of a combination of internal patient-dependent and external patient-independent factors.

Complicating the problem is that there is a well-reported disparity between patient clinician and patient satisfaction ratings. However, a TKA cannot be considered a success unless it results in a satisfied patient.
Since it is subjective in nature, patient satisfaction can only be self-reported by individual patients. The measurement of patient satisfaction is challenging, as the definition of satisfaction may differ from patient to patient, and satisfaction with the outcome of care can often be confused for satisfaction with the process of care.\textsuperscript{133–136} There have been many questionnaires used to assess patient satisfaction, but not all have been validated.\textsuperscript{134,135,137} Questionnaires will often report on factors that are associated with satisfaction, such as preoperative expectations and pain relief.\textsuperscript{124} The Forgotten Joint Score is one that assumes the greatest possible satisfaction will be achieved when a patient forgets about their joint replacement.\textsuperscript{138} It therefore asks a series of questions regarding a patient’s awareness of their joint replacement for a variety of relevant activities, and has been shown to have less ceiling effect compared to the WOMAC. Other questionnaires have been specifically designed to measure satisfaction in arthroplasty patients.\textsuperscript{139} Some questionnaires, like the KSS, have dedicated subsections for questions related to satisfaction, where patients use a Likert scale to respond to specific questions regarding their satisfaction with pain relief, performing activities of daily living, and participating in recreational activities, allowing clinicians and researchers to discern which goals of TKA are not being met.\textsuperscript{119}

1.7 Functional Outcomes

1.7.1 Tests of Patient Function

Functional tests are an effective way to compare knee OA patient function to normal patient function or to assess the efficacy of different treatments. Patients who perform better on functional tests after TKA are 6-8 times more likely to be satisfied with their surgery.\textsuperscript{140} There are many different tests recommended by the Osteoarthritis Research Society International (OARSI) that are each designed to study a patient performing a function and provide performance based outcome metrics, usually time to complete tests, distance travelled, or number of repetitions depending on the test.\textsuperscript{141} The thirty second chair stand test requires a patient to repeatedly rise from and sit in a chair, counting the number of repetitions completed in thirty seconds. A chair stand places a strain on both knees and more repetitions is indicative of better lower body strength and balance. The stair climb test is also a test of strength and balance, with patients ascending and descending a number of steps (9 recommended). The amount of time required to complete the ascent and descent
is recorded, with less time equaling better function. The 40 metre (m) fast paced walk test requires patients to continuously walk a 10 m distance four times, turning around after each 10 m segment. Patients are asked to walk as quickly as possible while being safe and the time to complete the total 40 m is recorded. A lower completion time signifies greater patient mobility and walking speed, which is often impairing in knee OA patients. The six minute walk test involves a patient to continuously walk for six minutes, with the total distance travelled being recorded. The walk test challenges patient stamina and mobility, with greater distances travelled indicating better function. The last test in the OARSI recommendations is the timed-up-and-go (TUG) test, which incorporates multiple activities into one functional test (Figure 1.16). Patients begin seated in a chair, stand and walk 3 m, turn around and walk back to the chair, then turn and sit back in the chair, with a shorter completion time indicating better overall patient function. The multiple stages and transitions required by the test provide a better assessment of the strength, balance, and mobility of patients than a single activity test. The test is easily implemented in a clinic since it only requires a chair, a stopwatch or timer, and 3 m of walking space.

![Figure 1.17: Stages of the timed-up-and-go (TUG) test. Wearable sensors are worn above and below each knee.](image)

While metrics of completion time, repetition number, and distance travelled have been shown to correlate to positive outcomes following OA interventions, there are still limitations to the traditional functional tests. No specific functional information is recorded about the joint in question, such as flexion ranges or joint velocities. This also ignores the many different compensation mechanisms patients might use to complete the
test. In addition, there may be confounding variables such as additional surgeries to other joints or poor health impacting a patient’s test performance that are not distinguishable in the traditional metrics.

### 1.7.2 Instrumented Timed-Up-and-Go Test

Wearable sensors can be used in conjunction with functional tests to overcome the limitations of the traditional test metrics. Inertial measurement units (IMUs), a type of wearable sensor containing an accelerometer, magnetometer, and gyroscope, are cost effective and user friendly devices for tracking human movement outside of the laboratory.\textsuperscript{144,145} Data from the IMUs, such as linear accelerations and angular velocities, can be used to determine a number of spatiotemporal and kinematic parameters for patients in a clinical setting.\textsuperscript{146} Bloomfield et al. designed and validated a wearable IMU sensor system that is designed to track joint function during a TUG test (Figure 1.11).\textsuperscript{147,148} The TUG test was chosen due to the multiple stages that include activities important for everyday joint performance.\textsuperscript{141} A sensor is worn above and below each knee to collect quantitative joint angle data. While the system can still track the traditional TUG test outcome metric of total completion time, as well as automatically recognizing and timing each activity of the TUG test, the real advantage is that the system can collect joint specific data, including flexion/extension velocities and accelerations and ranges of joint motion. This allows the functional performance of the operated knee to be analyzed and compared to both the contralateral joint and to joints of other patients, giving a more representative assessment of joint function than completion time alone.

### 1.8 Objectives and Hypotheses

The overall goal of this thesis was to determine if a new implant design, the BCS TKA, could provide better outcomes, regarding both biomechanical implant performance and patient self-reported and performance-based outcomes. The BCS device was implanted into a group of patients and studied \textit{in vivo} using radiographic imaging, wearable sensors, and patient questionnaires. The specific research objectives were:

1. To investigate the implant migration and inducible displacement and predict the long-term stability of BCS TKA performed using the GB and MR surgical
techniques, with the hypothesis that both techniques will have equivalent migration and displacement.

2. To examine the implant migration, tibiofemoral contact kinematics, objective measurements of patient function, PROMs, and demographic factors to determine if differences exist between satisfied and dissatisfied TKA patients, hypothesizing there will be worse metrics in dissatisfied patients.

3. To determine whether there is a relationship between implant migration and tibiofemoral contact kinematics for the BCS TKA implant design, with the hypothesis that abnormal kinematics will result in elevated levels of implant migration.

1.9 References


55. Williams HA, Broberg JS, Howard JL, Lanting BA, Teeter MG. Effect of gap balancing and measured resection techniques on implant migration and contact


Migration and Inducible Displacement of the Bi-cruciate Stabilized Total Knee Arthroplasty: A Randomized Controlled Trial of Gap Balancing and Measured Resection Techniques

A version of this chapter has been published in the Journal of Arthroplasty.


2.1 Introduction

Total knee arthroplasty (TKA) is a successful procedure for treating pain and returning function to patients with severe arthritis of the knee, however it continues to have high patient dissatisfaction rates.\(^1\) New technology has been introduced in an attempt to improve the outcomes of the procedure.\(^2\) A second-generation bi-cruciate stabilized (BCS) TKA was designed to more closely approximate a normal knee.\(^3\)–\(^10\) It replicates the function of the anterior and posterior cruciate ligaments with an asymmetric dual cam-post mechanism, and has asymmetrical femoral, tibial, and polyethylene components to reproduce the 3° of tibial varus.\(^4\) These design features helped the first-generation BCS design achieve kinematic patterns similar to normal knees; however the kinematic constraints were suspected to cause symptoms similar iliobibial band friction syndrome, leading to soft tissue stretching and knee pain.\(^11\) There was also a concern with tibiofemoral dislocation due to the height of the post and position of the cam presenting a short jump distance for the implant.\(^10,12\) Eventually, a recall was issued due to revision rates over 1.5 times greater than other standard TKA implants, with femoral component loosening being a main cause of device failure.\(^13\)–\(^16\) The second-generation design made alterations to relax the constraints of the original design while maintaining approximately normal kinematics.\(^3,4\) Recent studies have suggested these alterations have improved the early complication and revision rates of the second-generation BCS design; however there is a
lack of information on the best surgical technique to use with this non-traditional implant design.\textsuperscript{4,5,9,10}

Two common surgical techniques for TKA are gap balancing (GB) and measured resection (MR). GB involves generating equal rectangular joint spaces in flexion and extension through soft tissue balancing prior to final femoral resections, while MR relies on bony resection matching anatomical landmarks before soft tissues are released. It has been proposed that GB techniques may provide more reproducible flexion gap stability.\textsuperscript{17} MR has been reported to result in TKAs with greater coronal instability in the form of condylar separation, leading to unequal loading and therefore early loosening, suggesting that GB may have lower revision risks.\textsuperscript{18} GB has also been reported to result in better Knee Society Scores (KSS) for function than MR in a recent meta-analysis, but it remains unclear whether this translates to better functional results.\textsuperscript{19} GB also has potential drawbacks, including the risk of an elevated joint line, which may result in mid-flexion instability.\textsuperscript{19,20} Despite these differences, previous studies with other implant designs have shown that both surgical techniques provide equivalent implant fixation.\textsuperscript{21–24} However, no such comparison of implant fixation between surgical techniques has been made for this BCS TKA design, which emphasizes anatomically shaped components and recreation of the 3° tibial varus joint line. It is worth investigating whether the unique implant design benefits from either a GB or MR surgical technique, especially considering the issues the first-generation design had regarding femoral component loosening, soft tissue stretching, pain, and tibiofemoral dislocation.

The goal of this randomized controlled trial (RCT) was to investigate implant migration and inducible displacement using RSA to predict the long-term stability of a BCS TKA performed using the GB and MR surgical techniques, with the hypothesis that both techniques will have equivalent migration and displacement.
2.2 Materials and Methods

2.2.1 Study Design and Patient Recruitment

Ethics approval was obtained from our institutional research ethics board and the study was registered with clinicaltrials.gov (registration number NCT03290170). Sample size required to detect a difference >0.20 mm between 1 and 2 years representing stabilized fixation between cohorts, assuming a standard deviation of 0.24 mm within the groups, $\alpha = 0.05$, and power = 0.80, was 23 per group. Accounting for 20% dropout, we aimed to recruit a total of 56 patients. The CONSORT chart of participant flow through is shown in Figure 2.1. This was a prospective RCT with equal allocation to GB and MR surgical technique groups by the first author. Concealed envelopes were used for block randomization with alternating size 4 and 8 blocks generated using a random number generator, with patients blinded to their allocation status. All patients were recruited at University Hospital, London Health Sciences Centre between December 2017 and February 2019. Inclusion criteria were patients over the age of 18 years with osteoarthritis of the knee scheduled for a unilateral primary TKA. Patients were excluded if they received a diagnosis of inflammatory arthritis, had prior knee surgery, were or planned on becoming pregnant, had a cognitive or neuromuscular impairment, an inability to understand English, a history of alcoholism, a varus or valgus deformity $>15^\circ$, or a body mass index $>40$ kg/m$^2$. Patient reported outcome questionnaires were completed preoperatively and 1 year postoperation.
Figure 2.1: CONSORT (Consolidated Standards of Reporting Trials) diagram depicting participant flow through the study up to 2 years postoperation. All medical issues were unrelated to the arthroplasty procedure. GB, gap balancing; MR, measured resection.
2.2.2 Surgical Technique

Four fellowship-trained arthroplasty surgeons in both techniques performed operations for both groups using a standard midline incision and a medial parapatellar arthrotomy. For both groups, an intramedullary guide was used to make a 6° distal femoral cut and an extramedullary guide was used to cut the proximal tibia perpendicular to the mechanical shaft of the tibia in the coronal plane. In the MR group, femoral component rotation was set at 3° of external rotation relative to the posterior condylar axis and then soft tissue releases were used to balance the knee in flexion and extension. Gaps were assessed with a tensioner matched in both extension then flexion. No laminar spreader was used. In the GB group, the knee was balanced in extension after distal femoral and proximal tibial cuts using spacer blocks and a soft tissue tensioner by selected soft tissue releases. Next, the knee was flexed to 90° and femoral component rotation was determined using a soft tissue tensioner to create a balanced, symmetric flexion space. The target in both groups was neutral mechanical alignment. All patients received identical standard JOURNEY II™ BCS TKA implants (Smith & Nephew, Memphis, TN), with cobalt chromium alloy femoral components on highly cross-linked polyethylene liners with titanium tibial components and a resurfaced inlay button patella. Implants were fixated using a commercially available bone cement with an antibacterial coating of Erythromycin and Colistin (Stryker, Mahwah, NJ). Two bags were vacuum mixed in a single batch and applied to both bone and implant components prior to impaction. Up to 16 tantalum markers were inserted into the distal femur (8 markers) and proximal tibia (8 markers) intra-operatively to enable migration analysis using RSA. The postoperative care protocol was identical for all patients.

2.2.3 Radiostereometric Analysis

RSA images for migration analysis were acquired with patients assuming a standardized supine position and their knee placed within a biplanar calibration cage (RSA Biomedical, Umea, Sweden). Baseline examinations occurred 2 weeks postoperation, and follow-up examinations were at 6 weeks, 3 months, 6 months, 1 year, and 2 years postoperation. At 3 months and 1 year postoperation, additional exams were performed with the patient standing in a weightbearing position using a uniplanar calibration cage (RSA Biomedical).
Commercial RSA software (RSAcore, Leiden, Netherlands) was used for migration and inducible displacement analysis, with migration defined as the micromotions between the supine baseline exam and a follow-up supine exam, and inducible displacements defined as the micromotions between the standing and supine exams performed at the same follow-up visit (at 3 months and 1 year). Maximum total point motion (MTPM) was measured, as well as translations and rotations about the medial-lateral (x axis), superior-inferior (y axis), and anterior-posterior (z axis) axes. Lateral (x), superior (y), and anterior (z) directions were defined as positive translations and anterior tilt (x), external rotation (y), and valgus tilt (z) were defined as positive rotations. Fictive points (defined points where three-dimensional [3D] translation can be calculated) were placed at 7 locations (anterolateral, anteromedial, lateral, medial, posterolateral, posteromedial, and stem tip).26

2.2.4 Statistical Analysis

Statistical analysis was completed using Prism 8 (GraphPad Software, La Jolla, CA). Normality was assessed with a D’Agostino and Pearson omnibus normality test. Migration data (MTPM, translations, rotations, and fictive point 3D translations) acquired at all follow-up visits were compared between groups and within groups using a mixed-effects model for repeated measures data, as were inducible displacements. Patient demographics and outcome scores were compared between groups using an unpaired t-test or Mann-Whitney test (for continuous data), or a Fisher’s exact test (for categorical data).

2.3 Results

2.3.1 Patient Details and Outcomes

There were no significant differences between GB and MR groups in patient demographics or preoperative alignment (Table 2.1), nor were there differences preoperatively or at 1 year postoperation in any patient-reported outcome score (Table 2.2). There were no differences between GB and MR groups in patient comorbidities, including hypertension (58% vs 60%, P > 0.99), chronic obstructive pulmonary disease (9.7% vs 0%, P = 0.25), heart disease (16% vs 12%, P = 0.72), kidney disease (3.2% vs 8.0%, P = 0.58), gastroesophageal reflux disease (19% vs 44%, P = 0.078), diabetes (13% vs 24%, P =
0.32), anxiety (6.5% vs 4.0%, \( P > 0.99 \)), depression (9.7% vs 4.0%, \( P = 0.62 \)), dyslipidemia (29% vs 52%, \( P = 0.10 \)), hypothyroidism (3.2% vs 8.0%, \( P = 0.58 \)), sleep apnea (9.7% vs 20%, \( P = 0.44 \)), cancer (13% vs 16%, \( P > 0.99 \)), asthma (9.7% vs 4.0%, \( P = 0.62 \)), and epileptic seizures (3.2% vs 8.0%, \( P = 0.58 \)). Two complications occurred in the GB group, a manipulation under anesthesia and a hematoma that required no operation. One complication occurred in the MR group, a revision surgery for infection. In the GB group, 65% (20/31) of patients were assessed at 2 years postoperation, down from 81% (25/31) at 1 year postoperation. In the MR group, 48% (12/25) of patients were assessed at 2 years postoperation, down from 76% (19/25) at the 1 year postoperation (Figure 2.1).

Table 2.1: Patient Demographics and Preoperative Alignment for Gap Balancing and Measured Resection Groups (Mean and Standard Deviation).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Gap Balancing</th>
<th>Measured Resection</th>
<th>( P )-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>72.4 ± 9.2</td>
<td>69.6 ± 9.9</td>
<td>0.295</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.8 ± 10.0</td>
<td>167.5 ± 7.8</td>
<td>0.777</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>88.8 ± 14.1</td>
<td>90.9 ± 13.9</td>
<td>0.572</td>
</tr>
<tr>
<td>BMI (kg/m(^2))</td>
<td>32.0 ± 4.8</td>
<td>32.4 ± 4.6</td>
<td>0.732</td>
</tr>
<tr>
<td>Sex</td>
<td>14 male, 17 female</td>
<td>14 male, 11 female</td>
<td>0.591</td>
</tr>
<tr>
<td>Pre-operative alignment</td>
<td>19 varus, 5 valgus, 7 neutral</td>
<td>17 varus, 1 valgus, 7 neutral</td>
<td>0.340</td>
</tr>
</tbody>
</table>

\( P \)-value for BMI, body mass index
Table 2.2: Preoperation and 1 y Postoperation Outcome Scores for Gap Balancing and Measured Resection Groups (Mean and Standard Deviation).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Gap Balancing</th>
<th>Measured Resection</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Form 12 Mental Component Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-operation</td>
<td>52.6 ± 9.8</td>
<td>55.6 ± 8.9</td>
<td>0.286</td>
</tr>
<tr>
<td>Post-operation</td>
<td>52.1 ± 10.3</td>
<td>51.3 ± 12.1</td>
<td>0.829</td>
</tr>
<tr>
<td>Short Form 12 Physical Component Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-operation</td>
<td>33.4 ± 8.0</td>
<td>34.1 ± 10.1</td>
<td>0.788</td>
</tr>
<tr>
<td>Post-operation</td>
<td>38.9 ± 9.5</td>
<td>43.1 ± 7.4</td>
<td>0.143</td>
</tr>
<tr>
<td>Western Ontario and McMaster Universities Arthritis Index</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-operation</td>
<td>51.8 ± 15.0</td>
<td>51.3 ± 11.9</td>
<td>0.905</td>
</tr>
<tr>
<td>Post-operation</td>
<td>74.8 ± 18.6</td>
<td>81.9 ± 11.6</td>
<td>0.246</td>
</tr>
<tr>
<td>Knee Society Score Function Subsection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-operation</td>
<td>36.7 ± 12.4</td>
<td>43.9 ± 12.7</td>
<td>0.062</td>
</tr>
<tr>
<td>Post-operation</td>
<td>59.4 ± 20.0</td>
<td>67.8 ± 14.0</td>
<td>0.146</td>
</tr>
<tr>
<td>University of California, Los Angeles Activity Score</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-operation</td>
<td>4.2 ± 1.6</td>
<td>4.8 ± 1.8</td>
<td>0.191</td>
</tr>
<tr>
<td>Post-operation</td>
<td>5.3 ± 1.6</td>
<td>5.9 ± 1.9</td>
<td>0.283</td>
</tr>
</tbody>
</table>

2.3.2 Longitudinal Migration of Tibial Component

Table 2.3 contains the tibial component migrations (Figure 2.2). The use of a GB or MR surgical technique did not influence the tibial component MTPM over time ($P = 0.616$). In the GB group, the mean change in tibial component MTPM was less than 0.2 mm in both the stabilization periods between 6 months and 1 year (mean difference = 0.0142 mm, $P = 0.999$) and between 1 and 2 years (mean difference = 0.0174 mm, $P = 0.997$). Four implants in the GB group exceeded the 0.2 mm threshold during the 6-month to 1-year stabilization period and 3 implants exceeded the threshold during the 1-year to 2-year stabilization period. In the MR group, the mean change in tibial component MTPM was less than 0.2 mm between 6 months and 1 year (mean difference = 0.0169 mm, $P = 0.999$) and between 1 and 2 years (mean difference = 0.143 mm, $P = 0.600$). Two implants in the MR group exceeded the 0.2-mm threshold during the 6-month to 1-year stabilization period and 3 implants exceeded the threshold during the 1-year to 2-year stabilization period. No differences existed between GB and MR groups for tibial component translations or rotations in any individual plane across all follow-up exams.
Figure 2.2: Migration of the (A) gap balancing group and the (B) measured resection group (mean and standard deviation). Shown are magnitudes of femoral component (F-MTPM) and tibial component maximum total point motion (T-MTPM), as well as magnitudes of 3D translation at each fictive point on the tibial component. 3D, 3-dimensional; AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; ST, stem tip.

Fictive point 3D translations (Figure 2.2) are displayed in Table 2.4. The 3D translations of all seven fictive points, including anterolateral ($P = 0.671$), anteromedial ($P = 0.366$), lateral ($P = 0.715$), medial ($P = 0.421$), posterolateral ($P = 0.424$), posteromedial ($P = 0.825$), and stem tip ($P = 0.760$), were unaffected by GB or MR surgical technique. At 1 year postoperation, there were no significant differences between 3D translations of any two fictive points within both the GB and MR groups. At 2 years postoperation, the only significant difference was between the lateral and stem tip fictive points in the GB group (mean difference $= 0.101$ mm, $P = 0.024$).
Table 2.3: Migration of the Tibial Component (Mean and Range).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gap Balancing</th>
<th>Measured Resection</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total point motion (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.34 (0.10 – 1.08)</td>
<td>0.35 (0.17 – 0.62)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.40 (0.11 – 0.99)</td>
<td>0.37 (0.13 – 0.65)</td>
<td>0.992</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.34 (0.10 – 0.73)</td>
<td>0.33 (0.10 – 0.83)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.35 (0.14 – 0.66)</td>
<td>0.35 (0.13 – 0.96)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.37 (0.10 – 0.79)</td>
<td>0.49 (0.13 – 2.05)</td>
<td>0.975</td>
</tr>
<tr>
<td>Lateral-medial translation (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>–0.01 (–0.30 – 0.21)</td>
<td>–0.04 (–0.27 – 0.10)</td>
<td>0.865</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.01 (–0.23 – 0.16)</td>
<td>–0.04 (–0.21 – 0.09)</td>
<td>0.459</td>
</tr>
<tr>
<td>6 mo</td>
<td>–0.01 (–0.14 – 0.14)</td>
<td>–0.01 (–0.18 – 0.21)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>–0.00 (–0.23 – 0.23)</td>
<td>0.01 (–0.17 – 0.11)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>–0.01 (–0.21 – 0.17)</td>
<td>0.06 (–0.06 – 0.20)</td>
<td>0.337</td>
</tr>
<tr>
<td>Superior-inferior translation (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.01 (–0.12 – 0.10)</td>
<td>0.01 (–0.09 – 0.11)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.02 (–0.08 – 0.16)</td>
<td>–0.00 (–0.21 – 0.16)</td>
<td>0.863</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.03 (–0.18 – 0.22)</td>
<td>0.02 (–0.08 – 0.15)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.05 (–0.11 – 0.34)</td>
<td>0.03 (–0.07 – 0.19)</td>
<td>0.989</td>
</tr>
<tr>
<td>2 y</td>
<td>0.05 (–0.13 – 0.36)</td>
<td>0.03 (–0.13 – 0.14)</td>
<td>0.955</td>
</tr>
<tr>
<td>Anterior-posterior translation (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.01 (–0.21 – 0.33)</td>
<td>–0.01 (–0.18 – 0.12)</td>
<td>0.978</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.00 (–0.26 – 0.23)</td>
<td>–0.00 (–0.15 – 0.20)</td>
<td>0.999</td>
</tr>
<tr>
<td>6 mo</td>
<td>–0.02 (–0.39 – 0.24)</td>
<td>–0.02 (–0.15 – 0.12)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>–0.01 (–0.24 – 0.12)</td>
<td>–0.00 (–0.12 – 0.28)</td>
<td>0.998</td>
</tr>
<tr>
<td>2 y</td>
<td>–0.00 (–0.23 – 0.32)</td>
<td>0.04 (–0.12 – 0.73)</td>
<td>0.990</td>
</tr>
<tr>
<td>Anterior-posterior tilt (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>–0.02 (–0.33 – 0.32)</td>
<td>–0.03 (–0.37 – 0.23)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>–0.02 (–0.56 – 0.30)</td>
<td>0.03 (–0.23 – 0.36)</td>
<td>0.946</td>
</tr>
<tr>
<td>6 mo</td>
<td>–0.03 (–0.59 – 0.33)</td>
<td>–0.06 (–0.35 – 0.40)</td>
<td>0.998</td>
</tr>
<tr>
<td>1 y</td>
<td>–0.01 (–0.36 – 0.48)</td>
<td>–0.05 (–0.38 – 0.27)</td>
<td>0.970</td>
</tr>
<tr>
<td>2 y</td>
<td>–0.01 (–0.38 – 0.32)</td>
<td>–0.11 (–0.50 – 0.23)</td>
<td>0.733</td>
</tr>
<tr>
<td>External-internal rotation (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>–0.00 (–0.58 – 1.16)</td>
<td>–0.00 (–0.73 – 0.67)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.11 (–0.89 – 1.29)</td>
<td>–0.09 (–0.73 – 0.73)</td>
<td>0.551</td>
</tr>
<tr>
<td>6 mo</td>
<td>–0.05 (–0.70 – 1.00)</td>
<td>0.03 (–0.90 – 0.64)</td>
<td>0.989</td>
</tr>
<tr>
<td>1 y</td>
<td>–0.00 (–0.50 – 0.87)</td>
<td>–0.11 (–1.05 – 0.45)</td>
<td>0.916</td>
</tr>
<tr>
<td>2 y</td>
<td>0.11 (–0.60 – 0.93)</td>
<td>–0.20 (–2.01 – 0.73)</td>
<td>0.654</td>
</tr>
<tr>
<td>Valgus-varus tilt (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.02 (–0.29 – 0.27)</td>
<td>0.03 (–0.27 – 0.30)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>–0.03 (–0.30 – 0.36)</td>
<td>0.07 (–0.27 – 0.30)</td>
<td>0.424</td>
</tr>
<tr>
<td>6 mo</td>
<td>–0.01 (–0.26 – 0.23)</td>
<td>–0.04 (–0.31 – 0.25)</td>
<td>0.991</td>
</tr>
<tr>
<td>1 y</td>
<td>0.02 (–0.56 – 0.70)</td>
<td>–0.06 (–0.28 – 0.31)</td>
<td>0.701</td>
</tr>
<tr>
<td>2 y</td>
<td>–0.04 (–0.54 – 0.32)</td>
<td>–0.10 (–0.53 – 0.15)</td>
<td>0.951</td>
</tr>
</tbody>
</table>
Table 2.4: Tibial Component Fictive Point 3D Translations (Mean and Range).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gap Balancing</th>
<th>Measured Resection</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anterolateral (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.18 (0.05 – 0.54)</td>
<td>0.25 (0.02 – 0.49)</td>
<td>0.417</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.27 (0.09 – 0.64)</td>
<td>0.26 (0.11 – 0.54)</td>
<td>0.999</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.23 (0.04 – 0.52)</td>
<td>0.22 (0.03 – 0.63)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.24 (0.07 – 0.56)</td>
<td>0.23 (0.07 – 0.51)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.25 (0.07 – 0.57)</td>
<td>0.27 (0.07 – 1.10)</td>
<td>0.999</td>
</tr>
<tr>
<td><strong>Anteromedial (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.24 (0.06 – 0.65)</td>
<td>0.24 (0.04 – 0.51)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.27 (0.06 – 0.71)</td>
<td>0.29 (0.12 – 0.60)</td>
<td>0.999</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.24 (0.03 – 0.55)</td>
<td>0.24 (0.06 – 0.46)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.26 (0.05 – 0.58)</td>
<td>0.25 (0.09 – 0.79)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.26 (0.07 – 0.62)</td>
<td>0.39 (0.12 – 1.73)</td>
<td>0.912</td>
</tr>
<tr>
<td><strong>Lateral (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.23 (0.06 – 0.59)</td>
<td>0.29 (0.08 – 0.60)</td>
<td>0.841</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.32 (0.08 – 0.76)</td>
<td>0.26 (0.02 – 0.56)</td>
<td>0.890</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.26 (0.06 – 0.60)</td>
<td>0.26 (0.05 – 0.80)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.25 (0.03 – 0.64)</td>
<td>0.24 (0.04 – 0.58)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.28 (0.06 – 0.51)</td>
<td>0.25 (0.10 – 0.61)</td>
<td>0.998</td>
</tr>
<tr>
<td><strong>Medial (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.27 (0.07 – 0.99)</td>
<td>0.25 (0.05 – 0.57)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.29 (0.03 – 0.96)</td>
<td>0.30 (0.09 – 0.63)</td>
<td>0.999</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.27 (0.08 – 0.71)</td>
<td>0.26 (0.09 – 0.51)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.26 (0.03 – 0.64)</td>
<td>0.28 (0.13 – 0.93)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.28 (0.07 – 0.76)</td>
<td>0.43 (0.09 – 2.01)</td>
<td>0.939</td>
</tr>
<tr>
<td><strong>Posterolateral (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.24 (0.05 – 0.74)</td>
<td>0.23 (0.08 – 0.57)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.28 (0.04 – 0.58)</td>
<td>0.21 (0.07 – 0.46)</td>
<td>0.397</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.23 (0.05 – 0.54)</td>
<td>0.22 (0.04 – 0.65)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.21 (0.11 – 0.45)</td>
<td>0.20 (0.02 – 0.42)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.25 (0.06 – 0.42)</td>
<td>0.24 (0.06 – 0.45)</td>
<td>0.999</td>
</tr>
<tr>
<td><strong>Posteromedial (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.24 (0.06 – 0.97)</td>
<td>0.21 (0.05 – 0.50)</td>
<td>0.994</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.27 (0.05 – 0.84)</td>
<td>0.23 (0.07 – 0.53)</td>
<td>0.922</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.24 (0.08 – 0.62)</td>
<td>0.23 (0.05 – 0.48)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.22 (0.06 – 0.42)</td>
<td>0.22 (0.06 – 0.73)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.26 (0.07 – 0.61)</td>
<td>0.34 (0.07 – 1.50)</td>
<td>0.982</td>
</tr>
<tr>
<td><strong>Stem tip (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.12 (0.04 – 0.40)</td>
<td>0.12 (0.04 – 0.24)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.15 (0.01 – 0.30)</td>
<td>0.14 (0.03 – 0.46)</td>
<td>0.999</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.13 (0.02 – 0.28)</td>
<td>0.16 (0.05 – 0.31)</td>
<td>0.688</td>
</tr>
<tr>
<td>1 y</td>
<td>0.18 (0.06 – 0.47)</td>
<td>0.14 (0.04 – 0.30)</td>
<td>0.631</td>
</tr>
<tr>
<td>2 y</td>
<td>0.18 (0.03 – 0.51)</td>
<td>0.16 (0.06 – 0.37)</td>
<td>0.998</td>
</tr>
</tbody>
</table>
2.3.3 Longitudinal Migration of Femoral Component

Table 2.5 depicts the femoral component migration data (Figure 2.2). Surgical technique did not affect the femoral component MTPM over time ($P = 0.081$). No differences existed between groups for femoral component translations or rotations in any individual plane across all follow-up exams.
Table 2.5: Migration of the Femoral Component (Mean and Range).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gap Balancing</th>
<th>Measured Resection</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total point motion (MTPM, mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.34 (0.13 – 0.92)</td>
<td>0.44 (0.10 – 1.21)</td>
<td>0.582</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.38 (0.06 – 0.85)</td>
<td>0.46 (0.10 – 0.95)</td>
<td>0.877</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.43 (0.15 – 0.90)</td>
<td>0.56 (0.14 – 0.88)</td>
<td>0.227</td>
</tr>
<tr>
<td>1 y</td>
<td>0.49 (0.13 – 0.94)</td>
<td>0.53 (0.26 – 1.20)</td>
<td>0.986</td>
</tr>
<tr>
<td>2 y</td>
<td>0.48 (0.15 – 0.89)</td>
<td>0.54 (0.20 – 1.13)</td>
<td>0.991</td>
</tr>
<tr>
<td>Lateral-medial translation (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>–0.01 (–0.17 – 0.37)</td>
<td>–0.02 (–0.30 – 0.40)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>–0.01 (–0.22 – 0.32)</td>
<td>–0.07 (–0.60 – 0.18)</td>
<td>0.803</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.00 (–0.22 – 0.32)</td>
<td>0.05 (–0.19 – 0.28)</td>
<td>0.865</td>
</tr>
<tr>
<td>1 y</td>
<td>0.02 (–0.26 – 0.33)</td>
<td>0.03 (–0.20 – 0.31)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.05 (–0.19 – 0.25)</td>
<td>0.02 (–0.21 – 0.24)</td>
<td>0.997</td>
</tr>
<tr>
<td>Superior-inferior translation (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.02 (–0.10 – 0.16)</td>
<td>0.02 (–0.14 – 0.13)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.01 (–0.19 – 0.20)</td>
<td>0.04 (–0.09 – 0.27)</td>
<td>0.860</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.03 (–0.13 – 0.22)</td>
<td>0.06 (–0.07 – 0.24)</td>
<td>0.865</td>
</tr>
<tr>
<td>1 y</td>
<td>0.04 (–0.10 – 0.23)</td>
<td>0.03 (–0.23 – 0.20)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.03 (–0.09 – 0.17)</td>
<td>0.05 (–0.06 – 0.20)</td>
<td>0.987</td>
</tr>
<tr>
<td>Anterior-posterior translation (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.00 (–0.18 – 0.33)</td>
<td>–0.03 (–0.41 – 0.43)</td>
<td>0.957</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.04 (–0.31 – 0.52)</td>
<td>–0.02 (–0.37 – 0.21)</td>
<td>0.895</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.11 (–0.22 – 0.50)</td>
<td>0.01 (–0.39 – 0.37)</td>
<td>0.569</td>
</tr>
<tr>
<td>1 y</td>
<td>0.06 (–0.34 – 0.48)</td>
<td>–0.02 (–0.49 – 0.29)</td>
<td>0.788</td>
</tr>
<tr>
<td>2 y</td>
<td>0.07 (–0.34 – 0.51)</td>
<td>–0.08 (–0.35 – 0.17)</td>
<td>0.199</td>
</tr>
<tr>
<td>Anterior-posterior tilt (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.05 (–0.37 – 0.61)</td>
<td>0.07 (–0.33 – 0.51)</td>
<td>0.999</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.03 (–0.53 – 0.55)</td>
<td>–0.12 (–0.71 – 0.18)</td>
<td>0.282</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.07 (–0.50 – 0.60)</td>
<td>–0.01 (–0.68 – 0.68)</td>
<td>0.953</td>
</tr>
<tr>
<td>1 y</td>
<td>0.08 (–0.74 – 0.89)</td>
<td>0.04 (–0.39 – 0.56)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.03 (–0.62 – 0.60)</td>
<td>–0.05 (–0.39 – 0.51)</td>
<td>0.947</td>
</tr>
<tr>
<td>External-internal rotation (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.04 (–0.45 – 0.58)</td>
<td>–0.07 (–1.04 – 0.79)</td>
<td>0.860</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.08 (–0.22 – 0.45)</td>
<td>–0.00 (–0.92 – 0.60)</td>
<td>0.970</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.05 (–0.35 – 0.48)</td>
<td>0.06 (–0.99 – 0.72)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>–0.04 (–0.50 – 0.48)</td>
<td>–0.04 (–1.26 – 0.73)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>–0.12 (–0.68 – 0.45)</td>
<td>–0.11 (–1.08 – 0.64)</td>
<td>0.999</td>
</tr>
<tr>
<td>Valgus-varus tilt (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 wk</td>
<td>0.05 (–0.19 – 0.55)</td>
<td>–0.05 (–0.79 – 0.49)</td>
<td>0.572</td>
</tr>
<tr>
<td>3 mo</td>
<td>0.03 (–0.33 – 0.37)</td>
<td>0.01 (–0.46 – 0.36)</td>
<td>0.999</td>
</tr>
<tr>
<td>6 mo</td>
<td>0.08 (–0.20 – 0.49)</td>
<td>0.05 (–0.35 – 0.42)</td>
<td>0.999</td>
</tr>
<tr>
<td>1 y</td>
<td>0.03 (–0.31 – 0.28)</td>
<td>0.01 (–0.43 – 0.29)</td>
<td>0.999</td>
</tr>
<tr>
<td>2 y</td>
<td>0.02 (–0.24 – 0.29)</td>
<td>0.05 (–0.21 – 0.33)</td>
<td>0.996</td>
</tr>
</tbody>
</table>
2.3.4 Inducible Displacement of Tibial Component

Results from the inducible displacement (Figure 2.3) analysis are shown in Table 2.6. No differences existed between groups in tibial component MTPM or any fictive point 3D translation. There were no differences between 3-month and 1-year follow-ups in tibial component MTPM when comparing inducible displacement within both the GB group (mean difference = 0.0491 mm, $P = 0.743$) and MR group (mean difference = 0.0581 mm, $P = 0.530$), nor were there differences between follow-up visits within groups for any fictive point 3D translation.

![Figure 2.3: Inducible displacement of the (A) gap balancing group and the (B) measured resection group (mean and standard deviation). Shown are the magnitude of tibial component maximum total point motion (T-MTPM), as well as magnitudes of 3D translation at each fictive point on the tibial component. 3D, 3-dimensional; AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; ST, stem tip.](image-url)
Table 2.6: Inducible Displacement of the Tibial Component (Mean and Range).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gap Balancing</th>
<th>Measured Resection</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total point motion (MTPM, mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.45 (0.18 – 0.97)</td>
<td>0.54 (0.20 – 1.07)</td>
<td>0.383</td>
</tr>
<tr>
<td>1 y</td>
<td>0.50 (0.09 – 1.22)</td>
<td>0.48 (0.12 – 0.89)</td>
<td>0.959</td>
</tr>
<tr>
<td>Anterolateral (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.32 (0.05 – 0.81)</td>
<td>0.34 (0.13 – 0.66)</td>
<td>0.958</td>
</tr>
<tr>
<td>1 y</td>
<td>0.32 (0.04 – 0.78)</td>
<td>0.29 (0.08 – 0.62)</td>
<td>0.875</td>
</tr>
<tr>
<td>Anteromedial (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.32 (0.09 – 0.71)</td>
<td>0.39 (0.06 – 0.81)</td>
<td>0.370</td>
</tr>
<tr>
<td>1 y</td>
<td>0.35 (0.07 – 0.81)</td>
<td>0.33 (0.09 – 0.68)</td>
<td>0.943</td>
</tr>
<tr>
<td>Lateral (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.37 (0.06 – 0.92)</td>
<td>0.39 (0.13 – 0.82)</td>
<td>0.920</td>
</tr>
<tr>
<td>1 y</td>
<td>0.35 (0.04 – 0.97)</td>
<td>0.34 (0.10 – 0.77)</td>
<td>0.956</td>
</tr>
<tr>
<td>Medial (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.31 (0.10 – 0.70)</td>
<td>0.42 (0.07 – 1.02)</td>
<td>0.166</td>
</tr>
<tr>
<td>1 y</td>
<td>0.36 (0.05 – 1.14)</td>
<td>0.37 (0.08 – 0.80)</td>
<td>0.988</td>
</tr>
<tr>
<td>Posterolateral (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.30 (0.04 – 0.79)</td>
<td>0.39 (0.18 – 0.74)</td>
<td>0.189</td>
</tr>
<tr>
<td>1 y</td>
<td>0.33 (0.03 – 0.79)</td>
<td>0.32 (0.11 – 0.81)</td>
<td>0.980</td>
</tr>
<tr>
<td>Posteromedial (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.27 (0.04 – 0.47)</td>
<td>0.39 (0.12 – 0.90)</td>
<td>0.075</td>
</tr>
<tr>
<td>1 y</td>
<td>0.33 (0.05 – 1.07)</td>
<td>0.35 (0.09 – 0.83)</td>
<td>0.876</td>
</tr>
<tr>
<td>Stem tip (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 mo</td>
<td>0.15 (0.05 – 0.31)</td>
<td>0.18 (0.04 – 0.46)</td>
<td>0.344</td>
</tr>
<tr>
<td>1 y</td>
<td>0.13 (0.05 – 0.36)</td>
<td>0.19 (0.04 – 0.42)</td>
<td>0.087</td>
</tr>
</tbody>
</table>

2.4 Discussion

In this, the first RCT comparing GB and MR techniques with the BCS implant, we found no difference between groups for MTPM or translational and rotational migration about the 3 orthogonal axes at all timepoints for both femoral and tibial components. Furthermore, there were no differences between techniques for any of the 7 fictive point 3D translations across all follow-up exams, and at 2 years postoperation there were no differences in 3D translations within groups between any 2 fictive points. Additionally, no differences were found between GB and MR techniques in tibial component inducible displacement at both 3 months and 1 year postoperation.
The tibial component MTPM of both the GB group (0.34 mm) and MR group (0.33 mm) falls within the safe threshold established by Pijls et al., where MTPM less than 0.5 mm within the first 6 months is acceptable. Pijls et al. also determined that, for every 1-mm increase in MTPM at 1 year, the 5-year revision rate rises by 7.6% translating to revision rates of 2.7% for both the GB and MR groups in our study. This is consistent with the industry standard 3% revision rate, and supports findings from Harris et al. that revision estimates were 3.6 per 100 TKAs for the same BCS implant at 5 years, compared to revision estimates of 4.1 per 100 TKAs for cemented posterior-stabilized controls from the Australian Orthopedic Association National Joint Replacement Registry. Christen and Kopjar calculated cumulative revision estimates of 1.9 per 100 TKAs at 4 years for this BCS TKA. Additionally, the tibial component MTPM of both the GB group (0.37 mm) and MR group (0.49 mm) at 2 years found in this study is between the MTPM found in 2 studies by Teeter et al. (0.33 mm, 0.59 mm) of different cemented, posterior-stabilized implant designs by the same manufacturer. Ryd et al. originally found that a change in MTPM of less than 0.2 mm between 1 and 2 years postoperation indicates that acceptable stabilization of the tibial component has occurred, which Pijls et al. has recently found can be applied to the stabilization period between 6 months and 1 year postoperation as well. For both intervals of stabilization, the GB group (0.0142 mm; 0.0927 mm) and the MR group (0.0169 mm; 0.143 mm) had mean changes in MTPM within the 0.2-mm threshold. However, 4 tibial components in the GB group and 2 in the MR group exceeded this threshold between 6 months and 1 year postoperation. The GB and MR groups each had 3 components exceed the 0.2-mm threshold between 1 and 2 years postoperation, and these components warrant careful follow-up. To the best of our knowledge there are no other RSA studies on BCS implant components. The pattern of migration observed in this study is consistent with other cemented, non-cruciate retaining designs, where migration is greatest within first 6 weeks postoperation, then gradually diminishes, providing strong fixation even after a decade postoperation.

An analysis of the fictive point 3D translations shows that migration was evenly spread amongst all the points around the tibial tray and was lower at the stem tip. The exception is at 2 years postoperation, where the MR group has greater migration at the fictive points on the medial side of the baseplate, despite there being no significant differences between
groups. One patient in the MR group had an elevated medial side migration (and tibial component MTPM), which drove up the mean 3D translations at the anteromedial, medial, and posteromedial points. A previous study using fictive points revealed a different overall trend in fictive point migration, where the medial side generally had greater migration than the lateral side as early as 3 months post-operation.\textsuperscript{26} However, this study investigated cementless components, and thus were likely more prone to the greater loads placed on the medial condyle during the early bone ingrowth period. In this study, the cemented BCS components may be well fixed from an early stage and have good distribution of stresses leading to the balance in fictive point 3D translations.

Femoral component migration was also similar between GB and MR groups, although no thresholds currently exist for safe migration for femoral components limits as they do for tibial components. However, the femoral component MTPM at 2 years postoperation in this study for both the GB group (0.48 mm) and the MR group (0.54 mm) were less than that found in a previous study regarding a cemented, posterior-stabilized implant by the same manufacturer where the measured resection technique was used (0.66 mm).\textsuperscript{29} A study of a cemented, posterior-stabilized implant by a different manufacturer that compared GB and MR techniques also found no difference between surgical techniques at 2 years postoperation.\textsuperscript{24} The femoral component MTPM found in this study compares favourably for both the GB technique (0.48 mm versus 0.54 mm) and the MR group (0.54 mm versus 0.77 mm).

There were no differences in inducible displacement of the tibial component at 3 months and 1 year postoperation when investigating both the standing versus supine MTPMs and 3D translations at any fictive point. Again, no thresholds exist for safe inducible displacement but displacements up to 1.7 mm have been shown for stable components.\textsuperscript{32} No tibial components in either group exceeded a displacement of 1.3 mm, suggesting that all components are stable. Inducible displacements at 1 year post-operation in this study for both the GB group (0.50 mm) and the MR group (0.48 mm) were slightly greater than the displacements found in a study of a cemented, posterior-stabilized implant by a different manufacturer with follow-ups between 2 and 4 years postoperation (0.34 mm),
but falls within the range of inducible displacements expected for stable components (0.2–0.6 mm).\textsuperscript{33,34}

A limitation of this study is that we did not standardly acquire postoperative hip-knee-ankle radiographs and therefore could not concurrently analyze postoperative TKA alignment, which may be affected by surgical technique. Most RSA studies investigating knee implant migration, however, do not report limb alignment.\textsuperscript{27,28} Another limitation is that some patients (in large part due to the COVID-19 pandemic) did not return for 1-year or 2-year postoperative imaging. However, both groups had average migrations within the threshold of acceptable migration, suggesting any further distinctions between groups may have little clinical relevance. It was also impossible to blind the surgeon to which technique was being used, and surgeon variability may have influenced the results. However, all surgeons involved had patients randomized into either the GB or MR group, and the objective nature of migration and inducible displacement helps offset the bias.

In conclusion, we report no differences between the GB and MR surgical techniques for migration and inducible displacement of the BCS TKA implants. Both groups display patterns of migration that suggest that this implant can be expected to have revision risks on par with industry standards. Overall, the results of this study support using either surgical technique as a safe and effective option for BCS TKA.

2.5 References


Chapter 2

3 Patient and Implant Performance of Satisfied and Dissatisfied Total Knee Arthroplasty Patients

A version of this chapter has been published in the Journal of Arthroplasty, Proceedings of The Knee Society 2021.


3.1 Introduction

Total knee arthroplasty (TKA) is an effective solution to treat osteoarthritis of the knee, reducing pain and returning function to the affected joint in most patients. However, approximately 20% of patients remain dissatisfied following the procedure, and although it remains unclear why this is the case, it is thought to be because of a blend of multiple factors.\textsuperscript{1,2} Complicating the issue is that there is a well-reported disparity between patient and clinician satisfaction ratings.\textsuperscript{1,3} Yet, with modern health care systems increasingly focused on patient-centred care, a TKA cannot be considered a complete success unless it results in a satisfied patient.\textsuperscript{4,5}

Conflicting results have been found regarding the association of dissatisfaction with age and body mass index (BMI), whereas no correlations have been found between dissatisfaction and other sociodemographic factors, such as sex, education, income, or employment.\textsuperscript{6–8} Patient-reported outcome measures (PROMs) have been used to identify preoperative and postoperative factors that may contribute to patient dissatisfaction. Multiple studies found that poorer PROMs scores preoperatively were linked to increased dissatisfaction.\textsuperscript{6} Poorer mental health preoperatively and anxiety were also associated with dissatisfaction, as was greater sensitivity to pain.\textsuperscript{8–10} Expectedly, lower PROMs scores postoperation also resulted in increased dissatisfaction, as were increased pain, complications, and expectations not being met.\textsuperscript{1,6,11} Interestingly, no correlation has been found between dissatisfaction and cruciate retention, fixation method, patella resurfacing,
Dissatisfaction was also not found to improve with the use of modern implant designs or with custom surgical cutting guides. Although extensive research has been done on factors associated with TKA patient dissatisfaction, only a few studies have used new technologies to gather objective measurements that may differentiate satisfied and dissatisfied patients. Nishio et al and Warth et al both measured intraoperative pivot pattern using a computed tomography-guided navigation system and sensor-embedded tibial trials, respectively, to determine if a medial pivot pattern was associated with better patient satisfaction. Nishio et al found patients with a medial pivot pattern reported better satisfaction than those with a nonmedial pivot pattern, whereas Warth et al found no difference in satisfaction. Van Onsem et al used fluoroscopy to compare the kinematics of patients with high PROMs scores to patients with poor PROMs scores, finding that patients with poor PROMs had more medial anterior translation and midflexion instability, and less lateral posterior rollback.

Wearable sensors and radiostereometric analysis (RSA), a stereo x-ray technique commonly used for obtaining implant migration and joint kinematics, are 2 additional tools available that may be able to uncover potential factors in patient dissatisfaction. The goal of this study was to investigate the implant migration and joint kinematics obtained from RSA, the objective measurements of patient function from the wearable sensors, as well as PROMs and demographic factors, to determine any differences that may exist between satisfied patients and dissatisfied TKA patients. We hypothesized that between satisfied and dissatisfied patients, there will be differences in continuous implant migration, joint kinematics, objective functional measurements, and PROMs scores.

3.2 Materials and Methods

3.2.1 Study Design and Patient Recruitment

Patients included in this analysis were drawn from the 56 patients previously recruited to a prospective randomized controlled trial (RCT) that investigated the difference between gap balancing and measured resection surgical techniques for a bicruciate stabilizing (BCS) implant. Inclusion criteria for the RCT were patients with an osteoarthritic knee scheduled for a unilateral primary TKA. Exclusion criteria were patients with
neuromuscular or cognitive conditions, those who are pregnant or considering pregnancy, those with a body mass index (BMI) >40 kg/m², and those with varus or valgus deformities >15°. The RCT was approved by our institutional research ethics board and registered with clinicaltrials.gov (registration number NCT03290170). In the present study, the Knee Society Score (KSS) Satisfaction Subsection’s final 3 questions asking about satisfaction with function (1. Currently, how satisfied are you with your knee function while getting out of bed? 2. Currently, how satisfied are you with your knee function while performing light household duties? 3. Currently, how satisfied are you with your knee function while performing leisure recreational activities?) were used to split these patients into satisfied and dissatisfied groups. Patients were classified as satisfied if they answered “very satisfied” or “satisfied” on all 3 questions at least 6 months postoperation, when satisfaction has been shown to stabilize. Patients were classified as Dissatisfied if they answered “neutral,” “dissatisfied,” or “very dissatisfied” to at least 1 of the 3 questions. This resulted in 32 patients classified as satisfied and 18 classified as dissatisfied, for a total of 50 patients and an overall functional satisfaction rate of 64% (Figure 3.1). Six patients from the original RCT did not report a satisfaction score at least 6 months postoperation and were thus excluded. The rate of patients responding as satisfied to the KSS functional satisfaction questions was 82% to the first question, 72% to the second question, and 70% to the third question. There were no differences in preoperative patient demographics between groups (Table 3.1). Two complications occurred in the satisfied group, an irrigation and debridement surgery for infection and a hematoma that required no operation. One complication occurred in the dissatisfied group, a manipulation under anesthesia.
Figure 3.1: Flowchart depicting number of patients included in the present study from the original randomized controlled trial (RCT) and their assortment into satisfied and dissatisfied groups. There was no statistically significant difference in incidence of surgical technique in the satisfied and dissatisfied groups ($P = 0.15$). Of the 29 patients included in this study from the gap balancing group in the original RCT, 16 were classified as satisfied and 13 were classified as dissatisfied. Of the 21 patients included in this study from the measured resection group in the original RCT, 16 were classified as satisfied, and 5 were classified as dissatisfied.

Table 3.1: Patient Demographics for Satisfied and Dissatisfied Groups.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Satisfied</th>
<th>Dissatisfied</th>
<th>$P$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age, y (SD)</td>
<td>71.2 (7.8)</td>
<td>69.7 (10.4)</td>
<td>0.58</td>
</tr>
<tr>
<td>Male:female, n</td>
<td>16:16</td>
<td>8:10</td>
<td>0.77</td>
</tr>
<tr>
<td>Mean height, cm (SD)</td>
<td>166.1 (9.4)</td>
<td>167.8 (8.0)</td>
<td>0.52</td>
</tr>
<tr>
<td>Mean weight, kg (SD)</td>
<td>87.9 (14.5)</td>
<td>94.8 (12.9)</td>
<td>0.098</td>
</tr>
<tr>
<td>Mean BMI, kg/m² (SD)</td>
<td>31.9 (5.2)</td>
<td>33.6 (3.7)</td>
<td>0.22</td>
</tr>
</tbody>
</table>

SD, standard deviation; BMI, body mass index.
3.2.2 Surgical Technique

All patients received a cobalt-chromium alloy on highly cross-linked polyethylene JOURNEY II™ BCS TKA (Smith & Nephew, Memphis, TN) with a biconvex inlay patellar button using cemented fixation. Up to 8 tantalum markers were placed in the proximal tibia intraoperatively to enable migration analysis using RSA. Four fellowship-trained surgeons performed the surgeries using a medial parapatellar approach. The surgery and postoperative care were identical for each patient, excluding surgeon and surgical technique, and occurred within the same hospital and physiotherapy department.

3.2.3 Radiostereometric Analysis of Implant Migration

Migration analysis was performed with a validated model-based RSA method using images acquired with patients in a supine position within the first 2 weeks postoperation (baseline examination), at 6 weeks, 3 months, 6 months, 1 year, and 2 years postoperation. Model-based RSA software (MBRSA, RSAcore, Leiden, Netherlands) was used to find the maximum total point motion (MTPM) of the tibial baseplates. Longitudinal migration was defined as the MTPM between the supine baseline exam and a follow-up supine exam. Continuous migrations were defined as the differences between the MTPM from 6 months to 1 year and from 1 year to 2 years postoperation. The average condition number was 51 ± 29 and the mean error for rigid body fitting was 0.10 ± 0.06 mm, well within the standardized RSA thresholds for condition number (150) and mean error (0.35 mm).

3.2.4 Quasi-Static Radiostereometric Analysis of Contact Kinematics

Analysis of static kinematics was accomplished using RSA images acquired at 1-year postoperation with patients in weight-bearing positions at multiple flexion angles measured using a goniometer (0°, 20°, 40°, 60°, 80°, 100°, and 120°) as described previously. The position and orientation of the models were measured in MBRSA and used to determine the true anatomic flexion angle at which each pair of RSA images were acquired. A model of the polyethylene liner with the correct thickness was then added to the tibial baseplate model. Contact points were computed by finding the centre of all points where the tibiofemoral distance was within 0.5 mm of the magnitude of shortest distance for each
condyle. The anteroposterior (AP) positions of the contact point were normalized to a size 4 baseplate and reported in millimetres. The AP contact positions for each patient were then plotted as a function of the true flexion angles of the knee during the corresponding image acquisition. The medial and lateral contact points were also used to determine axial rotation of the femur relative to the tibia (Figure 3.2). External femoral rotations relative to the tibia were defined as positive axial rotations, with internal rotations of the femur relative to the tibia defined as negative. A polyfit function (MATLAB v2019b, The MathWorks Inc., Natick, MA) was then used to interpolate the AP contact positions and axial rotations at 1° increments of flexion from 0° to 120° for each patient. AP contact positions and axial rotations were statistically compared between satisfied and dissatisfied groups at 0°, 20°, 40°, 60°, 80°, 100°, and maximum flexion. The incidence of medial and nonmedial pivot pattern was also analyzed in a similar method to Dennis et al.25

![Figure 3.2](image)

**Figure 3.2:** Axial view of a tibial polyethylene insert for a right knee. Medial and lateral contact points are represented by the purple circles. Axial rotation is determined by the angle between the medial-lateral axis (black dashed line) and the line connecting the medial and lateral contact points.

### 3.2.5 Objective Functional Performance Analysis

A validated wearable sensor system with measurement accuracies approaching motion capture technology was worn above and below each knee to measure objective patient function.26 Patients performed 3 trials of the timed-up-and-go (TUG) test at a preoperative baseline and each postoperative visit.27 Measurements, including total test time and
flexion/extension velocities for the operative knees, were used to compare the satisfied and dissatisfied groups. All measurements were given as values relative to preoperative baseline test results.

### 3.2.6 Patient-Reported Outcomes

PROMs scores were collected preoperatively, and at 6 weeks, 3 months, 6 months, 1 year, and 2 years postoperation. The questionnaires included the KSS, the University of California, Los Angeles (UCLA) Activity Score, and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). The incidence of the gap balancing and measured resection surgical techniques in the satisfied and dissatisfied groups were also determined.

### 3.2.7 Statistical Analysis

Statistical analysis was completed using Prism 8 (GraphPad Software, San Diego, CA). Normality of the data distribution was evaluated with a Shapiro-Wilk test, and the appropriate parametric or nonparametric test was used. Migration, objective function, and PROMs were compared using a mixed-effects model. Preoperation and postoperation PROMs were analyzed using Sidak’s multiple comparisons tests. Kinematics, demographics, incidence of surgical technique, and incidence of continuous migration were compared between groups using an independent sample t-test or Mann-Whitney test (for continuous data), or a Fisher’s exact test (for categorical data).

### 3.3 Results

#### 3.3.1 Tibial Component Migration

Longitudinal migration of the tibial baseplate had no effect ($P = 0.35$) on satisfaction status (Figure 3.3). There were also no differences between the satisfied and dissatisfied groups in continuous migration from 6 months to 1 year ($-0.001 \text{ mm vs } -0.013 \text{ mm, } P = 0.86$) and 1–2 years postoperation ($0.038 \text{ mm vs } 0.092 \text{ mm, } P = 0.18$). Sixteen percent of satisfied patients and 7% of dissatisfied patients had continuous migration $>0.2$ mm from 6 months to 1 year ($P = 0.64$). Seventeen percent of satisfied patients and 22% of dissatisfied patients had continuous migration $>0.2$ mm from 1 to 2 years ($P > 0.99$).
Figure 3.3: Tibial component longitudinal migration (mean and 95% confidence interval), represented by maximum total point motion (MTPM, mm). There were no statistically significant differences between the 2 groups measured from the baseline examination (at 2 wk) to follow-up examinations at 6 wk ($P = 0.75$), 13 wk (3 mo, $P = 0.98$), 26 wk (6 mo, $P > 0.99$), 52 wk (1 y, $P = 0.57$), and 104 wk (2 y, $P = 0.99$) postoperation.

### 3.3.2 Tibiofemoral Contact Kinematics

A statistically significant difference was found in AP contact position (Figure 3.4) between satisfied and dissatisfied groups in lateral AP contact position at 20° ($P = 0.023$) and 40° ($P = 0.022$) of flexion, with the dissatisfied group having a more anterior position than the satisfied group. The average maximum flexion achieved in the kinematic examinations was 103° ± 12° for the satisfied group and 103° ± 14° for the dissatisfied group ($P = 0.66$). A medial pivot pattern was demonstrated by 6% of patients in the satisfied group and 19% of patients in the dissatisfied group ($P = 0.32$). A lateral pivot pattern was demonstrated by 48% of patients in the satisfied group and 75% of patients in the dissatisfied group ($P = 0.12$). The remaining patients had no prominent pivot pattern.
Figure 3.4: Tibiofemoral contact kinematics at 1-y postoperation (mean and 95% confidence interval), including (A) medial condyle anteroposterior (AP) contact position, (B) lateral condyle AP contact position, and (C) axial rotation. AP contact position was given in millimeters scaled to a size 4 tibial baseplate, with positive values being more anterior and negative values being more posterior. Axial rotation was given in degrees, with positive and negative values indicating external and internal rotation of the femur relative to the tibia, respectively. Statistically significant differences were seen in lateral condyle AP contact position at 20° ($P = 0.023$) and 40° ($P = 0.022$) of flexion.

3.3.3 Objective Functional Outcome Metrics

Total TUG test completion time ($P = 0.21$), operated knee flexion velocity ($P = 0.80$), or operated knee extension velocity ($P = 0.62$) relative to baseline measurements all had no effect on satisfaction status (Figure 3.5).
Figure 3.5: Objective measurements of patient function (mean and 95% confidence interval), including (A) total time to complete timed-up-and-go (TUG) test, (B) flexion velocity of operated knee during TUG test, and (C) extension velocity of operated knee during TUG test. All follow-up test results were reported as values relative to preoperative baseline test measurements. There were no statistically significant differences in total time to complete TUG test between the 2 groups at 2 wk ($P = 0.57$), 6 wk ($P > 0.99$), 13 wk (3 mo, $P = 0.99$), 26 wk (6 mo, $P > 0.99$), 52 wk (1 y, $P > 0.99$), and 104 wk (2 y, $P = 0.89$) postoperation. There were no statistically significant differences in flexion velocity of operated knee during TUG test between the 2 groups at 2 wk ($P = 0.69$), 6 wk ($P > 0.99$), 13 wk (3 mo, $P > 0.99$), 26 wk (6 mo, $P > 0.99$), 52 wk (1 y, $P > 0.99$), and 104 wk (2 y, $P > 0.99$) postoperation. There were no statistically significant differences in extension velocity of operated knee during TUG test between the 2 groups at 2 wk ($P = 0.42$), 6 wk ($P > 0.99$), 13 wk (3 mo, $P = 0.99$), 26 wk (6 mo, $P > 0.99$), 52 wk (1 y, $P > 0.99$), and 104 wk (2 y, $P = 0.99$) postoperation.

### 3.3.4 Patient-Reported Outcomes

Satisfaction status was affected by all PROMs scores (Figure 3.6), with the satisfied group reporting better outcomes for the KSS Satisfaction score ($P < 0.0001$), KSS Expectation score ($P < 0.0001$), UCLA Activity score ($P = 0.002$), WOMAC Pain score ($P = 0.0002$), WOMAC Stiffness score ($P = 0.0006$), and WOMAC Function score ($P < 0.0001$). The KSS Satisfaction score improved from preoperation as early as 6 weeks postoperation in the satisfied group ($P < 0.0001$), but not until 6 months postoperation in the dissatisfied group ($P = 0.018$). The KSS Expectation score worsened from preoperation as early as 6 weeks postoperation in both the satisfied group ($P < 0.0001$) and the dissatisfied group ($P$
The UCLA Activity score did not statistically significantly change from preoperation to postoperation in either the satisfied and dissatisfied groups. The WOMAC Pain score improved from preoperation as early as 6 weeks postoperation in the satisfied group \((P < 0.0001)\), but not until 6 months postoperation in the dissatisfied group \((P = 0.016)\). The WOMAC Stiffness score improved from preoperation as early as 3 months postoperation in the satisfied group \((P = 0.0002)\), but not until 1 year postoperation in the dissatisfied group \((P = 0.036)\). The WOMAC Function score improved from preoperation as early as 6 weeks postoperation in the satisfied group \((P = 0.0002)\), but not until 1 year postoperation in the dissatisfied group \((P = 0.018)\).

Figure 3.6: Satisfaction status was affected by all patient-reported outcome scores (mean and 95% confidence interval), including the (A) Knee Society Score (KSS) Satisfaction score \((P < 0.0001)\), (B) KSS Expectation score \((P < 0.0001)\), (C) University of California, Los Angeles (UCLA) Activity score \((P = 0.002)\), (D) Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) Pain score \((P = 0.0002)\), (E) WOMAC Stiffness score \((P = 0.0006)\), and (F) WOMAC Function score \((P < 0.00001)\). Sidak's multiple comparisons tests found statistically significant differences between the 2 groups in the KSS Satisfaction score at 6 wk \((P = 0.014)\) and 52 wk (1 y, \(P < 0.00001)\), KSS Expectation score at 52 wk (1 y, \(P = 0.006)\) and 104 wk (2 y, \(P = 0.012)\), UCLA Activity score at 6 wk \((P = 0.013)\), and WOMAC Function score at 52 wk (1 y, \(P = 0.006)\).
3.4 Discussion

Patient satisfaction remains a difficult challenge in TKA, with 1 in 5 patients feeling dissatisfied after their operation.\(^1\) It has been shown that dissatisfied patients report worse PROMs scores; however, no correlation has been found between patient satisfaction and the type of implant or surgical technique used.\(^6,7,11\) Only a few studies have used technologies such as sensors or imaging to identify objective differences between patients, and even these have reported conflicting results.\(^2,13–15\) The goal of this study was to use RSA and wearable sensors to determine if satisfied and dissatisfied patients differed in implant migration, joint kinematics, and objective functional measurements. We found that the rate of functional dissatisfaction in our study cohort was 37%, which is slightly higher than rates reported by other studies.\(^1,6\) However, the method of determining which patients were satisfied and dissatisfied in this study was fairly stringent in that a patient was considered dissatisfied if they responded “neutral”, “dissatisfied”, or “very dissatisfied” to at least 1 of the 3 questions.

No differences existed in both longitudinal and continuous migration between satisfied and dissatisfied patients, and both groups of patients had a similar incidence of continuous migration \(>0.2\) mm, the threshold established by Ryd et al\(^29\) for safe tibial baseplate migration. It is perhaps expected that there would be no large difference in migration between satisfied and dissatisfied patients because modern implant systems and surgical techniques have resulted in a much lower rate of aseptic loosening, and we observed a low amount of early implant migration indicating little loosening risk.\(^21\)

Kinematic abnormalities, such as paradoxical anterior femoral translation and reduced posterior femoral rollback have been suggested to result in detrimental effects that could influence a patient’s satisfaction with their function. Paradoxical anterior translation results in anterior positioning of the flexion axis, reducing maximum flexion and decreasing the quadriceps moment arm, thus decreasing its efficiency. Reduced femoral rollback can result in reduced maximum flexion because of knee impingement.\(^17,25\) In this study, there were kinematic differences between satisfied and dissatisfied patients at 1-year postoperation. The more anteriorly located contact on the lateral condyle at 20° and 40° in dissatisfied patients suggests that less posterior femoral rollback is occurring in early
flexion. This may result in detrimental effects, such as decreased quadriceps efficiency, that could lead to a more dissatisfied patient. A more anteriorly located contact position was also seen in the low PROMs cluster of patients in the fluoroscopic study by Van Onsem et al.\textsuperscript{15} As was seen in the study by Warth et al.\textsuperscript{14}, there was no difference between satisfied and dissatisfied patients regarding the incidence of pivot patterns present.

There were no statistically significant differences present in the objective measurements of patient function from the wearable sensors between satisfied and dissatisfied patient groups, despite the dissatisfied group reporting worse functional outcomes in the PROMs. This discrepancy may be due to dissatisfied patients expecting more returned function from the procedure, which is supported by these patients reporting far worse postoperative expectation scores. There is also the possibility that dissatisfied patients may also be able to perform functions at the same level as satisfied patients but experience more pain when doing so or experience fatigue when required to perform activities over the course of a day, influencing what they report on the PROMs.

Expectations not being met was found to be the greatest risk factor for dissatisfaction in a study by Bourne et al.; however, the reason for expectations not being met was unknown. The results of this study suggest that satisfied and dissatisfied patients have relatively few objective differences in function, kinematics, and implant migration. A large focus of the orthopaedic field has been on improving the implant design and surgical technique; however, the higher rates of clinician satisfaction imply that the technology is effective in achieving clinician goals, yet patient satisfaction rates remain unchanged.\textsuperscript{1} Innovations in managing patient expectations, such as the development of systems that can predict patient function after TKA, may be one area to help improve rates of TKA patient satisfaction.\textsuperscript{30}

Patients who reported dissatisfaction with their function also reported increased pain and joint stiffness, suggesting that pain and stiffness may be preventing dissatisfied TKA patients from reaching their desired level of function. There may also be a difference in the biological response between satisfied and dissatisfied patients that was not measured in this study. An inflammatory response could be occurring in dissatisfied patients that may be partly responsible for the increased joint stiffness and lower satisfaction scores.\textsuperscript{31,32}
However, a greater understanding of the biological response to TKA is needed, and future studies comparing satisfied and dissatisfied patient should consider investigating inflammatory markers such as cytokine levels.

This study was limited in that it used patients from a randomized controlled RSA trial, which traditionally have small groups of patients. Larger patient groups would help to strengthen the results. However, differences were still found between groups in the metrics for static kinematics and patient-reported outcomes. The study was also limited in that a single, BCS implant was used, and although the implant migrations and static kinematic patterns were similar to those of posterior stabilized implants by the same manufacturer, the results may not be generalizable to other implant designs.33–35 Furthermore, no patient in this study had a highly migrating implant that would suggest future early loosening, which may have been in part due to the exclusion of patients with a BMI >40kg/m², potentially limiting the generalizability of this study. A high value of migration that would be predictive of implant loosening and subsequent revision might result in a dissatisfied patient.21 Another limitation is that we did not evaluate limb alignment, which could be a factor in patient satisfaction; however, this has been investigated in previous studies.36 Another limitation is that we obtained static kinematics rather than dynamic kinematics; however, multiple studies have shown that static kinematics of straightforward motions can be representative of dynamic kinematics after TKA.17,37–39 In addition, surgeon variability may have influenced the results; however, no statistically significant differences were found in satisfaction rates between surgeons. Despite these limitations, this study provides novel insights into the differences, or lack thereof, between satisfied and dissatisfied TKA patients.

In conclusion, no major differences were found in migration or objective function between satisfied and dissatisfied patients. Functionally dissatisfied patients had more anteriorly positioned contact on the lateral condyle in early flexion and reported more pain and unmet expectations. These findings suggest that improving the functional satisfaction of TKA may require restoration of kinematics in early flexion and management of patient’s pain and expectations; however, further work to validate these observations is warranted.
3.5 References


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34. Teeter MG, Marsh JD, Howard JL, et al. A randomized controlled trial investigating the value of patient-specific instrumentation for total knee arthroplasty in the


Chapter 3

4 Correlating Contact Kinematics to Tibial Component Migration Following Cemented Bicruciate Stabilized Total Knee Arthroplasty

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4.1 Introduction

Total knee arthroplasty (TKA) is a very successful procedure at reducing pain and returning function to patients suffering from severe knee osteoarthritis. However, many TKA implants do not always restore the normal knee joint kinematics, which may be a factor in the 20% dissatisfaction rate in TKA.\textsuperscript{1,2} Many new technologies and techniques have been introduced to improve the TKA kinematics.\textsuperscript{3} One such innovation is the bicruciate stabilizing (BCS) TKA design, which aims to improve kinematics of the replaced knee by replicating anterior cruciate ligament function with an anterior cam-post system and having components that are intended to resemble natural knees.\textsuperscript{4,5} There have been previous studies that have shown BCS TKA designs more closely approximate normal knee kinematics, with anterior contact at full extension, posterior rollback in early flexion, reduced paradoxical anterior motion in midflexion, and posterior rollback again in deep flexion.\textsuperscript{4,6–11} However, one study that compared BCS TKA kinematics between satisfied and dissatisfied patients found that patients who were dissatisfied had less posterior rollback in early flexion.\textsuperscript{5} Another study that included a BCS TKA design in its analysis also found more anterior contact in early flexion in a cluster of patients with lower patient-reported outcome scores.\textsuperscript{12}

While joint kinematics appear to be an important factor for clinical outcomes of patients implanted with a BCS TKA, its effect on implant fixation has not been thoroughly
examined. Adequate implant fixation, with little to no migration within bone over time, is important for the longevity of any TKA design. The gold standard technique for measuring implant migration is radiostereometric analysis (RSA), which uses stereo x-ray acquisitions to track the micromotions of the implant relative to the surrounding bone.\textsuperscript{13} These measurements of micromotions can be used to predict early implant loosening.\textsuperscript{14,15} A previous RSA study of a BCS TKA design found average implant migrations within the safe thresholds for two different surgical techniques (gap balancing and measured resection) and 6 patients from a total of 56 that had migration between 1 year and 2 years postoperation that were above the 0.2-mm risk threshold for continuous migration.\textsuperscript{16} It was concluded that the BCS TKA design could be expected to provide long-lasting fixation. However, there have been studies of older TKA designs that found that abnormal kinematics can lead to elevated levels of migration, even for implant designs that have been shown, on average, to provide excellent fixation. Wolterbeek et al\textsuperscript{17} found that deviant kinematics in a highly congruent mobile-bearing implant resulted in increased early migration. Uvehammer\textsuperscript{18} found more anterior tilt under inducible displacement with a more medial position of the tibial plateau center. Teeter et al\textsuperscript{19} found multiple correlations between implant migration and contact kinematics for a posterior stabilized implant design, concluding that abnormal kinematics may be a factor in long-term implant loosening. The caveat with these studies is that they were all done on implant designs that are over a decade old. Mills et al\textsuperscript{20} recently presented migration and kinematic data, acquired with RSA and fluoroscopy, for a newer bicruciate retaining design. They found that natural kinematics were not fully restored and there were elevated levels of tibial component migration, but no direct correlations between kinematics and migration were made.

A study directly comparing implant migration and contact kinematics would be useful to understand how altered kinematics effect the longevity of new implants, such as the BCS design, especially considering their emphasis on guiding natural knee kinematics. Therefore, it is the goal of this study to determine whether there is a relationship between implant migration and contact kinematics for a BCS TKA implant design. It is hypothesized that abnormal kinematics will result in elevated levels of implant migration.
4.2 Materials and Methods

4.2.1 Study Design and Patient Recruitment

Data collected from patients enrolled in a prospective randomized controlled trial (RCT) were used in these analyses (clinicaltrials.gov registration number NCT03290170). In the present study, patients from gap balancing and measured resection groups were pooled together and collectively analyzed for correlations between migration and kinematics (Figure 4.1). Two patients from the original RCT did not have kinematic data and were excluded, leaving a total of 54 patients included in the current analysis. The average age of the patients included in the analysis was 71 years (range, 51–88). The average body mass index was 32.2 (range, 21.7–39.6). There were 27 men and 27 women included in the analyses. Three complications occurred, an irrigation and debridement surgery for infection, a hematoma that required no operation, and a manipulation under anesthesia. No revisions for aseptic loosening have been required.

Figure 4.1: Flowchart depicting number of patients included in the current study from the original randomized controlled trial. GB, gap balancing; MR, measured resection.
4.2.2 Surgical Technique

Four fellowship-trained surgeons performed the operations using a medial parapatellar approach. Patients all received a cobalt-chromium alloy on highly cross-linked polyethylene JOURNEY II™ BCS TKA (Smith & Nephew, Memphis, Tennessee) with a biconvex inlay patellar button fixed using bone cement. Up to 8 tantalum markers were placed in the proximal tibia intraoperatively to enable migration analysis using RSA. The surgery and postoperative care were identical for each patient, excluding surgeon and surgical technique, and occurred within the same hospital and physiotherapy department.

4.2.3 Radiostereometric Analysis of Implant Migration

A dedicated RSA lab was used to perform all image acquisitions for measuring implant migration, with patients in a supine position and images acquired within the first two weeks postoperation (baseline examination), at 6 weeks, 3 months, 6 months, 1 year, and 2 years postoperation. Model-based RSA software (MBRSA, RSACore, Leiden, Netherlands) was used to find the maximum total point motion (MTPM) of the tibial baseplates.\textsuperscript{21,22} Translations and rotations about the medial-lateral (x-axis), superior-inferior (y-axis), and anterior-posterior (z-axis) axes were measured. Lateral (x), superior (y), and anterior (z) directions were defined as positive translations and anterior tilt (x), external rotation (y), and valgus tilt (z) were defined as positive rotations. The maximum total point motion (MTPM) was calculated, as were the three-dimensional (3D) translations at 7 fictive points, which are points of interest located around the tibial component (Figure 4.2).\textsuperscript{16} Continuous migrations were defined as the differences between the MTPM and fictive point 3D translations from 1 year to 2 years postoperation.\textsuperscript{14} The condition number (51 ± 29) and mean error for rigid body fitting (0.10 ± 0.06 mm) were within standardized RSA thresholds (150 and 0.35 mm).\textsuperscript{23}
Figure 4.2: Inferior view of tibial component depicting location of fictive points. AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; ST, stem tip.

4.2.4 Quasi-Static Radiostereometric Analysis of Contact Kinematics

At 1-year postoperation, image pairs were acquired using RSA with patients in static weight-bearing positions at multiple flexion angles measured using a goniometer (0, 20, 40, 60, 80, 100, and 120° or maximum flexion) as described previously. The poses of the femoral and tibial models were measured in MBRSA and the true anatomical flexion angle at which each pair of RSA images were acquired was determined. The maximum flexion angle achieved by each patient during the deep knee bend was determined to be the active range of motion. A polyethylene liner model of correct thickness was attached to the tibial component model. Contact points between the femoral component and the polyethylene liner for each condyle were calculated by finding the centre of the contact area, defined as all points where the tibiofemoral distance was within 0.5 mm of the magnitude of shortest distance. The anteroposterior (AP) positions of the contact points were normalized to a size 4 baseplate and reported in mm. The AP contact positions for each patient were then plotted as a function of the true flexion angles of the knee during...
the corresponding image acquisition, and a polyfit function (MATLAB v2019b, The MathWorks Inc., Natick, Massachusetts) interpolated the overall AP contact positions at 1° increments of flexion from 0 to 120°. The most anterior and most posterior AP contact positions on the lateral and medial condyles were used for the correlation analysis, as was lateral and medial excursion (the AP range from the most anterior to the most posterior contact point).

4.2.5 Patient-Reported Outcomes

Patient-reported outcome measures (PROMs) were collected preoperation and 1-year postoperation from the Knee Society Score (KSS) questionnaire. PROMs included the KSS Symptoms score, the KSS Satisfaction score, the KSS Expectation score, and the KSS Functional Activities score.

4.2.6 Statistical Analysis

Statistical analyses were completed using Prism 9 (GraphPad Software, San Diego, California). Linear regressions were used to correlate the implant migrations to the contact kinematic measurements. Linear regressions were also used to correlate patient demographics and active range of motion to migration and PROMs to kinematics. R-squared values and P-values were calculated. MTPM of men and women at 2 years and from 1 year to 2 years postoperation were compared using Mann-Whitney tests. Statistical significance was set to $P < 0.05$.

4.3 Results

4.3.1 Tibial Component Migration

Tibial component migration is shown in Figure 4.3. The average MTPM progressed from $0.39 \pm 0.23$ mm at 6 weeks postoperation to $0.39 \pm 0.19$ mm at 3 months, $0.34 \pm 0.16$ mm at 6 months, $0.35 \pm 0.17$ mm at 1 year, and $0.42 \pm 0.35$ mm at 2 years postoperation. At 2 years postoperation, 31% of patients had the greatest fictive point migration at the medial fictive point, 25% at the lateral point, 19% at the anteromedial point, 13% at the posterolateral point, 6% at the stem tip point, 3% at the anterolateral point, and 3% at the posteromedial point. There was an average of $0.02 \pm 0.10$ mm of lateral translation, $0.04 \pm$
0.10 mm of superior translation, 0.02 ± 0.17 mm of anterior translation, 0.05 ± 0.19° of posterior tilt, 0.003 ± 0.52° of internal rotation, and 0.07 ± 0.197° of varus tilt of the tibial components at 2 years postoperation. Average continuous migration for MTPM of the tibial component from 1 year to 2 years postoperation was 0.05 ± 0.24 mm, and six patients had continuous migrations greater than 0.2 mm.

Figure 4.3: Migration of the tibial component. AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; ST, stem tip; MTPM, maximum total point motion.

4.3.2 Tibiofemoral Contact Kinematics

A fitted line of AP contact on the lateral condyle (Figure 4.4A) was positioned at 3.33 mm at full extension (0°), −3.11 mm at 20°, −5.50 mm at 40°, −5.73 mm at 60°, −5.66 mm at 80°, −7.17 mm at 100°, and −12.14 mm at 120° of knee flexion. A fitted line of AP contact on the medial condyle (Figure 4.4B) was positioned at −0.34 mm at full extension (0°), −4.69 mm at 20°, −5.49 mm at 40°, −4.67 mm at 60°, −4.15 mm at 80°, −5.84 mm at 100°, and −11.67 mm at 120° of knee flexion. The AP position and flexion angle of the most anterior and most posterior contact points for the lateral and medial condyles can be visualized in Figure 4.4. The average AP position of the most anterior contact point was
3.99 ± 4.07 mm on the lateral condyle and 1.99 ± 4.24 mm on the medial condyle. The most anterior contact point on the lateral condyle occurred exclusively at full extension (0°), whereas on the medial condyle it typically occurred at either full extension or in mid-flexion around 60° of flexion. The average AP position of the most posterior contact point was –8.07 ± 2.04 mm on the lateral condyle and –8.93 ± 2.52 mm on the medial condyle. The most posterior contact point on the lateral condyle mostly occurred in deep or maximum flexion, with some incidences in early and mid-flexion. On the medial condyle, the most posterior contact typically occurred during early flexion (0–40°) or in deep or maximum flexion. The average excursion on the lateral condyle was 12.06 ± 4.42 mm and the average excursion on the medial condyle was 10.92 ± 4.10 mm.
Figure 4.4: Tibiofemoral contact kinematics at 1 year post operation, including (A) lateral condyle AP contact position and (B) medial condyle AP contact position. AP contact position is in millimeters scaled to a size 4 tibial baseplate, with positive values being more anterior, negative values being more posterior, and zero being the middle of the tibial component in the AP direction. The grey outlined circles depict AP contact point locations at anatomical knee flexion angles. Circles filled in with red show the most anterior contact point for each patient and circles filled in with blue depict the most posterior contact point for each patient. The solid line is line fitted through all contact points indicating the overall pattern of AP contact throughout flexion, and dashed lines depict the upper and lower 95% PI for the fitted line. AP, anteroposterior; PI, prediction intervals.
4.3.3 Correlations between Migration and Kinematics

Representative examples of associations between contact kinematics and tibial component migration are displayed in Figure 4.5. There were associations between the location of the most anterior contact points, most posterior contact points, and excursion on the lateral condyle and the 2-year postoperation fictive point 3D translations and MTPM (Table 4.1). Greater tibial component migration occurred for MTPM ($r^2 = 0.18$, $P = 0.02$, Figure 4.5A) and at the anterolateral, anteromedial, medial, posterolateral, posteromedial, and stem tip fictive points when the most anterior contact point on the lateral condyle was positioned more posteriorly. When the most posterior contact point was positioned more anteriorly, greater migration occurred at the posterolateral ($r^2 = 0.18$, $P = 0.01$, Figure 4.5B) and stem tip fictive points. Greater migration occurred for MTPM ($r^2 = 0.19$, $P = 0.01$, Figure 4.5C) and at all 7 fictive points when excursion on the lateral condyle was reduced. There were associations between the location of the most anterior contact points and excursion on the medial condyle and the 2-year postoperation fictive point 3D translations and MTPM (Table 4.1). Greater tibial component migration occurred at the stem tip when the most anterior contact point on the medial condyle was positioned more posteriorly. Greater tibial component migration occurred at the posterolateral fictive point and the stem tip ($r^2 = 0.18$, $P = 0.02$, Figure 4.5D) with reduced excursions on the medial condyle. There were associations between the excursion on the lateral and medial condyles and the continuous migration from 1 year to 2 years postoperation (Table 4.2). Greater continuous tibial component migration occurred for MTPM ($r^2 = 0.22$, $P = 0.006$, Figure 4.5E) and at all 7 fictive points when excursion on the lateral condyle was reduced. Greater continuous tibial component migration occurred at the anterolateral, lateral ($r^2 = 0.25$, $P = 0.004$, Figure 4.5F), posterolateral, and stem tip fictive points when excursion on the medial condyle was reduced.
Figure 4.5: Representative results from regression analyses between kinematic variables and tibial component migration. Correlations were found between (A) 2 year MTPM and the most anterior point of contact on the lateral condyle, (B) 2 year migration at the PL fictive point and the most posterior point of contact on the lateral condyle, (C) 2 year MTPM and excursion on the lateral condyle, (D) 2 year migration at the stem tip fictive point and excursion on the medial condyle, (E) 1 to 2 year MTPM and excursion on the lateral condyle, and (F) 1-2 year continuous migration at the lateral fictive point and excursion on the medial condyle.
Table 4.1: Correlations Between Tibial Component Migration at 2 years Postoperation and Contact Kinematic Variables on the Lateral and Medial Condyles.

<table>
<thead>
<tr>
<th>Kinematic Variables</th>
<th>Lateral Condyle Contact</th>
<th>Medial Condyle Contact</th>
<th>Excursion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r²</td>
<td>r²</td>
<td>r²</td>
</tr>
<tr>
<td>Most</td>
<td>0.166</td>
<td>0.181</td>
<td>0.102</td>
</tr>
<tr>
<td>Most</td>
<td>0.173</td>
<td>0.177</td>
<td>0.180</td>
</tr>
<tr>
<td>Most</td>
<td>0.086</td>
<td>0.036</td>
<td>0.119</td>
</tr>
</tbody>
</table>

Bolded values are statistically significant.

3D, three-dimensional; AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; ST, stem tip; MTPM, maximum total point motion.
Table 4.2: Correlations Between Continuous Tibial Component Migration Between 1 year and 2 years Postoperation and Contact Point Excursion on the Lateral and Medial Condyles.

<table>
<thead>
<tr>
<th>Kinematic Variables</th>
<th>Fictive Points 3D Translations</th>
<th>MTPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Excursion</td>
<td>r^2 = 0.167 r^2 = 0.163 r^2 = 0.146 r^2 = 0.177 r^2 = 0.138 r^2 = 0.236 r^2 = 0.177 r^2 = 0.223</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P = 0.020 P = 0.022 P = 0.031 P = 0.017 P = 0.036 P = 0.005 P = 0.016 P = 0.006</td>
<td></td>
</tr>
<tr>
<td>Medial Excursion</td>
<td>r^2 = 0.163 r^2 = 0.052 r^2 = 0.246 r^2 = 0.048 r^2 = 0.141 r^2 = 0.036 r^2 = 0.160 r^2 = 0.073</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P = 0.022 P = 0.208 P = 0.004 P = 0.227 P = 0.034 P = 0.301 P = 0.024 P = 0.134</td>
<td></td>
</tr>
</tbody>
</table>

Bolded values are statistically significant.

3D, three-dimensional; AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; ST, stem tip; MTPM, maximum total point motion.

4.3.4 Case Studies of Continuous Migrators

Six patients had continuous migrations greater than 0.2 mm from 1 to 2 years postoperation, with MTPM ranging from 0.21 to 1.09 mm (Table 4.3, Figure 4.6). The contact kinematics on the lateral and medial condyles for the continuously migrating patients can be seen in Figure 4.7. Patient S12 and Patient S14 both had kinematic profiles that agreed with the full cohort’s overall contact kinematics for the lateral and medial condyle; however, they had limited range of flexion, only being able to flex their operated knee to 73 and 49° respectively when bearing weight, and therefore had limited posterior contact on both condyles that typically occurs in deep flexion. Patient S15 and Patient S56 both had very anterior contact on the lateral and medial condyles at full extension, and their most posterior contact positions on both condyles occurred in early to midflexion, unlike the full cohort’s overall contact kinematic pattern where the most posterior contact position occurs at maximum flexion. Patient S56 had substantial paradoxical anterior contact point translation on the medial condyle. Patient S65 had contact kinematics on both condyles that closely resembled the full cohort’s overall contact kinematics. Patient S30 had abnormal contact kinematic patterns on both the lateral and medial condyles. Laterally, Patient S30 had posterior contact relative to the overall pattern at full extension, and little
to no posterior AP contact point translation in early flexion before posteriorly translating slightly in mid-flexion. Medially, Patient S30 had their most posterior contact at full extension, then anterior AP contact point translation during early flexion before posteriorly translating slightly in mid-flexion. Patient S30 also only reached a maximum flexion angle of 88°.

Table 4.3: Details on Patients Who had Continuously Migrating Tibial Components, and the Mean and Standard Deviation of all Study Patients.

<table>
<thead>
<tr>
<th>Patients</th>
<th>S12</th>
<th>S14</th>
<th>S15</th>
<th>S30</th>
<th>S56</th>
<th>S65</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTPM at 1 y (mm)</td>
<td>0.262</td>
<td>0.168</td>
<td>0.216</td>
<td>0.962</td>
<td>0.361</td>
<td>0.142</td>
<td>0.352 ± 0.168</td>
</tr>
<tr>
<td>MTPM at 2 y (mm)</td>
<td>0.476</td>
<td>0.413</td>
<td>0.457</td>
<td>2.053</td>
<td>0.578</td>
<td>0.441</td>
<td>0.415 ± 0.345</td>
</tr>
<tr>
<td>MTPM 1 to 2 y (mm)</td>
<td>0.214</td>
<td>0.245</td>
<td>0.241</td>
<td>1.091</td>
<td>0.217</td>
<td>0.299</td>
<td>0.053 ± 0.244</td>
</tr>
<tr>
<td>Age (y)</td>
<td>68</td>
<td>76</td>
<td>84</td>
<td>71</td>
<td>69</td>
<td>76</td>
<td>71.3 ± 9.2</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>38.6</td>
<td>27.3</td>
<td>25.2</td>
<td>36.6</td>
<td>31.5</td>
<td>28.3</td>
<td>32.2 ± 4.7</td>
</tr>
<tr>
<td>Sex</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>27 M, 27 F</td>
</tr>
</tbody>
</table>

MTPM, maximum total point motion; BMI, body mass index; M, male; F, female; SD, standard deviation.
Figure 4.6: Tibial component migration for the 6 patients who had 1–2 year post operation MTPM values greater than 0.2 mm, indicating continuous migration. Mean and standard deviation of tibial component migration plotted as solid grey line with error bars.
Figure 4.7: Tibiofemoral contact kinematics at 1 year post operation, including (A) lateral condyle AP contact position and (B) medial condyle AP contact position for the 6 patients with continuous 1–2 year tibial component migration. Solid grey line depicts the overall fitted line for AP contact position throughout flexion for all study patients, with dashed grey lines depicting the upper and lower 95% PIs for the fitted line.
4.3.5 Correlations between Migration and Clinical Outcomes

There were significant correlations between active range of motion and 2-year migration at the lateral ($r^2 = 0.22, P = 0.007$) and posterolateral ($r^2 = 0.22, P = 0.008$) fictive points, as well as with the 1-to-2-year MTPM ($r^2 = 0.22, P = 0.03$) and migration at the anterolateral ($r^2 = 0.22, P = 0.004$), lateral ($r^2 = 0.22, P = 0.0004$), and posterolateral ($r^2 = 0.22, P = 0.005$) fictive points. Greater migration values correlated with reduced range of motion. There were no significant correlations between patient demographics, including height, weight, and BMI, and any implant migration measurement, including MTPM or fictive point translation at 2 years or from 1 year to 2 years. There was also no significant difference in 2-year MTPM ($P = 0.79$) or 1-to-2-year MTPM ($P = 0.43$) between men and women. Preoperative and postoperative PROMs are displayed in Table 4.4. There were no significant correlations between contact kinematics and preoperative PROMs; however, there was a significant correlation between the location of the most posterior contact point on the lateral condyle and the KSS Symptoms score at 1-year postoperation ($r^2 = 0.22, P = 0.03$), with a more anterior position correlating to a lower Symptoms score.

Table 4.4: Preoperative and 1-y Postoperative Patient-Reported Outcome Measures (Mean ± Standard Deviation) from the KSS.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pre-operative</th>
<th>Post-operative</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSS Symptoms</td>
<td>16.16 ± 3.63</td>
<td>23.34 ± 2.74</td>
</tr>
<tr>
<td>KSS Satisfaction</td>
<td>15.86 ± 7.00</td>
<td>31.47 ± 8.39</td>
</tr>
<tr>
<td>KSS Expectation</td>
<td>13.50 ± 1.54</td>
<td>9.79 ± 3.60</td>
</tr>
<tr>
<td>KSS Functional Activities</td>
<td>40.05 ± 12.85</td>
<td>62.57 ± 18.23</td>
</tr>
</tbody>
</table>

KSS, Knee Society Score.

4.4 Discussion

This study found that correlations exist between knee joint contact kinematics and tibial component migrations for a BCS TKA implant design. Most of the correlations were found between implant migration and lateral condyle contact kinematics. Greater continuous 1-to-2-year migration and migration at 2 years postoperation were both associated with reduced lateral condyle excursion, with the strongest associations observed with MTPM ($r^2 = 0.22$), the posteromedial ($r^2 = 0.24$), and the stem tip fictive points ($r^2 = 0.18$) for
continuous 1-to-2-year migration, and with MTPM ($r^2 = 0.19$), the posterolateral ($r^2 = 0.20$), and the posteromedial fictive points ($r^2 = 0.18$) for 2 year migration. Greater baseplate migrations at 2 years postoperation occurred when the most anterior points of contact on the lateral condyle were more posteriorly located, the strongest associations being with MTPM ($r^2 = 0.18$), the anteromedial ($r^2 = 0.18$), and anterolateral fictive points ($r^2 = 0.17$). Greater baseplate migrations at 2 years postoperation also occurred when the most posterior points of contact were more anteriorly located, the associations being with the posterolateral ($r^2 = 0.18$) and stem tip fictive points ($r^2 = 0.16$). Fewer associations were found between implant migration and medial condyle contact kinematics, with greater 2-year migration and continuous migration from 1 year to 2 years postoperation correlating with reduced medial excursion. The strongest correlation was between continuous 1-to-2-year migration at the lateral fictive point and medial excursion ($r^2 = 0.25$). The continuous 1-to-2-year migrations at the other two laterally located fictive points—the anterolateral ($r^2 = 0.16$) and posterolateral points ($r^2 = 0.14$)—and the stem tip fictive point ($r^2 = 0.16$) were also associated with reduced medial excursion, as were greater 2 year postoperation migrations at the posterolateral ($r^2 = 0.18$) and stem tip fictive points ($r^2 = 0.18$). Reduced active range of motion also correlated with greater migration values, both at 2 years and between 1 year and 2 years postoperation, at laterally located fictive points.

Lateral excursion appears to be the most consistent kinematic variable that is associated with tibial baseplate migrations for this implant design. There were correlations between lateral excursion and migrations at all 7 fictive points, for both the 2-year migration values and the continuous 1-to-2-year migration values. Again, decreased values of lateral excursion correlated with greater tibial component migration. The other correlations observed with lateral condyle contact kinematics also suggest that lateral excursion is the important variable, since more posteriorly located maximum anterior contact points and more anteriorly located maximum posterior contact points infer a reduced range of AP contact, and are both associated with greater implant migrations. This implies that to reduce the amount of implant migration, there needs to be a sufficient range of AP contact allowed throughout flexion on the lateral condyle, whether through less constraint or ensuring a proper active range of motion. More anteriorly located maximum posterior contact points was also associated with a worse KSS Symptoms score, implying that patients with less
posterior rollback on the lateral condyle have more pain and more abnormal feeling knees. Normal knees exhibit a greater range of lateral AP contact, pivoting about the medial condyle to create a fan-like contact pattern when viewed axially.\(^{27}\) One of the goals of the BCS TKA design is to replicate this medial pivot pattern by guiding motion using a dual cam-post mechanism and polyethylene liners that have concave medial condyles and convex lateral condyles.\(^{4,5}\) The results of the current study suggest that greater implant migration will occur when normal knee kinematics are not replicated as intended, and that patients will more frequently notice their knee does not feel normal. A study of a highly congruent mobile bearing TKA design by Wolterbeek et al\(^{17}\) found that diverging axial rotations and unexpected pivot points resulted in greater implant migrations. Teeter et al\(^{19}\) also found in a study of a posterior stabilized design that continuously migrating tibial components had contact kinematics that differed from the typical kinematic patterns seen in most other implants in their study. These findings support the results of the current study, which suggest that when kinematics deviate from the intended pattern, the implant will migrate more. While the resultant migrations were still fairly low in most cases in this study suggesting the tibial components will remain well-fixed, in general increased migration is associated with a higher risk of loosening.\(^{14}\)

The migration of the BCS design in this study was within the safe migration thresholds established by Pijls et al.\(^{14}\) At both 6 months and 1 year, the BCS tibial components had an average MTPM below the 0.5-mm threshold (0.33 mm at 6 months and 0.35 mm at 1 year), indicating revision rates will be below 3% at 5 years postoperation. At 2 years, the 3 medially located fictive points (medial = 0.34 mm, anteromedial = 0.31 mm, posteromedial = 0.29 mm) had greater migration than the 3 laterally located fictive points (medial = 0.27 mm, anterolateral = 0.26 mm, posterolateral = 0.24 mm), with the stem tip having the least amount of migration (0.173 mm). The mean continuous migration for the overall cohort of BCS tibial components was also lower than the 0.2-mm threshold established by Ryd et al,\(^{15}\) with an average 1-to-2-year MTPM of 0.053 mm. According to Ryd et al,\(^{15}\) tibial components above the 0.2-mm threshold have an 85% risk of becoming mechanically loose and a 20% risk of becoming clinically loose and requiring a revision within the first 10 years postoperation. No early revisions for aseptic loosening have been necessary yet, however six tibial components were above the 0.2-mm threshold and deemed continuous
migrants, suggesting that approximately one will require an early revision due to aseptic loosening.

Teeter et al$^{19}$ and Wolterbeek et al$^{17}$ found that abnormal kinematics resulted in continuously migrating implants, likely due to improper force transmissions. Six patients (Table 4.3) in this study had continuously migrating (>0.2 mm MTPM) tibial components, and most demonstrated contact kinematics that differed from the intended kinematic pattern for the BCS design$^{4,15}$. Demographic variables may have also factored alongside the kinematics to contribute to implant migration. Unintended force transmissions resulting from abnormal kinematics may pose a greater threat to implant migration in patients who have elevated body masses as has been shown by Berend et al$^{28}$ or in patients who may have poorer bone quality or bone turnover as suggested in osteoporotic cases, a common comorbidity in osteoarthritic patients requiring joint replacement$^{29-31}$. No correlations were found between implant migration and demographics such as BMI and age in this study; however, patients who had continuously migrating implants had demographic factors that, combined with abnormal kinematics, may have resulted in continuously migrating implants. Patient S30 had by far the greatest continuous migration from 1 year to 2 years (MTPM = 1.09 mm), leading to a 2-year MTPM of 2.05 mm. This patient, who was a 71-year-old woman and had a BMI of 36.6, had kinematics that revealed limited anterior contact on either condyle and very reduced lateral excursion. The age and sex of this patient hint at worse bone quality, potentially decreasing the ability to endure improper force transmissions that result from a less mobile lateral compartment, and when combined with greater forces from an elevated body mass, could have led to the extensive implant migration. Since bone quality was not assessed in this study, this possibility cannot be confirmed. The other 5 continuous migrators had 1-to-2-year MTPM values ranging from 0.21 mm to 0.30 mm, which are only slightly greater than the 0.2-mm at risk threshold, and therefore could still all be expected to have sufficient fixation. However, four of those patients (S12, S14, S15, and S56) did have a combination of demographic variables and abnormal kinematics that might combine and contribute to the observed continuous implant migration. Patient S12 was an obese man, and Patients S14 and S15 were older men (>75 years old), and Patient S56 was an obese postmenopausal woman. Each had abnormal kinematics, characterized by reduced posterior rollback likely due to limited range of
motion or a more constrained lateral condyle, which can both result from improper balancing of flexion-extension gaps. The other patient with a continuously migrating baseplate, a postmenopausal woman, appeared to have typical contact kinematics.

This study was not without limitations. Some patients were lost to follow up and did not complete the 2-year RSA examination (in large part due to the COVID-19 pandemic). However, the sample size was still sufficient to find statistically significant correlations. Additionally, the patients included in the present study were from a randomized controlled trial comparing 2 different surgical techniques; however, this trial found no differences between techniques for implant migration. Furthermore, the kinematics were acquired using a quasi-static technique rather than for a dynamic deep knee squat; however, there have been multiple studies demonstrating that static kinematics of straightforward motions can be representative of dynamic kinematics after TKA. Another limitation is that there were very few tibial components that experienced substantially elevated migration, and most of the continuously migrating tibial components had 1-to-2-year migrations that were only slightly above the 0.2-mm threshold and had fairly low 2-year MTPM, suggesting they will likely remain well-fixed. Therefore, while we could determine associations between kinematics and migration, it is difficult to confirm which kinematic patterns and demographic associations may result in implant loosening. We also did not acquire postoperative hip-knee-ankle radiographs as part of this study and therefore could not analyze postoperative TKA alignment. Most RSA studies investigating knee implant migration, however, do not report limb alignment. Surgeon variability may have also influenced the results, as intraoperative balance and soft tissue tension were likely different between surgeons.

In conclusion, associations were found that may help identify contact kinematics that could result in elevated migration for a BCS implant design. Excursion on the lateral condyle was identified as having an influence on the 2-year migration and continuous 1-to-2-year migration at all fictive points of the tibial baseplate. Continuously migrating implants appeared to have abnormal kinematics that may have been a result of unintended force transmissions. These results highlight the importance of restoring knee kinematics with
this BCS TKA design to minimize improper force transmissions and resultant increased implant migrations.

4.5 References


Chapter 4

5 Conclusions and Future Directions

5.1 Summary of Results

The goals of total knee arthroplasty (TKA) are to relieve pain, restore joint function, and to improve the quality of life for the patient.\(^1\) Although the procedure is considered a huge success and has revolutionized the treatment of severe knee osteoarthritis (OA), a persistently high number of patients, 1 in 5, remain dissatisfied with their replaced knee.\(^2\)

It is thought that a complex blend of patient-dependent and patient-independent factors influence the satisfaction of a TKA patient.\(^3,4\) Many hypotheses exist for how implant design and surgical technique may improve patient satisfaction.\(^3\) One such hypothesis led to the development of the bicruciate stabilized (BCS) TKA design, which aims to restore the natural kinematics of the knee joint through anatomically shaped prosthesis components and a system to replicate the function of both cruciate ligaments.\(^5–9\) The first BCS TKA appeared to achieve its goal of restoring kinematics.\(^5,8,10\) However, this was at the expense of worse implant revision rates, and a recall was required.\(^7,9,11–13\) The second-generation BCS device modified the design to rectify the issues of the original, while still aiming to restore normal knee kinematics.\(^11,14–16\) The \textit{in vivo} biomechanical, functional performance-based, and clinical outcomes for the second-generation BCS design were investigated in this thesis through radiographic imaging techniques, wearable sensor systems, and questionnaires in a cohort of TKA patients.

In Chapter 2, titled “Migration and Inducible Displacement of the Bi-cruciate Stabilized Total Knee Arthroplasty: A Randomized Controlled Trial of Gap Balancing and Measured Resection Techniques”, two surgical techniques—gap balancing (GB) and measured resection (MR)—were compared in a randomized controlled trial (RCT) to determine the technique that provides the best implant fixation, and thus long-term stability. We hypothesized there would be no differences between the GB and MR surgical techniques for two measures of fixation, implant migration and inducible displacement. Fifty-six patients were recruited and randomized to the GB or MR surgical technique before receiving a BCS TKA. Radiostereometric analysis (RSA) was used to track implant
migration longitudinally over 2 years and to measure inducible displacements. No differences existed between GB and MR groups for any measurement of tibial or femoral migration. Likewise, no differences were found between GB and MR groups for inducible displacement. The tibial component migration was shown to be within established thresholds for what is considered safe migration, suggesting the BCS device is predicted to have revision risks on par with industry standards. Overall, the results of this study support using either surgical technique as a safe and effective option for BCS TKA.

With the issues regarding the first BCS device seemingly resolved by the design modifications made to the second-generation device, attention was turned to the satisfaction of patients who were implanted with the BCS TKA. In Chapter 3, titled “Patient and Implant Performance of Satisfied and Dissatisfied Total Knee Arthroplasty Patients”, patients from the previous RCT were pooled together and multiple objective factors were analyzed to uncover any potential differences between satisfied and dissatisfied patients. The Knee Society Score Satisfaction Subsection questions regarding satisfaction with function were used at least 6 months postoperation to split 50 patients into satisfied and dissatisfied groups. Patients underwent radiostereometric analysis to evaluate implant migration and tibiofemoral contact kinematics. A wearable sensor system obtained objective measurements of patient function during timed-up-and-go (TUG) tests, and patient-reported outcome measures (PROMs) were collected preoperation and postoperation. No statistically significant differences were found in migration between satisfied and dissatisfied groups. Statistical kinematic differences existed in lateral anteroposterior contact location at 20° and 40° of flexion at 1 year, where the dissatisfied group had more anteriorly located lateral contact. No statistically significant differences were present in objective functional measurements. Satisfied and dissatisfied groups had differing PROMs at 4 timepoints or greater for each questionnaire. These findings suggest that improving the functional satisfaction of TKA may require management of patient's pain and expectations, as well as the restoration of kinematics in early flexion, especially in the lateral compartment.

Contact kinematics have also been shown to affect the tibial component migration; however, these relationships were found in studies of older TKA designs. In Chapter 4,
titled “Correlating Contact Kinematics to Tibial Component Migration Following Cemented Bicruciate Stabilized Total Knee Arthroplasty”, patients from the previous RCT were once again pooled together and relationships between tibial component migration and tibiofemoral contact kinematics for BCS TKA were investigated. A total of 54 knees implanted with a BCS TKA system were analyzed using radiostereometric analysis (RSA). Patients underwent RSA exams at 2 weeks, 6 weeks, 3 months, 6 months, 1 year, and 2 years post operation to measure tibial component migration. At 1 year, contact kinematics were evaluated during a quasi-static deep knee bend. Linear regression analyses were performed between kinematic variables and migration values. Significant correlations were found between contact kinematics and tibial component migration. Excursion on the lateral condyle was the most consistent variable correlating with implant migration, suggesting that there needs to be a sufficient range of anteroposterior (AP) contact allowed throughout flexion on the lateral condyle to reduce the amount of implant migration. A more anteriorly located maximum posterior contact point was also associated with a worse KSS Symptoms score, implying that patients with less posterior rollback on the lateral condyle have more pain and more abnormal feeling knees. A closer study of the 6 patients who were deemed continuous migrators—having >0.2 mm migrations from 1 to 2 years postoperation—revealed most had atypical contact kinematics and demographic factors that may indicate greater risk for implant loosening. An important goal of BCS TKA is to restore the kinematics of normal knees, which have a large range of AP contact. The results of the current study suggest that greater implant migration will occur when normal knee kinematics are not replicated as intended, and that patients will more frequently notice their knee does not feel normal.

Overall, the BCS TKA was determined to be a safe and effective device regardless of surgical technique, with the predicted revision rates appearing to have solved issues concerning the first-generation design. However, patient satisfaction was not shown to improve despite the advanced implant design. The overall kinematics of the cohort were good, approximating those of normal knees; however, there was a subgroup of patients with poorer kinematics who had worse outcomes. Of note was a more anterior contact positioning on the lateral condyle in early flexion in dissatisfied patients, consistent with results from a study of the same implant by Kono et al\textsuperscript{17} where a low-PROM group had
more anterior contact positioning on the lateral condyle. In Chapter 4 of this thesis, contact patterns indicating less posterior rollback in the lateral condyle were also shown to correlate with elevated tibial component migration, and resulted in patients reporting more pain and abnormal feeling in their knee. Abnormal kinematic patterns were also observed in most of the six patients with continuously migrating tibial components. This highlights the importance of properly restoring the kinematics—particularly in the lateral compartment—in BCS TKA, whether through less constraint or ensuring a proper active range of motion. Doing so may result in reduced implant migrations, better pain and feeling in the knee, and ultimately, a more satisfied patient.

5.2 Related Future Directions

The work in this thesis, specifically Chapter 2, represents the first RSA study of the BCS TKA device. The primary goal of the original RCT was to determine if there were differences in implant migration between 2 surgical techniques. As such, the study was powered for RSA. One of the advantages of RSA is that only a small number of patients are required per group (28 in this case), which limits the number of patients exposed to a new treatment before widespread adoption occurs. The implant migration results in this cohort of patients were generally excellent, with only six tibial components having continuous migration from 1 year to 2 years postoperation. Thus, only 1 patient (perhaps Patient S30 seen in Chapter 4) is expected to require a revision due to aseptic loosening. The problem, from a research lens, with only having 1 expected case of clinical loosening is that it becomes very difficult to decipher which factors may lead to loosening. Although correlations were found between kinematics and migration (Chapter 4), they were not very strong, likely due to a lack of cases with high migration. Therefore, larger scale studies, with more cases of continuous migration, could further uncover kinematic patterns that may increase the risk of implant loosening. Longer term follow-up with the patients in this study could also help to elaborate on the influence kinematics have on migration when the long-term fixation status of the implants—particularly the continuously migrating baseplates—is clearer.

Another missing piece in this work is the role of alignment, which is not regularly reported in RSA studies. Malalignment is associated with numerous negative outcomes, including
increased implant wear rates, decreased function, joint instability, and early implant failure.\textsuperscript{19–24} An enormous amount of effort has investigated the role of alignment and approaches to improve surgical precision to achieve the best alignment in the most patients.\textsuperscript{25–27} Neutral mechanical alignment has long been the target for TKA; however, there is no clear association between PROMs and coronal alignment after TKA.\textsuperscript{25} Kinematic alignment is an alternative alignment strategy that aims to match a patient’s prearthritic knee orientation to restore kinematics, which may help to improve patient outcomes. Anatomic alignment is another technique that aims to restore the natural joint line. The BCS TKA simulates anatomic alignment by incorporating the 3° joint line obliquity into the implant design. However, debate remains surrounding the optimal alignment target. One of the barriers to deviations from neutral mechanical alignment in the past was insufficient surgical precision.\textsuperscript{26} Mechanical alignment was the safest option, since a ±3° offset in alignment would still result in a fairly neutral knee. The risk with other alignment options, such as anatomic alignment, is that missing the target alignment could result in an excessively varus limb, which could have negative outcomes.\textsuperscript{21,26} However, computer navigation and robotic-assisted systems have been developed that improve the precision of implant positioning.\textsuperscript{27,28} These tools can help surgeons hit their targets, and may encourage the use of different alignment strategies. Future research should investigate how different alignments influence clinical outcomes such as patient satisfaction—especially in newer implant designs such as the BCS TKA.

Although computer navigation has been shown to improve the precision of limb alignment and component positioning, these advantages have not resulted in improved functional outcomes.\textsuperscript{27} Robotic-assisted TKA is a promising innovation that has been shown to provide even greater surgical precision than computer navigation, resulting in less mechanical axis outliers.\textsuperscript{27,29–31} Robotic-assisted TKA also improves the control of soft tissue balancing, and has been shown to result in better flexion-extension gaps and ligament tensions.\textsuperscript{29} Studies have hinted at improved short-term PROMs in patients who underwent a robotic-assisted TKA, although more evidence is needed to determine if these improvements are clinically relevant and generalizable to all available robotic systems.\textsuperscript{30–32} This thesis highlighted the importance of restoring kinematics in a BCS design, suggesting that less constraint or greater ranges of motion may result in better outcomes.
Future research should investigate if robotic-assisted TKA can improve contact kinematics and help mitigate the negative outcomes that can arise when proper balancing does not occur in BCS TKA.

Limitations also remain in the reporting of patient satisfaction. Many of the PROMs used in TKA are not validated, can suffer from ceiling effects, and may be outdated, no longer assessing the evolving goals and greater expectations of TKA patients.\textsuperscript{25,33,34} Furthermore, the definition of satisfaction differs for different patients.\textsuperscript{35} Since TKA is widely considered a very successful procedure, it is important that instruments used to assess the clinical outcomes of TKA are able to detect small but potentially important differences between patients. Future effort should be spent developing improved outcome metrics to further expose who is dissatisfied and why so that we may finally improve patient satisfaction following TKA.

5.3 References


29. Song EK, Seon JK, Yim JH, Netravali NA, Bargar WL. Robotic-assisted TKA reduces postoperative alignment outliers and improves gap balance compared to


Appendices

Appendix A: Ethics Approval Notices

LAWSON APPROVAL

LAWSON APPROVAL NUMBER: R-17-356

PROJECT TITLE: Radiostereometric analysis of gap balancing versus measured resection for the Journey II total knee replacement

PRINCIPAL INVESTIGATOR: Dr. Douglas Neudie

LAWSON APPROVAL DATE: Wednesday, 4 October 2017

Health Sciences REB#: 109512

RaDA ID: 2901

Overall Study Status: Active

Please be advised the above project was reviewed by Lawson Administration and the project was approved.

Please provide your Lawson Approval Number (R#) to the appropriate contact(s) in supporting departments (eg. Lab Services, Diagnostic Imaging, etc.) to inform them that your study is starting. The Lawson Approval Number must be provided each time services are requested.

Dr. David Hill
V.P. Research
Principal Investigator: Dr. Douglas Naudie
Department & Institution: Schulich School of Medicine and Dentistry\Surgery. London Health Sciences Centre

Review Type: Full Board
HSREB File Number: 109512
Study Title: Radiostereometric analysis of gap balancing versus measured resection for the Journey II total knee replacement

HSREB Initial Approval Date: October 02, 2017
HSREB Expiry Date: October 02, 2018

Documents Approved and/or Received for Information:

<table>
<thead>
<tr>
<th>Document Name</th>
<th>Comments</th>
<th>Version Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revised Western University Protocol</td>
<td>Received July 25, 2017</td>
<td></td>
</tr>
<tr>
<td>Revised Letter of Information &amp; Consent</td>
<td></td>
<td>2017/07/25</td>
</tr>
<tr>
<td>Data Collection Form/Case Report Form</td>
<td>RSA Data Collection Form (29-Jun-2017)</td>
<td></td>
</tr>
<tr>
<td>Data Collection Form/Case Report Form</td>
<td>KSS (Clinician) Questionnaire</td>
<td></td>
</tr>
<tr>
<td>Data Collection Form/Case Report Form</td>
<td>KSS (Patient) Questionnaire</td>
<td></td>
</tr>
<tr>
<td>Instruments</td>
<td>WOMAC Questionnaire</td>
<td>2017/06/22</td>
</tr>
<tr>
<td>Instruments</td>
<td>UCLA Activity Score Questionnaire</td>
<td>2017/06/22</td>
</tr>
<tr>
<td>Instruments</td>
<td>Short Form-12 (SF-12) Questionnaire</td>
<td></td>
</tr>
<tr>
<td>Recruitment Items</td>
<td>Recruitment Letter</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Registration NCT# 03290170</td>
<td></td>
</tr>
</tbody>
</table>

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.
Appendix B: Letter of Information and Consent

Letter of Information and Consent Form

Radiostereometric analysis of gap balancing versus measured resection for the Journey II total knee replacement

Principal Investigator: Dr. Douglas Naudie
Co-Investigators: Dr. James Howard, Dr. Richard McCalden, Dr. Brent Lanting, Dr. Edward Vasarhelyi, Dr. Matthew Teeter

Study Coordinators: Jordan Broberg, Bryn Zomar, Maxwell Perecut, Harley Williams

You are being invited to participate in a research study designed for patients who will receive a primary total knee replacement under Dr. Douglas Naudie’s, Dr. Richard McCalden’s, Dr. James Howard’s, Dr. Brent Lanting’s or Dr. Edward Vasarhelyi’s care. This letter of information describes the research study and your role as a participant. The purpose of this letter is to provide you with the information you require to make an informed decision about participating in this research. Please read this form carefully.

Study Purpose
The stability of a total knee replacement (TKR) surgery depends on soft tissue balance (i.e. balance of supporting ligaments) and bony cuts made during surgery that determine the rotation of the part of the TKR implant located in the thigh bone (called the femoral
component). Abnormal rotation of this component has been associated with adverse effects including knee instability, knee pain, scar tissue, and abnormal knee motion. Controversy exists, however, regarding the best surgical technique to minimize rotation of the femoral component. Some doctors prefer a measured resection technique where landmarks on the thigh bone are used to determine where to place the femoral component. Others recommend a gap-balancing technique where the femoral component is positioned by balancing the ligaments of the knee (i.e. placing it in the position where each ligament is equally stretched).

The purpose of this study is to compare the measured resection and gap-balancing surgical techniques, used with cemented implants, by evaluating implant migration (movement) over time, contact kinematics (how the knee moves) and patient-reported knee outcome scores. Implant migration and contact kinematics are assessed using a special kind of x-ray called radiostereometric analysis (RSA). Knee outcome scores are assessed from the responses given by patients to questions about outcomes associated with TKR related to pain, symptoms, activities of daily living, sport and recreational function, and knee-related quality of life.

**Procedure**

This is a randomized study with 28 participants in each group for a total of 56 participants. Eligible patients receiving TKR surgery will be enrolled if they meet the inclusion criteria, and will then be randomized to undergo a TKR using either the measured resection or gap-balancing technique. Both surgical techniques are used by the surgeons in their standard practice. You will be randomly assigned, like the flip of a coin, to one of the two groups. If you decide to participate in this study, you will have the same knee replacement parts implanted regardless of what surgical technique is used by your surgeon.

During your surgery you will have tantalum beads inserted into the end of your thigh bone and the top of your shin bone. These beads are the size of the head of a pin and will have no impact on how your knee will function after the surgery. The tantalum beads will be used as markers to assess for any microscopic movement of the implant. To measure this movement, we will ask you to have a special kind of x-ray called RSA taken after surgery at 2 weeks, 6 weeks, 3 months, 6 months, 1 year and 2 years. At your 3-month and 1-year follow-up we will also perform a series of RSA x-rays taken while you bend your knee to measure the position of your implant components relative to each other. A member of the study team will escort you to Robarts Research Institute (attached to University Hospital) where the x-rays will be taken, and a wheelchair will be provided for you if needed. The x-ray will take less than 15 minutes to complete, but at 3 months and 1 year they will take up to 30 minutes.

You will be asked to complete questionnaires that will assess your functional ability and quality of life. The questionnaires will be collected at your preadmission visit, 2 weeks, 6 weeks, 3 months, 6 months, 1 year and 2 years after surgery. These questionnaires will take approximately 15 minutes to complete.
You will also be asked to perform the Timed Up and Go (TUG) at each visit. The TUG involves getting up from a chair, walking 3 meters to a point marked on the floor, turning around and returning to sitting in the chair. Any gait aids (such as a cane, crutches or walker) that are normally used will be permitted during the TUG. During the TUG we will have you wear sensors that will measure speed, step length, stride length, etc.

**Risk**

There is always a slight chance of cancer from excessive exposure to radiation. However, special care is taken during x-ray examinations to use the lowest radiation dose possible while producing the best images for evaluation.

The scientific unit of measurement for radiation dose is the milliSv (mSv). People are exposed to radiation from natural sources all the time. The average person receives an effective dose of about 3 mSv per year from naturally occurring radioactive materials and cosmic radiation from outer space. Each RSA examination of the knee will expose the patient to 0.001 mSv (or 1 uSv) of ionizing radiation, or 0.033% of the background radiation we are all exposed to yearly. The RSA exams for flexion at 3 months and 1 year post-operation require a maximum of 8 images for each visit (at 0°, 20°, 40°, 60°, 80°, 100°, 120°, and 140° of flexion) and the longitudinal RSA for migration requires 6 images (2 weeks, 6 weeks, 3 months, 6 months, 1 year, and 2 years). The sum of radiation exposure across the 8 RSA time points is 0.022 mSv (22 uSv), equivalent to approximately 0.73% of yearly background radiation exposure.

There is also a small risk of falling as the x-rays are taken in weight-bearing positions and the TUG test involves walking and sitting. This risk is minimized by providing a handrail to be used as a support during imaging.

Data from your medical record will be gathered for this study. There is a risk for breaching confidentiality of this information; however procedures are set in place to minimize this risk (see below).

**Benefits & Compensation**

Participation in this study will provide no known benefit to you. Information learned from this study may help lead to improvements TKR procedures in the future.

There will be no compensation for your participation in this study.

**Voluntary Participation**

Your participation in this study is voluntary. You may refuse to participate or discontinue your participation at any time without affecting the care being provided to you. Should you choose to withdraw, no further information will be collected. The data you have contributed to that point will be used to help answer our research question.
**Conflict of Interest**

Drs. Douglas Naudie, Richard McCalden and Brent Lanting are paid consultants for Smith & Nephew, which is the company that manufactures the Journey II implant. If this study were to find very positive outcomes of this implant, it is very unlikely that these consultants will receive any benefit. Smith & Nephew is not involved in study conduct and will not be privy to study results whether positive or negative once the study is complete.

**Confidentiality**

All information will be kept confidential to the best of our ability. All RSA image data and TUG data will be stored on a password protected computer in a secure facility (Robarts Research Institute and Sandy Kirkley Centre for Musculoskeletal Health Research, respectively) and will contain only your unique identifying number and no personal identifiers. Even with this high level of security, there always remains a remote chance that your information could be breached by someone without permission to your information. The chance that this information will be accidentally released is minimal. In any publication, presentation or report, all results will be de-identified and any information that would reveal your identity will not be published.

You will be given a copy of this letter of information and consent form once it has been signed. You do not waive any legal rights by signing the consent form. Representatives of The University of Western Ontario Health Sciences Research Ethics Board may contact you or require access to your study-related records to monitor the conduct of the research.

Qualified representatives of the Lawson Quality Assurance Education Program may look at your medical/clinical study records at the site where these records are held, for quality assurance (to check that the information collected for the study is correct and follows proper laws and guidelines).

---

Sincerely,

Dr. Douglas Naudie, MD, FRCSC
Dr. Richard McCalden, MD, FRCSC
Dr. James Howard, MD, FRCSC
Dr. Brent Lanting, MD, FRCSC
Dr. Edward Vasarhelyi, MD, FRCSC

Dr. Matthew Teeter, PhD
Bryn Zomar, MSc, PhD(c)
Jordan Broberg, Master’s Student
Maxwell Perelgut, Master’s Student
Harley Williams, Master’s Student
Radiostereometric analysis of gap balancing versus measured resection for the Journey II total knee replacement

Principal Investigator: Dr. Douglas Naudie

Informed Consent Form

Agreement of Participant

I have read the accompanying letter of information regarding this study and give my informed consent to participate. All questions have been answered to my satisfaction.

Print Participant’s Full Name

Participant’s Signature Date

Name of Person Obtaining Consent

Signature of Person Obtaining Consent Date
Appendix C: Journal Author Rights

Migration and Inducible Displacement of the Bicruciate-Stabilized Total Knee Arthroplasty: A Randomized Controlled Trial of Gap Balancing and Measured Resection Techniques
Author: Jordan S. Broberg, Edward M. Vascular, Brent A. Lanting, James L. Howard, Matthew G. Teeter, Douglas D.R. Naude
Publication: The Journal of Arthroplasty
Publisher: Elsevier
Date: February 2022
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Patient and Implant Performance of Satisfied and Dissatisfied Total Knee Arthroplasty Patients
Author: Jordan S. Broberg, Douglas D.R. Naude, Brent A. Lanting, James L. Howard, Edward M. Vascular, Matthew G. Teeter
Publication: The Journal of Arthroplasty
Publisher: Elsevier
Date: June 2022
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Correlating Contact Kinematics to Tibial Component Migration Following Cemented Bicruciate Stabilized Total Knee Arthroplasty
Author: Jordan S. Broberg, Douglas D.R. Naude, James L. Howard, Brent A. Lanting, Edward M. Vascular, Matthew G. Teeter
Publication: The Journal of Arthroplasty
Publisher: Elsevier
Date: Available online 8 February 2023
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Appendix D: Short Form 12

SF-12

INSTRUCTIONS: This survey asks for your views about your health. This information will help keep track of how you feel and how well you are able to do your usual activities. Answer every question by marking the answer as indicated. If you are unsure about how to answer a question, please give the best answer you can.

1. In general, would you say your health is: | Excellent (1) | Very Good (2) | Good (3) | Fair (4) | Poor (5) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Yes, Limited A Lot</th>
<th>Yes, Limited A Little</th>
<th>No, Not Limited At All</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Moderate activities, such as moving a table, pushing a vacuum cleaner, bowing, or playing golf.</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3. Climbing several flights of stairs.</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Accomplished less than you would like.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5. Were limited in the kind of work or other activities.</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Accomplished less than you would like.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7. Didn’t do work or other activities as carefully as usual.</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Not at All (1)</th>
<th>A little bit (2)</th>
<th>Moderately (3)</th>
<th>Quite a bit (4)</th>
<th>Extremely (5)</th>
</tr>
</thead>
</table>

These questions are about how you feel and how things have been with you during the past 4 weeks. For each question, please give the one answer that comes closest to the way you have been feeling. How much of the time during the past 4 weeks?

<table>
<thead>
<tr>
<th></th>
<th>All of the time</th>
<th>Most of the time</th>
<th>A good bit of the time</th>
<th>Some of the time</th>
<th>A little of the time</th>
<th>None of the time</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. Have you felt calm and peaceful?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>10. Did you have a lot of energy?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>11. Have you felt downhearted and blue?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>All of the time (1)</th>
<th>Most of the time (2)</th>
<th>Some of the time (3)</th>
<th>A little of the time (4)</th>
<th>None of the time (5)</th>
</tr>
</thead>
</table>

Version: 22-Jun-2017
Appendix E: Western Ontario and McMaster Universities Osteoarthritis Index

Study ID: __________
Date: __________

**WOMAC**

A. Think about the *pain* you felt in your hip/knee during the last 48 hours.

<table>
<thead>
<tr>
<th>Question: How much pain do you have?</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Walking on a flat surface</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2. Going up or down stairs</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3. At night while in bed, pain disturbs your sleep</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4. Sitting or lying</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5. Standing upright</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

B. Think about the *stiffness* (not pain) you felt in your hip/knee during the last 48 hours. Stiffness is a sensation of decreased ease in moving your joint.

<table>
<thead>
<tr>
<th>Question: How severe is your stiffness after first awakening in the morning?</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. How severe is your stiffness after first awakening in the morning?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>7. How severe is your stiffness after sitting, lying, or resting later in the day?</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

C. Think about the *difficulty* you had in doing the following daily physical activities due to your hip/knee during the last 48 hours. By this we mean your ability to move around and look after yourself.

<table>
<thead>
<tr>
<th>Question: What degree of difficulty do you have?</th>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. Descending stairs</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>9. Ascending stairs</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>10. Rising from sitting</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>11. Standing</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>12. Bending to the floor</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>13. Walking on a flat surface</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>14. Getting in and out of a car, or on or off a bus</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>15. Going shopping</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>16. Putting on your socks or stockings</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>17. Rising from bed</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>18. Taking off your socks or stockings</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>19. Lying in bed</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>20. Getting in or out of the bath</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>21. Sitting</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>22. Getting on or off the toilet</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>23. Performing heavy domestic duties</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>24. Performing light domestic duties</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Version 22-Jun-2017
Appendix F: Knee Society Score (Patient)

### Patient Satisfaction

1. **Currently, how satisfied are you with the pain level of your knee while sitting?**
   - Very Satisfied (8 pts)
   - Satisfied (6 pts)
   - Neutral (4 pts)
   - Dissatisfied (2 pts)
   - Very Dissatisfied (0 pts)

2. **Currently, how satisfied are you with the pain level of your knee while lying in bed?**
   - Very Satisfied (6 pts)
   - Satisfied (6 pts)
   - Neutral (4 pts)
   - Dissatisfied (2 pts)
   - Very Dissatisfied (0 pts)

3. **Currently, how satisfied are you with your knee function while getting out of bed?**
   - Very Satisfied (6 pts)
   - Satisfied (6 pts)
   - Neutral (4 pts)
   - Dissatisfied (2 pts)
   - Very Dissatisfied (0 pts)

4. **Currently, how satisfied are you with your knee function while performing light household duties?**
   - Very Satisfied (6 pts)
   - Satisfied (6 pts)
   - Neutral (4 pts)
   - Dissatisfied (2 pts)
   - Very Dissatisfied (0 pts)

5. **Currently, how satisfied are you with your knee function while performing leisure recreational activities?**
   - Very Satisfied (5 pts)
   - Satisfied (5 pts)
   - Neutral (4 pts)
   - Dissatisfied (2 pts)
   - Very Dissatisfied (0 pts)

Maximum total points (40 points)
### PATIENT EXPECTATION

(To be completed by patient)

Compared to what you expected before your knee replacement:

<table>
<thead>
<tr>
<th>1- My expectations for pain relief were...</th>
<th>(5 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>✖ Too High: &quot;I'm a lot worse than I thought&quot; (1 pt)</td>
<td></td>
</tr>
<tr>
<td>✖ Too High: &quot;I'm somewhat worse than I thought&quot; (2 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Just Right: &quot;My expectations were met&quot; (3 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Too Low: &quot;I'm somewhat better than I thought&quot; (4 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Too Low: &quot;I'm a lot better than I thought&quot; (5 pts)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2- My expectations for being able to do my normal activities of daily living were...</th>
<th>(5 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>✖ Too High: &quot;I'm a lot worse than I thought&quot; (1 pt)</td>
<td></td>
</tr>
<tr>
<td>✖ Too High: &quot;I'm somewhat worse than I thought&quot; (2 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Just Right: &quot;My expectations were met&quot; (3 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Too Low: &quot;I'm somewhat better than I thought&quot; (4 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Too Low: &quot;I'm a lot better than I thought&quot; (5 pts)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3- My expectations for being able to do my leisure, recreational or sports activities were...</th>
<th>(5 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>✖ Too High: &quot;I'm a lot worse than I thought&quot; (1 pt)</td>
<td></td>
</tr>
<tr>
<td>✖ Too High: &quot;I'm somewhat worse than I thought&quot; (2 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Just Right: &quot;My expectations were met&quot; (3 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Too Low: &quot;I'm somewhat better than I thought&quot; (4 pts)</td>
<td></td>
</tr>
<tr>
<td>✖ Too Low: &quot;I'm a lot better than I thought&quot; (5 pts)</td>
<td></td>
</tr>
</tbody>
</table>

**Maximum total points (15 points)**

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## FUNCTIONAL ACTIVITIES
(To be completed by patient)

### WALKING AND STANDING (30 points)

1. Can you walk without any aids (such as a cane, crutches or wheelchair)?
   - Yes  
   - No  
   - (0 points)

2. If no, which of the following aid(s) do you use?
   - Wheelchair (-10 pts)
   - Walker (-8 pts)
   - Crutches (-8 pts)
   - Two canes (-6 pts)
   - One crutch (-4 pts)
   - One cane (-4 pts)
   - Knee sleeve/brace (-2 pts)
   - Other
   - (-10 points)

3. Do you use these aid(s) because of your knees?
   - Yes  
   - No  
   - (0 points)

4. For how long can you stand (with or without aid) before sitting due to knee discomfort?
   - Cannot stand (0 pts)
   - 0-5 minutes (3 pts)
   - 6-15 minutes (6 pts)
   - 16-30 minutes (9 pts)
   - 31-60 minutes (12 pts)
   - More than an hour (15 pts)
   - (15 points)

5. For how long can you walk (with or without aid) before stopping due to knee discomfort?
   - Cannot walk (0 pts)
   - 0-5 minutes (3 pts)
   - 6-15 minutes (6 pts)
   - 16-30 minutes (9 pts)
   - 31-60 minutes (12 pts)
   - More than an hour (15 pts)
   - (15 points)

**Maximum points (30 points)**
<table>
<thead>
<tr>
<th>STANDARD ACTIVITIES (30 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>How much does your knee bother you during each of the following activities?</strong></td>
</tr>
<tr>
<td><strong>no bother</strong></td>
</tr>
<tr>
<td>1 - Walking on an uneven surface</td>
</tr>
<tr>
<td>2 - Turning or pivoting on your leg</td>
</tr>
<tr>
<td>3 - Climbing up or down a flight of stairs</td>
</tr>
<tr>
<td>4 - Getting up from a low couch or a chair without arms</td>
</tr>
<tr>
<td>5 - Getting into or out of a car</td>
</tr>
<tr>
<td>6 - Moving laterally (stepping to the side)</td>
</tr>
</tbody>
</table>

**Maximum points (30 points)**

<table>
<thead>
<tr>
<th>ADVANCED ACTIVITIES (25 points)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 - Climbing a ladder or step stool</strong></td>
</tr>
<tr>
<td><strong>2 - Carrying a shopping bag for a block</strong></td>
</tr>
<tr>
<td><strong>3 - Squatting</strong></td>
</tr>
<tr>
<td><strong>4 - Kneeling</strong></td>
</tr>
<tr>
<td><strong>5 - Running</strong></td>
</tr>
</tbody>
</table>

**Maximum points (25 points)**

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**DISCRETIONARY KNEE ACTIVITIES (15 points)**

Please check 3 of the activities below that you consider most important to you.  
(Please do not write in additional activities)

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

**Workout and Gym Activities**
- Weight-lifting
- Leg Extensions
- Stair-Climber
- Stationary Biking / Spinning
- Leg Press
- Jogging
- Elliptical Trainer
- Aerobic Exercises

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

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

<table>
<thead>
<tr>
<th>Activity (Please write the 3 activities from list above)</th>
<th>no bother</th>
<th>slight</th>
<th>moderate</th>
<th>severe</th>
<th>very severe</th>
<th>cannot do (because of knee)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

1. [ ]

2. [ ]

3. [ ]

Maximum points (15 points)

Maximum total points (100 points)
Appendix G: Knee Society Score (Clinician)

**KNEE SOCIETY SCORE: POST-OP**

*to be completed by staff*

<table>
<thead>
<tr>
<th>Pain</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Mild or Occasional</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Stairs Only</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Walking and Stairs</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Moderate Occasional</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Moderate Continual</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Severe</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range of Motion</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of Flexion (Degrees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of Flexion (Degrees)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Anterior/Posterior Instability: Measured at 90°**

<table>
<thead>
<tr>
<th>Range</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5mm</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>5-10mm</td>
<td>Moderate &lt;5mm</td>
<td>Moderate &lt;5mm</td>
</tr>
<tr>
<td>10mm</td>
<td>Severe &gt;5mm</td>
<td>Severe &gt;5mm</td>
</tr>
</tbody>
</table>

**Medial/Lateral Instability: Measured in Full Extension**

<table>
<thead>
<tr>
<th>Range</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5°</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>5-10°</td>
<td>Little &lt;5mm</td>
<td>Moderate &lt;5mm</td>
</tr>
<tr>
<td>10-14°</td>
<td>Moderate 5mm</td>
<td>Severe &gt;5mm</td>
</tr>
<tr>
<td>15°</td>
<td>Severe &gt;5mm</td>
<td>Severe &gt;5mm</td>
</tr>
</tbody>
</table>

**Flexion Contracture**

<table>
<thead>
<tr>
<th>Range</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5°</td>
<td>1-5°</td>
<td>1-5°</td>
</tr>
<tr>
<td>5-10°</td>
<td>6-10°</td>
<td>6-10°</td>
</tr>
<tr>
<td>10-15°</td>
<td>11-15°</td>
<td>11-15°</td>
</tr>
<tr>
<td>16-20°</td>
<td>&gt;15°</td>
<td>&gt;15°</td>
</tr>
<tr>
<td>&gt;20°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Extension Lag**

<table>
<thead>
<tr>
<th>Range</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>&lt;10”</td>
<td>&lt;10”</td>
</tr>
<tr>
<td>&lt;10”</td>
<td>10 20”</td>
<td>10 20”</td>
</tr>
<tr>
<td>&gt;20”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Walking**

<table>
<thead>
<tr>
<th>Range</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlimited</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>&gt;10 blocks</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>5-10 blocks</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>&lt;5 blocks</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>House Bound</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Unable</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Stairs**

<table>
<thead>
<tr>
<th>Range</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Up and Down</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Normal Up; Down with Rail</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Up and Down with Rail</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Up with Rail; Unable Down</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Unable</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Support**

<table>
<thead>
<tr>
<th>Range</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cane</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Two Crutches</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>Crutches or Walker</td>
<td>-20</td>
<td>-20</td>
</tr>
</tbody>
</table>

**Charnley Functional Classification**

<table>
<thead>
<tr>
<th>A</th>
<th>B1</th>
<th>B2</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Unilateral Knee Arthritis</td>
<td>B1: Unilateral TKA, Opposite Knee Arthritic</td>
<td>B2: Bilateral TKA</td>
<td>C1: TKA, but remote arthritis affecting ambulation</td>
<td>C2: TKA, but medical condition affecting ambulation</td>
<td>C3: Unilateral or Bilateral TKA with Unilateral or Bilateral TKA</td>
</tr>
</tbody>
</table>

**Radiographic Findings**

<table>
<thead>
<tr>
<th>Alignment: Measured on AP Xray</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10° Valgus</td>
<td>Neutral: 2-10° valgus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-11° Valgus</td>
<td>Varus: &lt;2° Valgus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-12° Valgus</td>
<td>Valgus: &gt;15° Valgus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-13° Valgus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-14° Valgus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15° Valgus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Varus OR &gt;15° Valgus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Radiosclerotic Lines** (cementless)

<table>
<thead>
<tr>
<th>Right</th>
<th>No</th>
<th>Yes:</th>
<th>Femur Tibia (AP)</th>
<th>Tibia (Lat)</th>
<th>Tibial Screws</th>
<th>Patella (skylines)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes</td>
<td>Femur Tibia (AP)</td>
<td>Tibia (Lat)</td>
<td>Tibial Screws</td>
<td>Patella (skylines)</td>
</tr>
</tbody>
</table>

**Radiolucent Lines** (cemented)

<table>
<thead>
<tr>
<th>Right</th>
<th>No</th>
<th>Yes:</th>
<th>Femur Tibia (AP)</th>
<th>Tibia (Lat)</th>
<th>Patella (skylines)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes</td>
<td>Femur Tibia (AP)</td>
<td>Tibia (Lat)</td>
<td>Patella (skylines)</td>
</tr>
</tbody>
</table>

**Loosening**

<table>
<thead>
<tr>
<th>Right</th>
<th>No</th>
<th>Possible</th>
<th>T</th>
<th>P</th>
<th>Probable</th>
<th>T</th>
<th>P</th>
<th>Definite</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>Possible</td>
<td>T</td>
<td>P</td>
<td>Probable</td>
<td>T</td>
<td>P</td>
<td>Definite</td>
<td>T</td>
<td>P</td>
</tr>
</tbody>
</table>

**Implant Problems**

<table>
<thead>
<tr>
<th>Right</th>
<th>No</th>
<th>Yes:</th>
<th>Wear</th>
<th>Osteolysis:</th>
<th>T</th>
<th>P</th>
<th>Patella, tilted</th>
<th>Patella, tilted</th>
<th>dislocated fracture</th>
<th>AVN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes:</td>
<td>Wear</td>
<td>Osteolysis:</td>
<td>T</td>
<td>P</td>
<td>Patella, tilted</td>
<td>Patella, tilted</td>
<td>dislocated fracture</td>
<td>AVN</td>
</tr>
</tbody>
</table>

**Adverse Events**

<table>
<thead>
<tr>
<th>Right</th>
<th>No</th>
<th>Yes:</th>
<th>Deep Infection</th>
<th>Superficial Infection</th>
<th>DVT/PE</th>
<th>Other:</th>
<th>Deep Infection</th>
<th>Superficial Infection</th>
<th>DVT/PE</th>
<th>Other:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes:</td>
<td>Deep Infection</td>
<td>Superficial Infection</td>
<td>DVT/PE</td>
<td>Other:</td>
<td>Deep Infection</td>
<td>Superficial Infection</td>
<td>DVT/PE</td>
<td>Other:</td>
</tr>
</tbody>
</table>

**Anterior Knee Pain**

<table>
<thead>
<tr>
<th>Right</th>
<th>No</th>
<th>Yes:</th>
<th>Daily</th>
<th>Weekly</th>
<th>Monthly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>No</td>
<td>Yes:</td>
<td>Daily</td>
<td>Weekly</td>
<td>Monthly</td>
</tr>
</tbody>
</table>

Comments:

Examiner:
Appendix H: University of California, Los Angeles Activity Score

Journey II

Study ID: ____________
Date: ________________

UCLA Activity Score

Check one box that best describes current activity level.

- 1: Wholly Inactive, dependent on others, and can not leave residence
- 2: Mostly Inactive or restricted to minimum activities of daily living
- 3: Sometimes participates in mild activities, such as walking, limited housework and limited shopping
- 4: Regularly Participates in mild activities
- 5: Sometimes participates in moderate activities such as swimming or could do unlimited housework or shopping
- 6: Regularly participates in moderate activities
- 7: Regularly participates in active events such as bicycling
- 8: Regularly participates in active events, such as golf or bowling
- 9: Sometimes participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor or backpacking
- 10: Regularly participates in impact sports

Version: 22-Jun-2017
Curriculum Vitae

Jordan S. Broberg

EDUCATION

09/17 – 04/23  Ph.D. Medical Biophysics
Western University, London, Ontario

09/13 – 04/17  B.MSc. (Honours Specialization) Medical Biophysics
Western University, London, Ontario

HONOURS, SCHOLARSHIPS AND AWARDS

2023 – 2025  Postdoctoral Fellowship ($90,000/2 years)
National Sciences and Engineering Research Council of Canada

2021 – 2022  Transdisciplinary Bone & Joint Training Award ($4,750)
Collaborative Specialization in Musculoskeletal Health Research, Western University

2020 – 2023  Frederick Banting and Charles Best Canada Graduate Scholarships Doctoral Award ($105,000/3 years)
Canadian Institutes of Health Research

2020  Brian Keith Reid Scholarship Award ($1,900)
Dept. of Medical Biophysics, Western University

2020 – 2021  Ontario Graduate Scholarship – Declined ($15,000)
Ontario Ministry of Training, Colleges and Universities

2020 – 2021  Transdisciplinary Bone & Joint Training Award ($4,750)
Collaborative Specialization in Musculoskeletal Health Research, Western University

2020  High Scoring Poster (Contact Kinematics of Total Knee Arthroplasty: Anatomical vs. Traditional Implant Designs)
Canadian Orthopaedic Association Annual Meeting

2020  High Scoring Poster (Contact Kinematics of Anatomically Designed Total Knee Arthroplasty: Gap Balancing vs. Measured Resection Techniques)
Canadian Orthopaedic Association Annual Meeting

2019 – 2020  Ontario Graduate Scholarship ($15,000)
Ontario Ministry of Training, Colleges and Universities

2019 – 2020  Transdisciplinary Bone & Joint Training Award ($4,750)
Collaborative Specialization in Musculoskeletal Health Research, Western University
2019  Top 10 Research Advances of 2019  
Arthritis Society

2018 – 2019  Canada Graduate Scholarship – Masters Award  ($17,500)  
Canadian Institutes of Health Research

2018 – 2019  Ontario Graduate Scholarship – Declined  ($15,000)  
Ontario Ministry of Training, Colleges and Universities

2017 – 2018  Ontario Graduate Scholarship  ($15,000)  
Ontario Ministry of Training, Colleges and Universities

2017 – 2022  Western Graduate Research Scholarship  ($4,500/year)  
Western University

2016  Richard Konrad Scholarship of Science  ($1,500)  
Western University

2013 – 2017  Dean’s Honour List  
Western University

2013  Entrance Scholarship  ($10,000)  
Western University

2013  Entrance Scholarship – Declined  ($8,000)  
Queen’s University

PEER REVIEWED PUBLICATIONS


7. **Broberg JS**, Vasarhelyi EM, Lanting BA, Howard JL, Teeter MG, Naudie DDR. Migration and Inducible Displacement of Bi-Cruciate Stabilized Total Knee


**CONFERENCE ABSTRACTS AND PRESENTATIONS, PEER REVIEWED**


3. **Broberg JS**, Naudie DDR, Howard JL, Lanting BA, Vasarhelyi EM, Teeter MG. Lateral Condyle Kinematics Correlate to Tibial Component Migration Following...
Cemented Bi-Cruciate Stabilized Total Knee Replacement. Oral presentation at the 2022 Knee Society Meeting, Park City, UT.

4. **Broberg JS**, Naudie DDR, Howard JL, Lanting BA, Vasarhelyi EM, Teeter MG. Contact Kinematics Correlates to Tibial Component Migration Following Cemented Bi-Cruciate Stabilized Total Knee Replacement. Oral presentation at the 2022 International Society for Technology in Arthroplasty Meeting, Maui, HI.

5. **Broberg JS**, Koff MF, Howard JL, Lanting BA, Potter HG, Teeter MG. Tibial Component Fixation of Cementless Total Knee Replacements Measured With RSA and MRI. Poster presentation at the 2022 International Society for Technology in Arthroplasty Meeting, Maui, HI.


7. **Broberg JS**, Koff MF, Howard JL, Lanting BA, Potter HG, Teeter MG. Cementless Total Knee Replacement Tibial Component Fixation Measured with RSA and MRI. Podium presentation at the 2022 Canadian Orthopaedic Research Society Annual Meeting, Quebec City, QB.


INVITED LECTURES AND TALKS


TEACHING EXPERIENCE

2021  Teaching Assistant (MSK 9000)
Western University

2019 – 2020  Teaching Assistant (Biology 1001A/1002B)
Western University