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# Evaluating the Effects of Patellofemoral Offset Changes and Trochlear Design in Total Knee Arthroplasty: A Radiographic, Visual, and Topographical Analysis

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Surgery

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## Abstract

Total knee arthroplasty (TKA) is a common procedure for the treatment of advanced knee osteoarthritis. Complications involving the patellofemoral joint (PFJ) are common following TKA, and the etiology is controversial. The purpose of this thesis was to evaluate two potentially modifiable factors affecting the PFJ: (i) changes in patellofemoral offset (PFO) and (ii) trochlear design.

Through a retrospective radiographic review, we demonstrated that PFO changes occur frequently post-TKA, and that the PFJ can tolerate these changes without adverse clinical outcomes. Retrieval analysis provided additional evidence that PFO changes are not associated with femoral component surface damage or wear.

In order to explore the association between trochlear design and patellofemoral contact, retrieved femoral components were examined. The retrieval studies showed that some trochlear designs are associated with increased femoral component surface wear. This information improves our understanding of patellofemoral contact mechanics and trochlear wear.

*Keywords: Total Knee Arthroplasty, Patellofemoral, Patellofemoral Offset, Overstuffing, Profilometry, Trochlea, Wear, Surface Damage, Retrieval*

# Co-Authorship Statement

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## List of Abbreviations

AP – Anteroposterior

ANOVA – Analysis of variance

BMI – Body mass index

CoCr – Cobalt-chromium

KSS – Knee Society Score

LHSC – London Health Sciences Centre

NSAID – Non-steroidal anti-inflammatory

OA - Osteoarthritis

PFJ – Patellofemoral joint

PFO – Patellofemoral offset

TIV – Time-in-vivo

TKA – Total knee arthroplasty

WOMAC – Western Ontario and McMaster Universities Osteoarthritis Index

# Chapter 1

## 1 Introduction

*Overview: The purpose of the thesis is to assess the influence of patellofemoral offset and trochlear design on patient-reported outcomes and implant wear following total knee arthroplasty. In this chapter, a brief introduction to the anatomy and biomechanics of the knee, and specifically the patellofemoral joint, will be provided. A discussion about osteoarthritis and knee arthroplasty follows. This chapter then discusses the most pertinent complications that can take place in the patellofemoral joint and their treatments. Finally, remaining questions as well as the objectives of the thesis are discussed.*

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### 1.1 Anatomy and Biomechanics of the Patellofemoral Joint

The knee is a complex joint consisting of two main articulating surfaces: the tibiofemoral and the patellofemoral joints (Figure 1-1). The tibiofemoral joint provides the main weight bearing surface of the knee, while the patellofemoral joint functions to transmit the forces of the extensor mechanism and increase its efficiency.<sup>1</sup> The main plane of knee motion is in the sagittal plane, but both rotational and translational motions take place.<sup>2</sup>

The patella articulates with the femoral trochlea and forms the patellofemoral joint. The patella is attached superiorly to the quadriceps tendon and inferiorly by the patellar tendon. The articular surface of the patella has three facets.<sup>2</sup> The lateral facet is concave and forms two-thirds of the articular surface. The medial facet is more convex and represents one-third of the articular surface. The “odd facet” of the patella is most medial and does not articulate with the femur until flexion exceeds 135°. Previous studies reported average patellar dimensions as  $22.4 \pm 2.3$  mm thick,  $44.8 \pm 4.8$  mm wide, and  $34.3 \pm 3.8$  mm long.<sup>3</sup> The patella controls knee flexion and extension by transmitting the

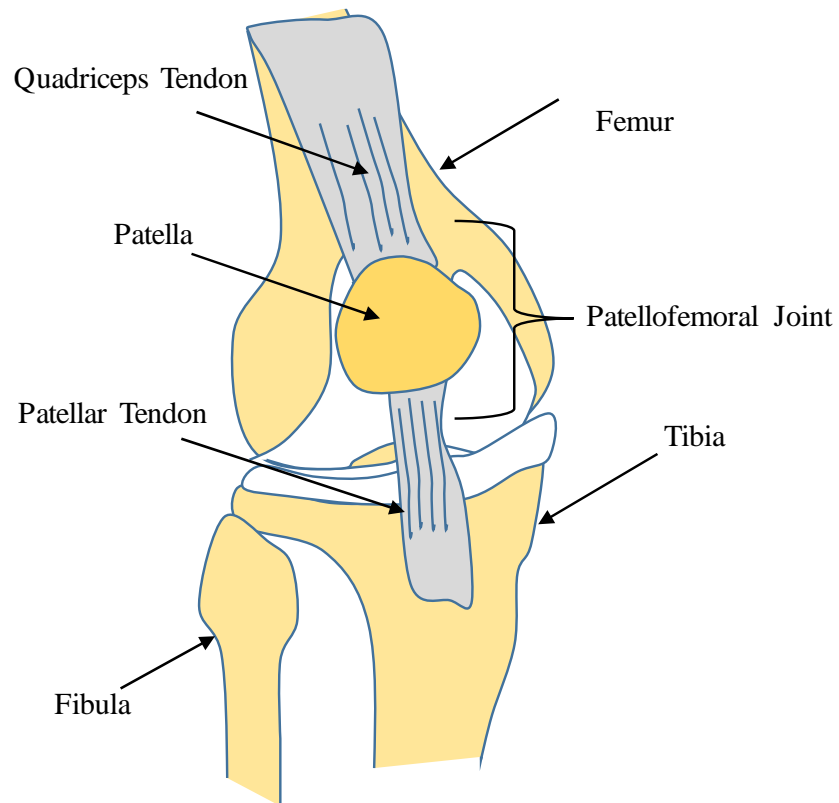
forces of the extensor mechanism. It articulates with the femoral trochlea, a depression formed between the two asymmetrical condyles of the distal femur. The trochlea extends around 3 cm along the anterior surface of the femur and is concave medio-laterally. The lateral condyle is longer in the AP plane and forms the lateral wall of the trochlea. The cartilage in the normal trochlea is thickest centrally, at around 3.4 mm.<sup>2</sup>

The most important function of the patellofemoral joint is to increase the efficacy of the quadriceps muscle, facilitating knee extension.<sup>4</sup> Studies have shown that the patella increases the extension force by at least 30%.<sup>5</sup> As a result, the forces at the patellofemoral joint create a demanding biomechanical environment, with patellofemoral joint reactive forces reaching 6.5 times the patient's body weight with certain activities such as climbing or descending stairs.<sup>6</sup>

The femoral anatomical axis is 7-9° of valgus and the tibial anatomic axis is varus of 2-3°.<sup>2</sup> Due to the physiological valgus of the distal femur, the quadriceps and the patellar tendon axis are divergent by approximately 15° (Q angle).<sup>2</sup> During flexion, therefore, the patella tends to move laterally and is kept in the trochlear groove by static (the lateral side of the trochlea) and dynamic stabilizers (the medial patellar retinaculum and medial patellofemoral ligament (MPFL), the vastus medialis (VMO), and external rotation of the femur on the tibia during unlocking the knee).<sup>2</sup> As the knee moves into flexion, the constraints of the patella increase due to the compressive force of the extensor mechanism.

The location and areas of contact of the patellofemoral joint vary according to the amount of flexion.<sup>7</sup> In general, patellofemoral forces increase with increasing flexion in both native and prosthetic knees.<sup>8</sup> The patella engages with the trochlea between 10-20° of flexion.<sup>2</sup> In early flexion, most of the contact is at the distal end of the patella.<sup>7</sup> As flexion increases, the contact area moves more proximally, and maximum contact area is achieved at 60°. The contact area remains constant up until 90°, at which point, most of the contact is in the proximal portion of the patella.<sup>6</sup> Beyond 90°, the total contact area decreases and two separate contact areas occur with the medial and lateral condyles.<sup>6</sup>





**Figure 1-1. The native knee consists of the tibiofemoral and a patellofemoral joint. The patella articulates with the femoral trochlea and is superiorly attached to the quadriceps tendon and inferiorly to the patellar tendon. (Courtesy of J. Matz)**

## 1.2 Osteoarthritis

Osteoarthritis (OA) is a degenerative condition affecting joints and leading to articular cartilage degeneration. OA is particularly common in the large weight bearing joints, the hips and the knees<sup>9</sup>. The most pronounced symptoms of OA are pain and joint stiffness, and it is a leading cause of disability for those over 65 years.<sup>10</sup> For individuals affected by OA, the pain is typically exacerbated by activity<sup>10</sup>, and as OA becomes more advanced, the pain can interfere with sleep and lead to difficulties with normal day to day activities.<sup>10</sup> Other symptoms of OA include swelling, crepitus, and joint instability.<sup>2</sup>

The underlying etiology of OA can be primary or secondary. The etiology of primary OA is likely multifactorial, involving both genetic and environmental causes, and a specific cause cannot always be identified.<sup>2</sup> The degeneration of the articular cartilage leads to loss of joint congruity and subtle instability with changes in the loading of the joint, and the eventual formation of osteophytes. The loss of articular cartilage also leads to overload of the subchondral bone and eventual bone sclerosis. These changes, along with synovitis, lead to pain, disability, and a reduction in the quality of life. Secondary OA can be caused by another disease or condition, such as an inflammatory systemic disease, previous trauma, or congenital abnormalities.<sup>2</sup>

OA is common and is a significant cause of disability. Estimates show that 14.6% of the Canadian population is affected, particularly those over the age of 65.<sup>11</sup> The estimated annual cost is \$10 billion in direct health care costs in Canada.<sup>12</sup> In the next 30 years, the number of Canadians with OA is expected to increase to over 10 million, with approximately 500,000 Canadians experiencing moderate to severe disability caused by OA.<sup>12</sup> Furthermore, nearly 30% of Canadians in the labor force will experience problems working because of OA. It is expected that the rates of OA are likely to continue increasing due to an aging population and increasing obesity rates.<sup>12</sup>

The goals of treating OA are to alleviate pain, restore function, and improve mobility. The initial treatment modalities are conservative. Weight loss has been shown to be an effective treatment in obese patients<sup>13</sup>. Bracing to offload the affected compartment can

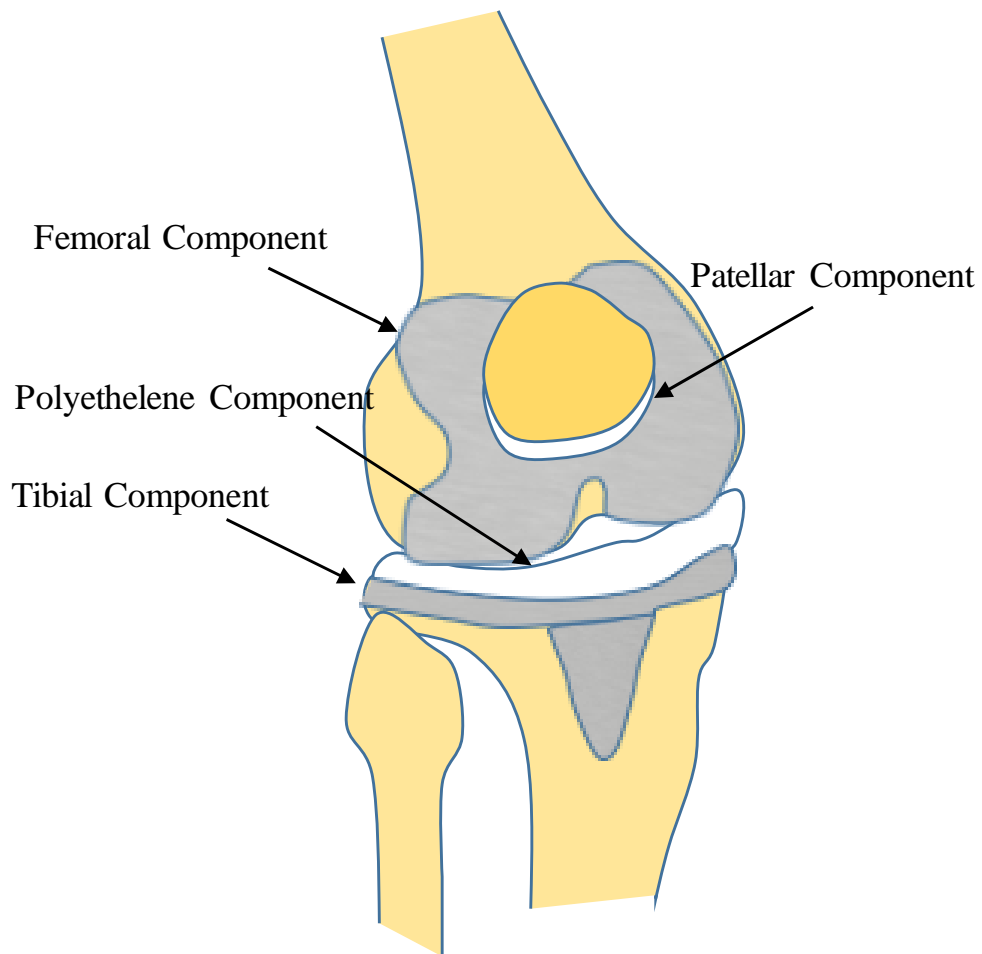
help reduce symptoms<sup>14</sup>. Pharmacologic treatment consists of oral medication and joint injections. Tylenol or non-steroidal anti-inflammatories can be helpful analgesics.<sup>15</sup> Injections into the joint with steroid or visco-supplementation can also provide some pain relief.<sup>16</sup> If osteoarthritis interferes significantly with everyday life and the symptoms fail to improve with conservative management, two main surgical options exist. For younger patients, a high tibial osteotomy is a worthy option to realign the leg and offload the diseased compartment.<sup>17</sup> In older patients and those with arthritis involving more than one compartment, total knee arthroplasty is the gold standard.<sup>18</sup>

### 1.3 Total Knee Arthroplasty

In total knee arthroplasty (TKA), the damaged articular surfaces of the femur, tibia, and occasionally the patella are removed and replaced with a new weight bearing surface (Figure 1-2). This allows for a reduction in pain and an improvement in the function of the knee.<sup>18</sup> The modern era of total knee arthroplasty was started with the introduction of the total condylar prosthesis by Insall and others in 1973<sup>19</sup>, which still serves as the basis for modern design. The design featured a femoral component with symmetrical femoral condyles with a decreasing sagittal radius posteriorly, a congruent all-polyethylene tibial component, and a dome-shaped patella. This design set a new standard for survival of a total knee replacement with survivorship reported over 75% at 15- to 20- year follow up.<sup>19</sup> The design of a modern total knee arthroplasty consists of a femoral component, tibial component, a tibial polyethylene insert, and potentially a patellar component (Figure 1-3). The particular features of modern knee arthroplasty components will be discussed below (“Implant Features”).

The rates of TKA are increasing substantially and this trend is likely to continue based on the aging population, the increasing life expectancy, and trends in obesity.<sup>20</sup> Recent survivorship data for total knee replacement shows survival rate of 87% at 20 years’ follow-up.<sup>21</sup> The procedure is associated with high levels of patient satisfaction due to improvements in function and reduced levels of pain<sup>18</sup>. These improvements have been demonstrated using validated patient outcome scores, such as the Western Ontario and McMaster Osteoarthritis Index (WOMAC) and the Knee Society Score (KSS).<sup>18</sup>

However, despite the overall success of knee arthroplasty, the literature suggests that about 20% of patients who have undergone TKA are dissatisfied at one year post-surgery.<sup>22</sup> Specific complications are discussed below (“Complications Related to the Patellofemoral Joint”).



**Figure 1-2. Total knee arthroplasty involves using metal and polyethylene components to replace the damaged surfaces of the femur, tibia, and potentially the patella. (Courtesy of J. Matz)**



**Figure 1-3. The components of a total knee arthroplasty: femoral component, tibial tray, patellar component, and a polyethylene tibial insert. (Photograph taken at the LHSC Implant Retrieval Laboratory)**

### 1.3.1 Surgical Technique in Total Knee Arthroplasty

The primary goal of TKA is to achieve a functional and painless knee that is neutrally-aligned, stable, and has a full range-of-motion. In order to obtain these goals, the surgery involves a series of bony cuts and soft tissue releases to obtain a symmetric space in flexion and extension.

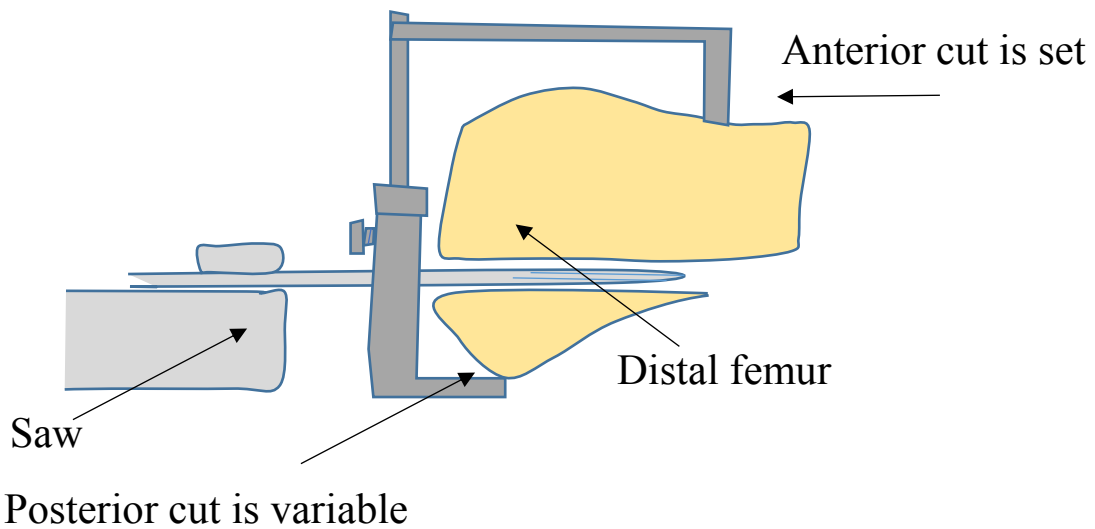
The standard technique to access the knee joint is through an anterior midline incision followed by a medial parapatellar arthrotomy, which allows access both medially and laterally in the knee joint. The patella is then either everted or dislocated laterally. There are several standard bony cuts in a TKA. On the femoral side, these are the distal femoral cut, and the anterior and posterior femoral cuts. The amount of bone resected typically corresponds to the thickness of the prosthesis. The thickness of the distal femoral cut influences the extension gap and the joint line. Excessive distal femoral resection can lead to joint line elevation. The posterior femoral cut influences the flexion gap. Increasing the resection amount is considered in cases of flexion tightness but excessive resection should be avoided to prevent flexion instability. The anterior femoral cut goal is

to remove as much bone as will be replaced by the implant without excessively cutting into the anterior cortex of the femur. Finally, the thickness of the tibial cut affects both flexion and extension gaps.

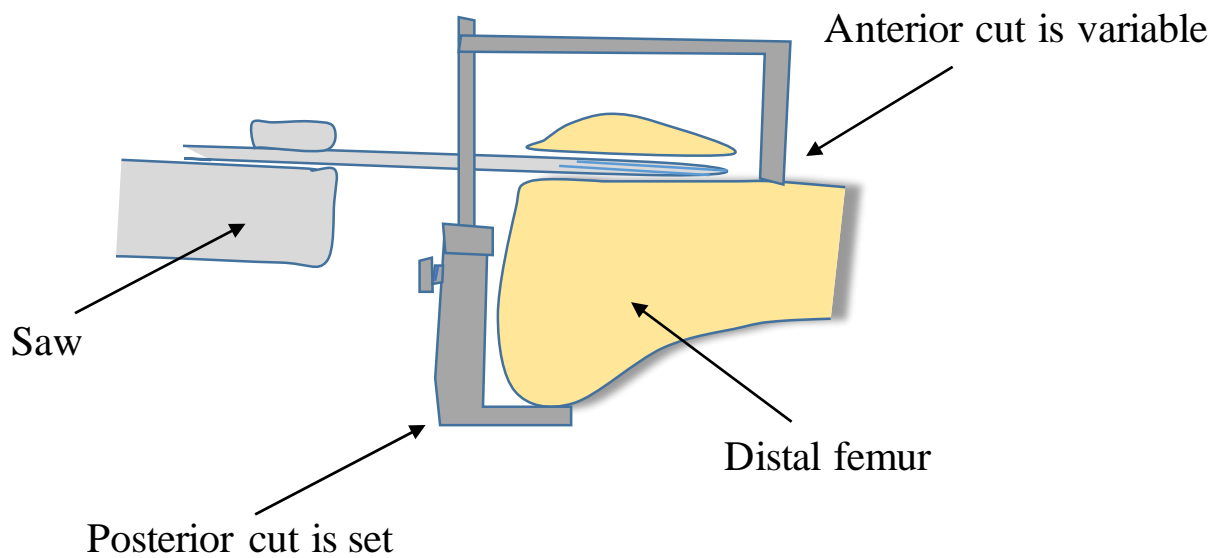
The sizing of the femoral component is an important part of the operation. Anterior and posterior referencing methods exist for component sizing.<sup>23</sup> In an anterior referencing system, the anterior femoral cut is carefully selected and measured, while the posterior cut is variable. When selecting between sizes, downsizing the femoral component may lead to flexion instability, while conversely, upsizing may lead to tightness in flexion (Figure 1-4).<sup>23</sup> In a posterior referencing system, the posterior femoral cut is chosen, and the anterior cut is variable. When between sizes, reducing the size may lead to femoral notching, whereas upsizing may lead to increased patellofemoral offset (Figure 1-5).<sup>23</sup> Traditionally, the recommendation has been to downsize in an anterior referenced system and upsize in a posterior referenced system, however, practises are variable between surgeons and posterior-referenced systems often allow downsizing and accepting a small femoral notch.<sup>2</sup>

Whether to resurface the patella remains controversial among surgeons.<sup>24</sup> Resurfacing the patella involves resecting the articular portion of the patella and replacing it with a polyethylene component (patellar button). The two methods of patellar preparation are the inlay and onlay techniques. The onlay technique refers to cutting the entire surface of the patella and then placing the patellar button in the desired position. The inlay technique involves placing the patellar button into a cavity in the patellar surface. The goal of both techniques is to reproduce the thickness of the patella of each patient's unique anatomy, which is on average 22-24mm.<sup>3</sup>

Once the bony surfaces have been prepared and the alignment of the knee has been restored, the prosthetic components are cemented to the femur, the tibia, and the patella.



**Figure 1-4. Demonstration of an anterior-referencing total knee system. The anterior cut is set, while the posterior cut is variable. When choosing between sizes, surgeons have the option of selecting a larger size or a smaller size. When selecting a larger size, surgeons may increase flexion space, potentially contributing to flexion instability. Conversely, when choosing the smaller size, tightness in flexion may occur. (Courtesy of J. Matz)**



**Figure 1-5. Demonstration of a posterior-referencing total knee system. The posterior cut is set, while the anterior cut is variable. When choosing between sizes, surgeons have the option of selecting a larger size or a smaller size. When selecting a larger size, surgeons may increase the patellofemoral offset, potentially contributing to patellofemoral complications. If a smaller size is selected, a femoral notch may occur. (Courtesy of J. Matz)**



## 1.3.2 Knee Biomechanics Following Total Knee Arthroplasty

While there are similarities in the patellofemoral kinematics between native and prosthetic knees, differences exist with respect to the magnitude of contact forces, exact points of contact, patellar tilt, medial-lateral translation, and the normal external rotation “screw home” mechanism.<sup>25</sup> Overall, patellofemoral contact forces appear to increase substantially after TKA.<sup>8</sup> While the etiology is likely multifactorial, it may be partially explained by reduced, or occasionally reversed, femoral roll-back following knee arthroplasty.<sup>26</sup> Similar to the native patella, the prosthetic patella experiences most of the contact distally in low amounts of flexion. The point of contact migrates more proximally with increasing flexion, reaching the superior pole in 60°-90° of flexion<sup>27</sup>. Patellar tilt appears to increase with increasing flexion in both native and prosthetic knees, however, the increase appears to be more substantial post TKA.<sup>25</sup> The native patella exhibits medial translation (2mm) in early flexion followed by progressively increased lateral translation (5mm) with increased flexion<sup>25</sup>. Following TKA, the position of the patella tends to be more medial throughout flexion<sup>25</sup>. Finally, prosthetic knees lose the normal 5° external rotation of the tibia on the femur (“screw home mechanism”), and instead, may exhibit internal rotation.<sup>25</sup>

## 1.3.3 Component Features

Understanding the native anatomy serves as a basis for creation of replacement components. Features of the native patellofemoral joint have been adapted to prosthetic implants. The morphological features of femoral and patellar components can have substantial effects on patellofemoral kinematics.

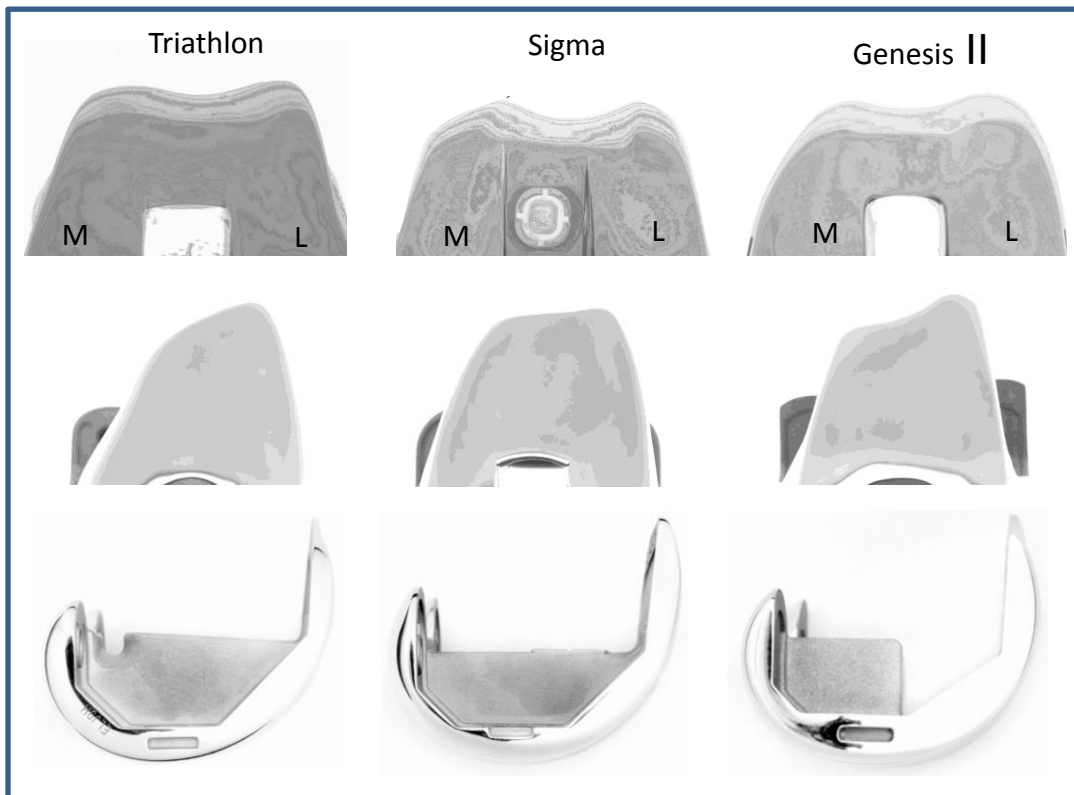
### 1.3.3.1 Femoral Component

The importance of trochlear design was highlighted by Kulkarni<sup>28</sup> who argued that given the relatively similar outcomes between resurfaced and non-resurfaced knees, the more important determinant of proper patellofemoral kinematics and clinical outcomes is the design of the trochlea.

Among the various features of the femoral trochlea, certain anatomical features have been found to be important for prosthetic design (Figure 1-6), such as the asymmetry of the medial and lateral condyles in their AP dimension, the depth of the trochlear groove, and the proximal extension of the trochlea<sup>28-30</sup>. Kulkarni recommended extending the trochlea proximally to ensure that the patella enters the trochlear groove properly. This was based on the observation that in femoral components where the trochlear surface was terminated at the proximal extent of the femoral cartilage, the patella is not engaged in prosthesis in full extension, leaving room for tracking abnormalities as the patella enters the trochlear groove.<sup>28</sup> In an early biomechanical study, Yoshii<sup>29</sup> performed an in vitro comparison of various trochlear designs and found that a deepened trochlear groove and a raised lateral flange allowed the patellar button to be constrained in the groove and minimized tracking abnormalities. Similar findings were reported by Petersilge<sup>31</sup> in a cadaveric study, and Theiss<sup>30</sup> in a retrospective clinical study. Over time, improvements in femoral component design were amalgamated to create “patella-friendly” designs. In general, these designs incorporate features such as a more congruent articulation, a deeper trochlear groove with a raised lateral border, and extension of the trochlea proximally and distally<sup>29, 30</sup>. However, incorporating these design elements can result in potential problems. While conformity between components increases the contact areas and stability, Shervin<sup>32</sup> highlights that the downside of increased conformity is increased shear forces and potential adverse effects on fixation. Therefore, a balance between conformity and the “freedom to align itself” is sought. Furthermore, the need for deepening the trochlear groove must be balanced against the possibility of decreasing the moment arm of the quadriceps or creating instability.

The orientation of the trochlear groove in the coronal plane is another factor previously considered in implant design. In modern implants, the groove is typically in 5-7° valgus (“anatomic design”) to approximate the anatomic axis of the femur and the direction of the extensor mechanism<sup>26</sup>. Valgus alignment of the trochlea reduced shear forces in low flexion angles but not at angles close to 90°.<sup>26</sup> This is likely because the main valgus component is located proximally.<sup>26</sup>

Finally, while the patella articulates with the trochlea with most day-to-day activities, as flexion increases beyond 90°, the patella articulates with the condyles at two separate contact areas. The transition zone is important and a smoother transition zone with a greater radius of curvature may reduce the risk of the patella catching, or generating “patellar clunk”.<sup>33</sup>



**Figure 1-6. AP, axial, and sagittal photographs of Triathlon® (Stryker, Mahwah, NJ), Sigma® (DePuy, Warsaw, IN), and Genesis II™ (Smith & Nephew, Memphis, TN) femoral components. Modern components share common features, such as proximal extension of the trochlea, raised lateral trochlear flange, lateralized groove, and deepened trochlea. M = medial, and L= lateral. (Photographs taken at the LHSC Implant Retrieval Laboratory)**

### 1.3.3.2 Patellar Component

Over the years, various prosthetic patella designs have been proposed (all-polyethylene, dome shaped, modified dome, anatomical, metal-backed, and mobile bearing) and currently there is no clear consensus regarding the optimal design. Metal-backed components were introduced in the 1980s and quickly fell out of favour due to numerous complications, including fatigue fracture, wear and loosening. Evidently, these components could not withstand the high shear forces of the patellofemoral joint.<sup>8</sup> While loosening of the patellar component comprised a significant issue with previous designs, particularly metal-backed patella, with current designs and surgical techniques loosening has a lesser role in failure. Currently, the all-polyethylene dome shaped patella is most commonly used for its relative ease of application, reduced risk of malalignment, and excellent track record.<sup>34</sup> Reports of failure of the dome all-polyethylene patella are few. Risk factors of failure for the all-polyethylene patellar components that have been identified are increased body weight, high preoperative flexion, retinacular release, weakness of the pegs of the component, and AVN of the patella.<sup>35</sup>

### 1.3.3.3 Tibial Component

The current standard of care in TKA is a fixed-bearing, modular tibial baseplate.<sup>2</sup> Since tibial component alignment was previously found to affect patellofemoral kinematics<sup>36</sup>, a rotating bearing design was proposed in order to decrease the effect of tibial component positioning. From a conceptual standpoint, the advantage of a rotating platform design is the ability of the femoral-tibial articulation to align itself, irrespective of any malalignment of the tibial components. In an intraoperative study, Sawaguchi<sup>37</sup> showed that rotating platform inserts in TKA significantly improved patellar tracking and decreased patellofemoral contact stress. However, other clinical studies have failed to show an advantage. Pagnano<sup>38</sup>, in a randomized study, found that rotating tibial platforms did not decrease the prevalence of lateral release or improve stair climbing ability. In a recent Cochrane Review<sup>39</sup>, no significant differences were noted between mobile and fixed bearing designs with respect to knee pain, clinical or functional scores. Other recent studies suggest a higher overall risk of revision with mobile bearing knee designs.<sup>40</sup>

## 1.4 Complications Related to the Patellofemoral Joint

Although component design and arthroplasty technique has evolved substantially, patellofemoral joint complications still occur following TKA. Anterior knee pain is most prevalent, affecting up to 23% of knee replacements,<sup>41</sup> and its etiology is multifactorial. Less common (<1%) complications are maltracking, fracture, AVN, patellar clunk, and component loosening, each of which can be debilitating and contribute to anterior knee pain and dysfunction.

### 1.4.1 Anterior Knee Pain

The patellofemoral joint is heavily innervated and anterior knee pain can occur from a variety of sources. A large number of free nerve endings and fibers exist, particularly in the quadriceps muscles, retinacula, patellar tendon, and synovium.<sup>42</sup> Anterior knee pain can result from any one of these sources and clinicians typically have difficulty identifying the exact source. Clearly, the state of the cartilage is not the only consideration, as radiographic changes of patellofemoral osteoarthritis does not correlate with patellofemoral symptoms<sup>43</sup>, and addressing degenerative articular surface by resurfacing the patella has not universally resolved patellofemoral symptoms. More recent data suggests that perhaps more subtle histological changes occur in the patellar cartilage which may correlate better with anterior knee pain than radiographic signs.<sup>44</sup>

Although in many cases we cannot identify specific etiology, pain after TKA has been demonstrated to be associated with certain patient factors. Previous studies identified female gender, younger age, depression, and increased BMI to be a risk factor for more pain post TKA.<sup>22</sup>

Based on the presence of a large number of terminal nerve branches around the patella, electro-cautery around the patella has been proposed as a technique to reduce the incidence of anterior knee pain. Despite this logic, Kwon<sup>45</sup> performed a RCT that found no benefit with 5 year follow-up. More encouraging findings are reported by a recent systematic review of the topic concluded that although the rates of anterior knee pain

remain similar, evidence points to improved functional scores with electro-cautery patellar denervation<sup>46</sup>.

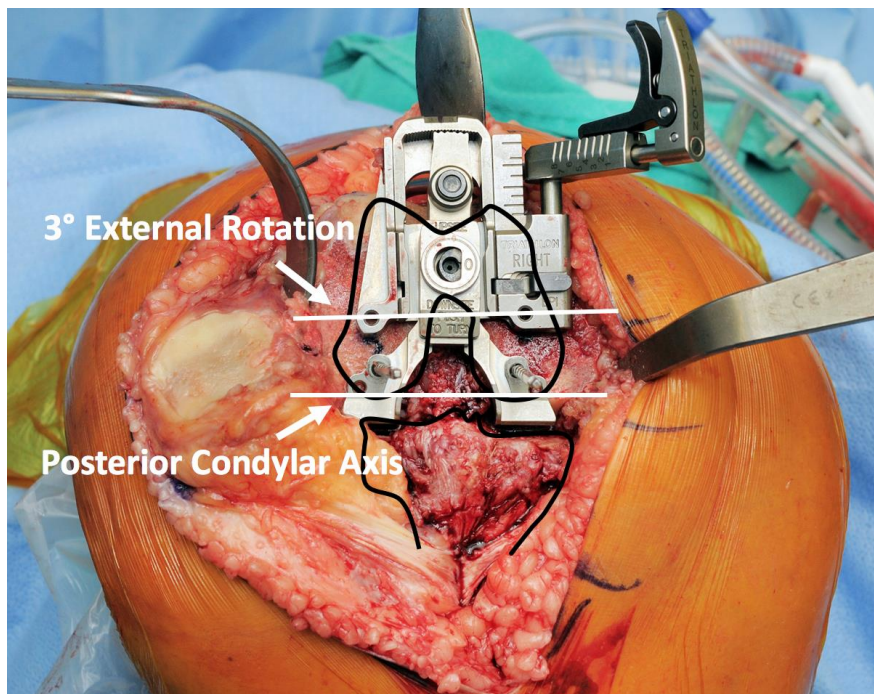
Despite modern technique and implant design in TKA, up to 23% of patients have anterior knee pain<sup>41</sup>, and currently the etiology and treatment is unknown. Some researchers believe that any alteration in the biomechanical properties can lead to abnormal activation of free nerve endings. Currently, one of the main downsides of the literature is the absence of a specific, widely-used, standardized patellofemoral rating system to study outcomes. This may help us refine our outcome measures and allow us to identify the factors involved in this complication.

## 1.4.2 Maltracking

Patellofemoral complications can be affected by surgical technique and decision making. Malrotation of the femoral and tibial components and its effect on patellar maltracking is one of the most discussed variables in the literature. The substantial influence of femoral component rotation on quadriceps forces, collateral ligament forces, and varus/valgus kinematics was demonstrated by computer modelling.<sup>47</sup> Previous retrospective radiographic studies have shown that poor rotational alignment of the femoral component can lead to patellar maltracking and adverse patient outcomes.<sup>36</sup> Barrack<sup>36</sup> identified that component malrotation is a contributing factor to anterior knee pain, but is clearly not the only factor involved, as some patients with evidence of malrotation were symptom-free, pointing to the multifactorial nature of anterior knee pain. With respect to the femoral component, the amount of external rotation that clinically matters seems to vary but most studies suggest that between 2-5° of external rotation (Figure 1-7) leads to optimal outcomes.<sup>48</sup>

Malrotation of the tibial component appears to affect outcomes as well.<sup>36</sup> In an analysis of post-operative CT scans, Bedard<sup>49</sup> found that internal rotation of the tibial component may contribute to knee stiffness post TKA. Nicoll<sup>50</sup> found that tibial component internal

rotation is associated with medial and anterior knee pain. Ideal rotation has not been identified and some anatomical references have been proposed, such as the central third of the tibial tubercle<sup>50</sup> or the middle of the talus<sup>51</sup> (Figure 1-8), but most studies agree that any amount of internal rotation, either the femur or tibia individually, or a combination of both, is undesirable.<sup>36</sup>



**Figure 1-7. Alignment of the femoral component. The black lines represent the position of the femur (top) and tibia (bottom). The femoral component is placed in 3° external rotation compared to the posterior condylar axis. (Photograph taken at LHSC)**

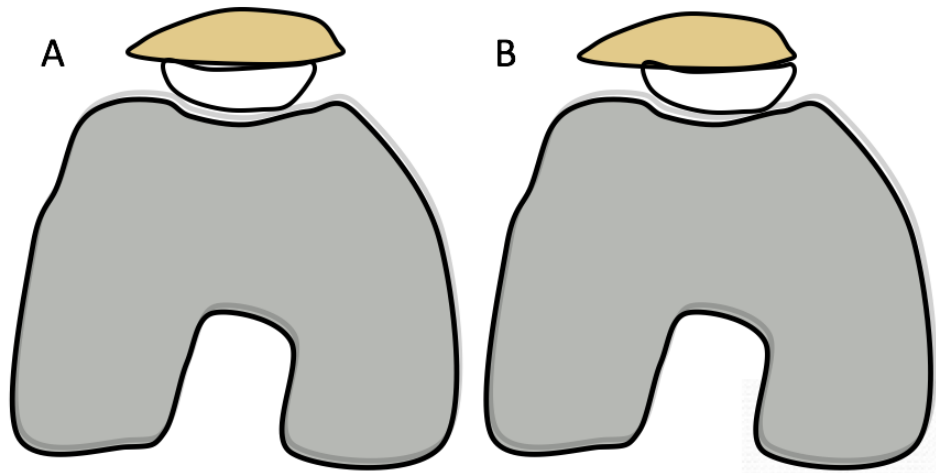


**Figure 1-8. Alignment of the tibial component. The black lines represent the position of the tibia (right) and fibula (left). The tibial component is placed in external rotation; various landmarks can be used, such as the tibial tubercle or the centre of the ankle. (Photograph taken at LHSC)**



When resurfacing the patella, the location of the patellar component plays a role in affecting knee kinematics. In a laboratory study, Yoshii<sup>29</sup> found that a medialized position of the patellar button led to a decrease Q angle and improved patellar tracking. Furthermore, placing the patella in a medialized position may improve implant survivorship and decrease lateral retinacular release. This has been confirmed by computer modelling, which showed that a medialized button position (Figure 1-9) leads to a significant reduction in patellofemoral lateral shear forces.<sup>26</sup>

A lateral release is one of the commonly described methods to manage patellar maltracking.<sup>52</sup> It is a procedure where the lateral retinaculum on the lateral aspect of the patella is released.<sup>53</sup> Reports about the rates of lateral release vary substantially between 3 to 45%.<sup>52</sup> Release has been reported to achieve good tracking intraoperatively. Some of the possible complications of this technique are patellar AVN and fracture.<sup>52</sup> The other described technique to deal with patellar maltracking is a lateral facetectomy, which also has been reported as successful in improving patellar tracking, with little downside.<sup>54</sup>



**Figure 1-9. Centered (A) and medialized (B) patellar button placement. Medialized patellar button placement (B) allows a reduction in patellar shear forces. (Courtesy of J. Matz)**

### 1.4.3 Other Complications

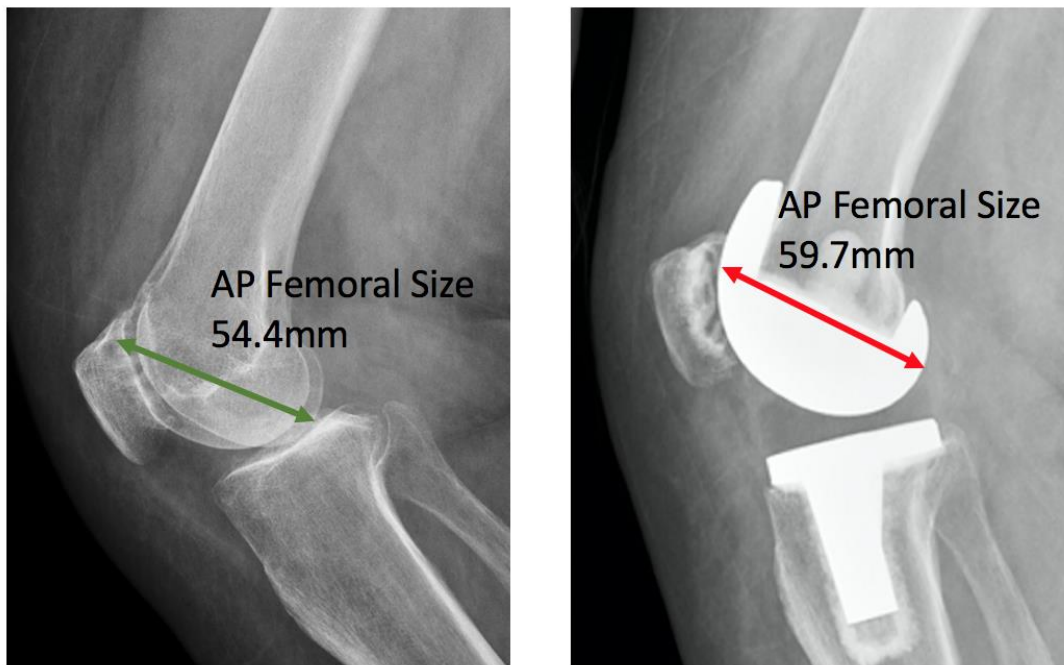
Other patellofemoral complications occur rarely (<1%), but can be quite disabling and challenging to manage. Patellar fracture post TKA in the setting of a resurfaced patella is quite rare, reported from 0.12-3.9%.<sup>55</sup> Unless the fracture is completely undisplaced, the management of these complications is quite challenging and results are often disappointing. Non-operative management has been recommended for undisplaced fractures, while operative intervention is required for displaced fractures.<sup>55</sup>

A possible complication following TKA that may contribute to anterior knee pain is avascular necrosis of the patella.<sup>56</sup> The prevalence is quite low at 0.05-2%.<sup>56</sup> With respect to surgical approach, both the commonly used median parapatellar and subvastus approaches to the knee result in similar changes in patellar vascularity, and no clear association between surgical approach and avascular necrosis has been shown.<sup>56</sup> Performing a lateral retinacular release during total knee arthroplasty may be a risk factor for patellar avascular necrosis.<sup>57</sup> Overall, it remains unclear whether intraosseous patellar blood flow correlates with anterior knee pain post TKA.

Another potential complication is patellar clunk, with an incidence of 0-14%. Patellar clunk occurs more often in posterior-stabilized (PS) knee designs<sup>33</sup>. It is secondary to proliferative fibrous tissue at the junction of the superior pole of the patella and distal quadriceps tendon<sup>33</sup>. This tissue gets trapped within the intercondylar box and limits patellar excursion, until the soft tissue interference is overcome and motion is resumed with a “clunk”. Theories regarding etiology are femoral component design, particularly those with an abrupt transition zone at the superior end of the box in PS components. Factors such as decreased patellar height and increased posterior condylar offset were found to be associated with this complication<sup>33</sup>.

## 1.5 Changes in Patellofemoral Offset – Role in Patellofemoral Complications?

Increased patellofemoral offset (PFO) has long been implicated to be a potential contributory factor to patellofemoral complications. Increasing the patellofemoral offset refers to a mismatch between the preoperative and post-operative anteroposterior dimensions of the patellofemoral joint. Changes in patellofemoral joint offset can be attributed to surgical technique and intraoperative decision-making.<sup>58</sup> Sizing of the femoral component as well as its AP positioning compared to the geometry of the resected native bone affects patellofemoral stuffing (Figure 1-10). As well, the thickness of the patellar button can affect PFO.<sup>59</sup> Theoretically, the PFO could lead to increased patellofemoral forces, anterior knee pain, decreased range of motion, and increased component wear.



**Figure 1-10. Increasing the patellofemoral offset may be a contributing factor to anterior knee pain, and may occur when the size of the femoral or patellar component are greater than the amount of bone that was resected.**

Biomechanical data<sup>60, 61</sup> suggests that increased PFO can adversely affect patellofemoral contact forces, knee range of motion, and patellar tilt. Recently, computer-based modeling combined with cadaveric knee experimentation demonstrated that knee flexion decreased with increasing patellar thickness.<sup>60</sup> In particular, they found that for every 1 mm of increased patellar thickness, knee flexion decreased by 1.08°. It was recommended to restore preoperative patellar thickness in order to maximize post-operative knee flexion. Other in vitro studies have demonstrated that a thicker patella or femoral components larger than the anterior condyle resected may have an adverse effect on contact forces, lead to increased shear forces, and contribute to abnormal patellofemoral motion.<sup>58</sup> While increases in the size of the femoral component can lead to increased PFO in posterior referenced systems, decreases in the size of the component can lead to notching and heighten the potential for fracture.<sup>62</sup> Furthermore, although not demonstrated in literature, decreasing PFO may lead to quadriceps insufficiency, weakness, and instability.

Previous clinical studies have not shown adverse effects of changes in PFO on patient outcomes<sup>63, 64</sup>. Pierson<sup>63</sup> conducted the first retrospective clinical study examining the effect of overstuffing the PFJ in resurfaced knees with two different knee designs, finding no adverse effects associated with increased PFO. Beldman<sup>64</sup> recently evaluated the effect of overstuffing the PFJ on clinical outcomes or anterior knee pain in total knee arthroplasty without patellar resurfacing. They found no association between overstuffing and anterior knee pain or patient reported outcomes.

The importance of changes in PFO remains controversial. While clinical studies have not conclusively demonstrated adverse effects to changes in PFO, intuitively one can expect it to play a role in effecting outcomes, and may only affect outliers with excessive amounts of changes to PFO.

## 1.6 Tribology of Femoral Components

Metallic components are widely used in orthopedics for their high load bearing capacity, low friction, and high resistance to corrosion and wear.<sup>65</sup> The most commonly used metals are stainless steel, cobalt chromium, and titanium alloy.<sup>65</sup> In TKA, the “gold standard” femoral component has been made of cobalt-chromium alloy<sup>66</sup>, the tibial tray is typically titanium or cobalt chromium alloy<sup>67</sup>, and the tibial insert as well as the patellar component are made of polyethylene.<sup>68</sup> These materials must be able to withstand great forces, particularly at the patellofemoral joint, where compressive and shear forces can be several times body weight.<sup>6</sup>

As a younger and more active population is increasingly exposed to arthroplasty procedures<sup>69</sup>, it is becoming more important to optimize and restore biomechanics to normality as closely as possible in order to avoid abnormal loading, wear, and early failure of components.<sup>70</sup> Abnormal biomechanics following joint arthroplasty have previously been shown to lead to component surface changes, such as plastic deformation, damage, and wear.<sup>71-73</sup> The mechanisms are varied and primarily relate to increased compressive<sup>74</sup>, rotational<sup>75</sup>, and shear forces<sup>71, 73</sup>, increased sliding motion between components<sup>76</sup>, and edge loading of the components<sup>77, 78</sup>.

Implant retrieval is a commonly used and recognized method of understanding component performance, kinematics, and investigating failure modes.<sup>65, 79</sup> Previously used methods of evaluating surface damage include visual inspection<sup>80, 81</sup>, microscopy (light and electron), and contact and non-contact profilometry.<sup>67, 66</sup> Surface profilometry is a technique where either optic or a stylus methods are used to produce a topographical representation of the surface, capable of vertical resolution of 1 nm or less.<sup>82, 83</sup> Previous studies used profilometry to examine the surface wear characteristics of the femoral condyles of retrieved TKA femoral components. Brant<sup>81</sup> compared 26 matched cobalt chromium and oxidized zirconium implants, finding that some of the roughness parameters of the retrieved cobalt chromium components were significantly higher than the oxidized zirconium. Similar findings were reported by Heyse<sup>80</sup>. With respect to the

patellofemoral joint, while the patterns of patellar polyethylene wear were previously reported<sup>84</sup>, we are unaware of previous reports specific to trochlear wear.

In addition to component surface wear and damage as outlined above, abnormal biomechanics, and subsequently abnormal forces, may lead to non-physiologic loading of the knee and likely play a role in decreased patient satisfaction, increased pain, and decreased knee function.<sup>85-87</sup> As such, assessing femoral component damage may be helpful in identifying areas of abnormal patellofemoral contact and lead to a better understanding of the patellofemoral joint kinematics.

## 1.7 Research Objectives

Given the increasing rate of TKA<sup>88</sup>, optimizing post-operative outcomes remains a priority. The objectives of this thesis are to improve the understanding of changes in patellofemoral offset and trochlear design on patient outcomes and implant wear in TKA. As outlined above, information about specific factors leading to anterior knee pain and knee dysfunction is still limited. While the causes are likely multifactorial, changes in patellofemoral offset are potentially a substantial contributor, and may represent an easily modifiable factor. It remains unclear whether these changes in fact lead to unfavorable outcomes. The first objective of this thesis is to characterize the effect of patellofemoral offset changes on the post-operative outcomes of a large patient population following TKA. By combining radiographic data with component retrieval findings, the second objective of this thesis was to determine if changes in patellofemoral offset is a factor contributing to increased surface damage to the femoral component following *in-vivo* use. The third goal of the thesis was to characterize the damage of retrieved femoral components, particularly in the femoral trochlea, which may help elucidate details regarding abnormal patellofemoral contact and design features that may adversely affect the patellofemoral joint. Finally, the fourth objective of the thesis is to determine whether different trochlear designs lead to different magnitude and patterns of femoral component wear based on visual inspection and surface profilometry.

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## Chapter 2

# 2 Do Changes in Patellofemoral Offset Lead to Adverse Outcomes in Total Knee Arthroplasty with Patellar Resurfacing? A Radiographic Review

*Overview: Information about specific factors leading to adverse patellofemoral outcomes following total knee arthroplasty is currently limited. Changes in patellofemoral offset were implicated as a potential contributor to adverse outcomes. This chapter investigates the association between changes in patellofemoral offset and patient-reported outcomes.*

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### 2.1 Introduction

Despite significant advances in surgical technique, component design, and perioperative management in total knee arthroplasty (TKA), complications related to the patellofemoral joint (PFJ) continue to be a substantial source of patient morbidity, causing anterior knee pain, instability, and dysfunction.<sup>1,2</sup> As the volume and patient demands for TKA increase, a greater understanding of the PFJ is required.<sup>3</sup>

Following TKA, the patellofemoral joint offset (PFO) may be decreased, maintained, or increased. Changing the patellofemoral joint offset (PFO) results in a mismatch between the AP geometry of the host bones and the AP diameter of the femoral and patellar components. Changing the PFO may occur by placing a femoral component or a patellar component that is smaller or larger than the space created for the implant by the bone cuts. Translation of the femoral component may also affect the PFO.

Recently, computer-based modeling combined with cadaveric knee experimentation demonstrated that knee flexion decreased exponentially with increasing patellar thickness.<sup>4</sup> It was recommended to restore preoperative patellar thickness in order to maximize post-operative knee flexion. Other in vitro studies have demonstrated that a

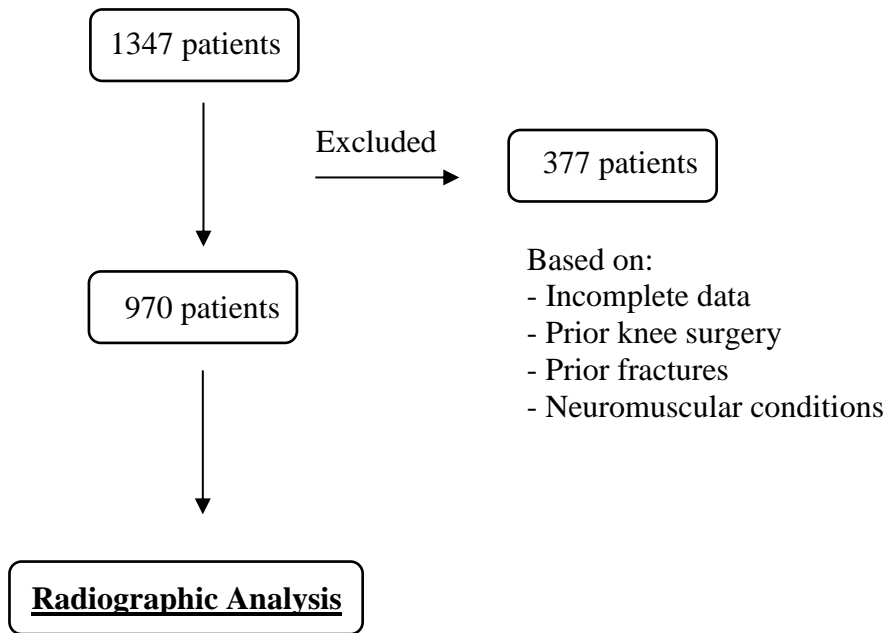
thicker patella or femoral components larger than the anterior condyle resected may have an adverse effect on contact forces, lead to increased shear forces, and contribute to abnormal patellofemoral motion.<sup>5-7</sup> Conceptually, this may result in early component loosening, increased wear, and anterior knee pain. Although not demonstrated in the literature, decreasing the PFO may lead to quadriceps insufficiency, weakness, and instability.

While some biomechanical studies have demonstrated the importance of reproducing the AP diameter of the host bone, limited clinical evidence exists to support this notion.<sup>8-10</sup> It is important to establish whether changes in PFO in resurfaced knees are associated with poor satisfaction and patient reported outcomes.<sup>11</sup> This study will provide comprehensive clinical evidence on the relationship between changing the PFO and outcomes in TKA.

## 2.2 Materials & Methods

A retrospective review was completed of 1374 primary total knee arthroplasty surgeries performed between 2004-2014 at University Hospital, London Health Sciences Centre. The protocol was approved by our Research Ethics Board. The review was limited to a single, posterior stabilized implant with patellar resurfacing using an inlay technique (Genesis II™, Smith & Nephew, Memphis, TN). The surgeries were performed by one of six fellowship trained arthroplasty surgeons. Patients with follow-up of less than 2 years were excluded from the study. Other exclusion criteria included incomplete data postoperatively, prior open knee surgery, prior fractures, and neuromuscular conditions. Following exclusions, a total of 975 patients were included. The patient demographic data is outlined in Table 2-1.





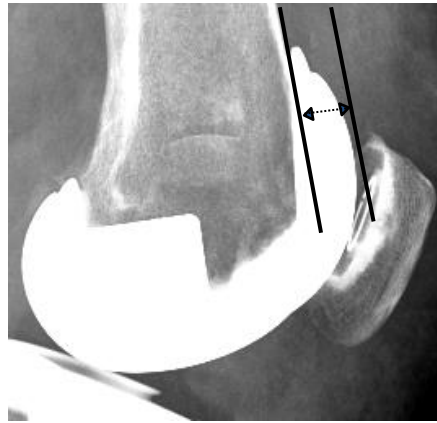
**Figure 2-1. Patient selection for radiographic analysis.**

**Table 2-1. Demographic Data.**

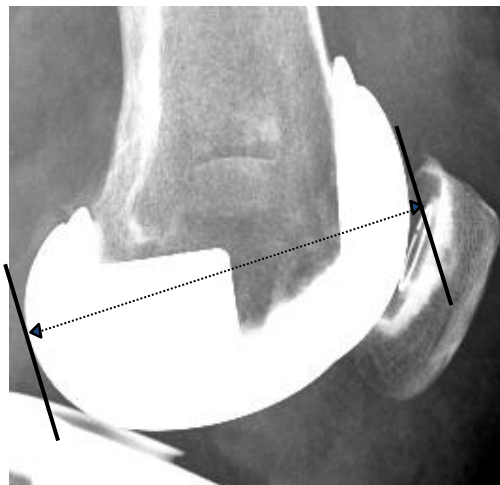
<b>Age at the time of revision (years)</b>	76 ± 9
<b>Gender (female/male)</b>	607/363
<b>Side (right/left)</b>	512/458
<b>BMI (kg/m<sup>2</sup>)</b>	33 ± 8

Standard preoperative and post-operative (1-3 years) lateral and skyline knee radiographs were reviewed and measurements performed. On the lateral radiograph, measurements were performed assessing anterior femoral offset and anteroposterior (AP) femoral size (Figures 2-1, 2-2).<sup>9,10</sup> The anterior femoral offset was measured between the anterior edge of the femoral cortex and the anterior aspect of the anterior femoral condyle. The AP femoral size was defined as the distance between the posterior condylar line and the anterior condylar line. On the skyline radiograph, anterior patellar offset and patellar tilt were measured. Anterior patellar offset was defined as the distance from the deepest part of the trochlear groove to the anterior cortex of the patella. The anterior femoral offset, AP femoral size, and anterior patellar offset were used to quantify the PFO. An additional measure, total PFO, was defined as the combined change of AP femoral size and anterior patellar offset. The patellar tilt was measured by drawing a line on the anterior aspect of the femoral condyles and another line along the posterior aspect of the articular surface of the patella.<sup>12</sup> The angle between the two lines defined the patellar tilt (Figure 2-3). Calibration based on known component size or a calibration marker was performed for all radiographic measurements. Radiographic measurements were carried out by two independent observers. To assess inter-rater correlation, both observers performed measurements of the same radiographs for 20% of the total sample. To account for measurement error, changes in PFO within one mm from the pre-operative measurement were classified as “maintained”. Changes in PFO greater than one mm in a positive or negative direction were classified as “increased” or “decreased” PFO, respectively.

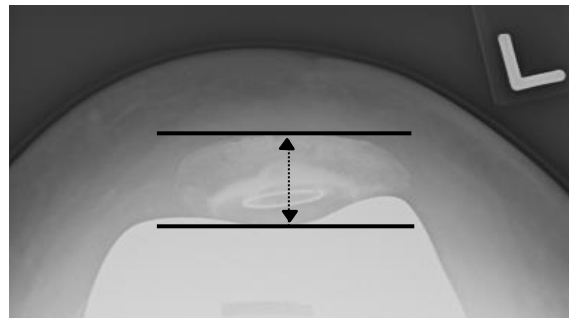
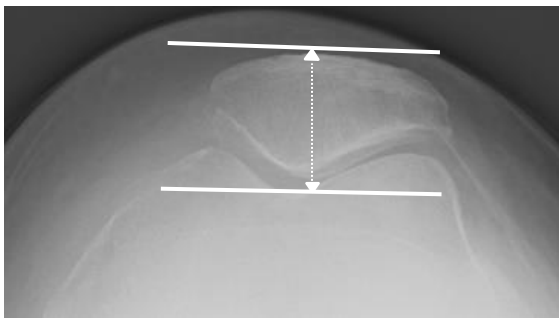
Patients completed the Western Ontario and McMasters Osteoarthritis Index (WOMAC) and Knee Society Score (KSS) questionnaires both preoperatively and post-operatively at 1-3 years post TKA.



**Figure 2-2. Measurement of Anterior Femoral Offset.**



**Figure 2-3. Measurement of AP Femoral Size.**

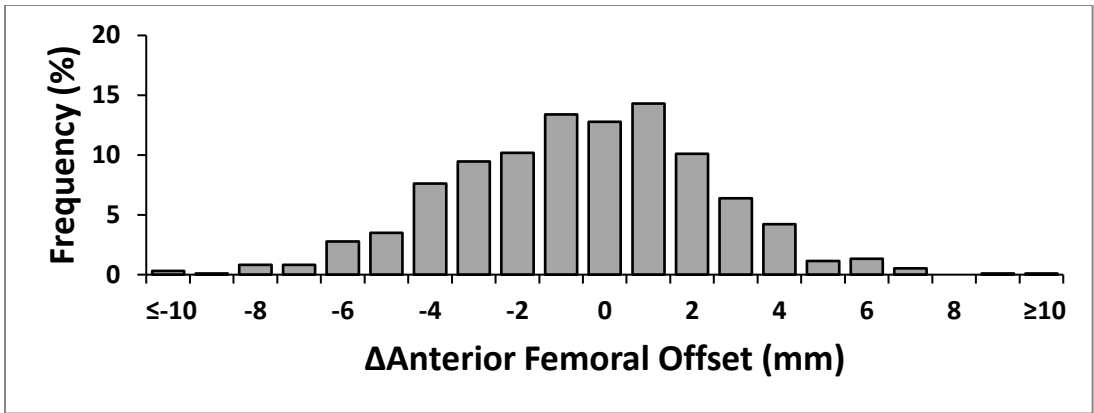


**Figure 2-4. Measurement of Anterior Patellar Offset.**

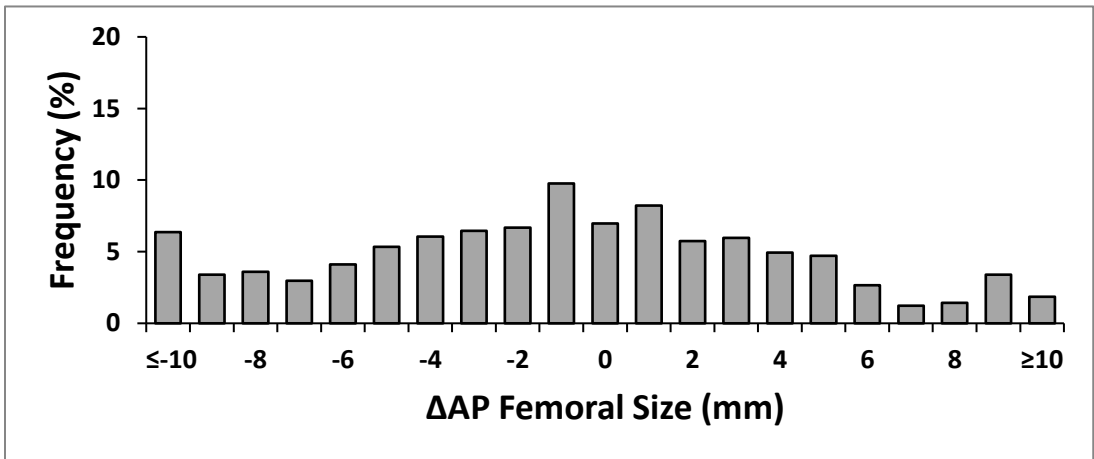
Statistical analysis was carried out using SPSS® statistics version 23 (SPSS Inc., Chicago, IL). Statistical comparisons between groups with increased, maintained, and decreased PFO and their patient-reported outcome scores were made using the Kruskal-Wallis test. Spearman correlation was used in order to assess the association between patellofemoral offset changes and patellar tilt and knee range of motion. All p values were for two-sided tests and p values of <0.05 were considered statistically significant. A posthoc power analysis was performed given our sample size of 970. This analysis showed that with a significance level of 0.05, we had 80% power to detect any significant differences (G\*Power 3.0 software, Heinrich Heine University, Dusseldorf, Germany).

## 2.3 Results

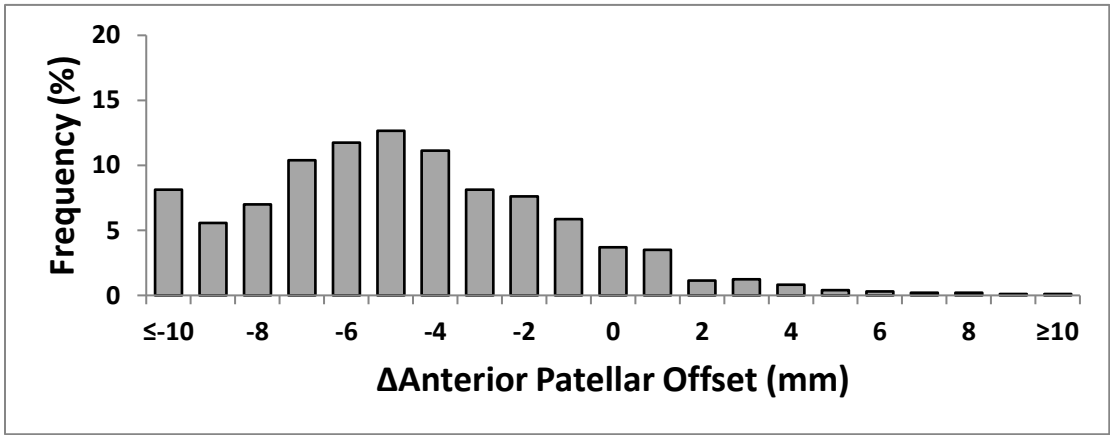
Post-operative anterior femoral offset was increased in 50.8%, maintained in 13.4%, and decreased in 35.6% of patients (Figure 2-4). The total AP femoral size was increased in 43.6%, maintained in 9.8%, and decreased in 45.1% of patients (Figure 2-5). Finally, anterior patellar offset was increased in 11.5%, maintained in 5.9%, and decreased in 82.4% of patients (Figure 2-6). The magnitude of increase in anterior femoral offset, AP femoral size, anterior patellar offset, was, on average (SD), 2.8mm (1.5), 4.7mm (4.0), and 3.1mm (2.1), respectively. In knees where the PFO was decreased, anterior femoral offset, AP femoral size, or anterior patellar offset were decreased, on average (SD), 3.1mm (1.7), 5.7mm (3.7), and 5.5mm (2.8), respectively. Overall, on average (SD), anterior femoral offset was unchanged (mean 0mm, SD 2.9), AP femoral size was decreased 0.7mm (5.9), and anterior patellar offset was decreased 4.2mm (3.8). To assess for combined changes in patellar and femoral offset, total PFO was measured. Total PFO was increased in 15% patients, maintained in 12% patients, and decreased in 72% of patients. The average (SD) increase in total PFO was 5 mm (4.6) and the average decrease was 8 mm (5.2). The inter-rater correlation coefficients for the above radiographic measurements in were all good/excellent (range 0.7–0.98).



**Figure 2-5. Changes in Anterior Femoral Offset (Post-operative Anterior Femoral Offset – Pre-operative Anterior Femoral Offset)**



**Figure 2-6. Changes in AP Femoral Size (Post-operative AP Femoral Size – Pre-operative AP Femoral Size)**



**Figure 2-7. Changes in Anterior Patellar Offset (Post-operative Anterior Patellar Offset – Pre-operative Anterior Patellar Offset)**

Patient outcome scores and range of motion were evaluated on the basis of PFO measurements (Tables 2-2 & 2-3). Increased, maintained, or decreased anterior femoral offset was not significantly associated with post-operative total WOMAC scores ( $p=0.68$ ) or subscale scores, including pain ( $p=0.90$ ), function ( $p=0.64$ ), and stiffness ( $p=0.09$ ). Similarly, post-operative KSS scores were not affected ( $p=0.88$ ), or subscales for pain ( $p=0.73$ ) or function ( $p=0.51$ ). AP femoral size was not significantly associated with changes in WOMAC patient outcomes ( $p=0.58$ ), and subscale WOMAC outcomes such as pain ( $p=0.25$ ), function ( $p=0.31$ ), and stiffness ( $p=0.31$ ). Changes in AP femoral size were not associated with post-operative KSS scores ( $p=0.62$ ), and subscale scores for pain ( $p=0.30$ ) and function ( $p=0.44$ ). Changing the anterior patellar offset was not significantly associated with post-operative WOMAC ( $p=0.70$ ), pain ( $p=0.65$ ), function ( $p=0.57$ ), stiffness ( $p=0.95$ ), or KSS scores ( $p=0.62$ ). Finally, changes in total PFO were not associated with post-operative WOMAC ( $p=0.71$ ) and KSS scores ( $p=0.56$ ).

Post-operative range of motion was not affected by changes in anterior femoral offset, AP femoral size, or anterior patellar offset ( $p=0.69$ ,  $p=0.88$ ,  $p=0.06$ , respectively).

The mean post-operative patellar tilt was  $6.7^\circ$ . A positive correlation was found between increased anterior patellar offset and increased patellar tilt post-operatively ( $p<0.01$ ,  $r=0.21$ ). Post-operative patellar tilt was not associated with changes in anterior femoral offset ( $p=0.27$ ) or AP femoral size ( $p=0.60$ ). The post-operative patellar tilt was not correlated with patient outcome scores, such as WOMAC ( $p=0.82$ ) or KSS ( $p=0.06$ ), as well as subscales for WOMAC pain ( $p=0.60$ ), function ( $p=0.40$ ) and stiffness ( $p=0.97$ ). Range of motion was not correlated with post-operative patellar tilt ( $p=0.05$ ).

	Decreased Anterior Femoral Offset (mean ± SD)	Maintained Anterior Femoral Offset (mean ± SD)	Increased Anterior Femoral Offset (mean ± SD)	p-value
<b>Pre-operative WOMAC Pain</b>	49.12 ± 17.67	50.99 ± 18.73	51.10 ± 20.29	p=0.48
<b>Pre-operative WOMAC Stiffness</b>	46.98 ± 17.74	50.58 ± 18.58	49.83 ± 19.27	p=0.15
<b>Pre-operative WOMAC Function</b>	40.73 ± 20.58	43.39 ± 22.28	43.39 ± 22.28	p=0.25
<b>Pre-operative WOMAC Total</b>	46.56 ± 16.14	49.24 ± 17.71	49.08 ± 18.00	p=0.32
<b>1-3 yr WOMAC Pain</b>	80.18 ± 19.74	80.23 ± 19.82	80.63 ± 20.04	p=0.90
<b>1-3 yr WOMAC Stiffness</b>	73.07 ± 22.79	70.35 ± 21.92	74.64 ± 20.36	p=0.09
<b>1-3 yr WOMAC Function</b>	78.01 ± 19.59	76.04 ± 19.92	77.04 ± 19.72	p=0.64
<b>1-3 yr WOMAC Total</b>	77.92 ± 18.85	76.70 ± 18.54	78.19 ± 17.98	p=0.68
	Decreased AP Femoral Size (mean ± SD)	Maintained AP Femoral Size (mean ± SD)	Increased AP Femoral Size (mean ± SD)	
<b>Pre-operative WOMAC Pain</b>	49.41 ± 17.93	51.23 ± 18.68	51.10 ± 20.29	p=0.50
<b>Pre-operative WOMAC Stiffness</b>	47.85 ± 17.80	50.24 ± 19.06	49.83 ± 19.27	p=0.44
<b>Pre-operative WOMAC Function</b>	41.49 ± 20.88	42.84 ± 22.54	43.72 ± 20.96	p=0.45
<b>Pre-operative WOMAC Total</b>	47.17 ± 16.39	49.10 ± 18.02	49.08 ± 19.00	p=0.53
<b>1-3 yr WOMAC Pain</b>	80.76 ± 19.37	82.62 ± 18.70	78.79 ± 20.87	p=0.25
<b>1-3 yr WOMAC Stiffness</b>	73.16 ± 21.25	74.26 ± 21.03	71.96 ± 22.61	p=0.31
<b>1-3 yr WOMAC Function</b>	77.77 ± 19.42	77.90 ± 19.20	76.18 ± 20.32	p=0.31
<b>1-3 yr WOMAC Total</b>	78.25 ± 18.08	78.66 ± 18.21	76.54 ± 18.96	p=0.58
	Decreased Anterior Patellar Offset (mean ± SD)	Maintained Anterior Patellar Offset (mean ± SD)	Increased Anterior Patellar Offset (mean ± SD)	
<b>Pre-operative WOMAC Pain</b>	50.42 ± 18.36	48.03 ± 20.56	52.84 ± 22.67	p=0.44
<b>Pre-operative WOMAC Stiffness</b>	48.81 ± 18.23	47.35 ± 19.54	53.19 ± 20.59	p=0.20
<b>Pre-operative WOMAC Function</b>	42.47 ± 21.10	42.11 ± 21.32	44.23 ± 22.32	p=0.67
<b>Pre-operative WOMAC Total</b>	48.16 ± 16.90	46.54 ± 17.91	51.16 ± 20.30	p=0.23
<b>1-3 yr WOMAC Pain</b>	80.61 ± 19.73	80.06 ± 20.35	78.19 ± 20.66	p=0.65
<b>1-3 yr WOMAC Stiffness</b>	72.91 ± 22.06	72.38 ± 21.16	71.73 ± 18.83	p=0.95
<b>1-3 yr WOMAC Function</b>	77.43 ± 19.68	77.27 ± 19.44	74.78 ± 20.62	p=0.57
<b>1-3 yr WOMAC Total</b>	77.85 ± 18.47	77.41 ± 18.63	76.38 ± 18.04	p=0.70

**Table 2-2. Patient outcomes based on WOMAC scores for decreased, maintained, and increased anterior femoral offset, AP femoral size, and anterior patellar offset.**

	<b>Decreased Anterior Femoral Offset (mean ± SD)</b>	<b>Maintained Anterior Femoral Offset (mean ± SD)</b>	<b>Increased Anterior Femoral Offset (mean ± SD)</b>	<b>p-value</b>
<b>Pre-operative KSS Pain</b>	19.23 ± 8.61	19.62 ± 9.09	19.68 ± 8.69	p=0.91
<b>Pre-operative KSS Function</b>	43.73 ± 16.14	45.55 ± 16.80	46.32 ± 15.33	p=0.10
<b>Pre-operative KSS Total</b>	95.13 ± 23.88	96.81 ± 26.48	98.52 ± 23.28	p=0.49
<b>1-3 yr KSS Pain</b>	46.28 ± 6.71	46.31 ± 6.99	76.53 ± 24.26	p=0.73
<b>1-3 yr KSS Function</b>	77.60 ± 24.06	76.53 ± 24.26	76.76 ± 21.22	p=0.51
<b>1-3 yr KSS Total</b>	170.48 ± 27.42	169.68 ± 27.52	170.94 ± 23.56	p=0.88
	<b>Decreased AP Femoral Size (mean ± SD)</b>	<b>Maintained AP Femoral Size (mean ± SD)</b>	<b>Increased AP Femoral Size (mean ± SD)</b>	
<b>Pre-operative KSS Pain</b>	19.24 ± 8.63	19.79 ± 9.30	19.68 ± 8.69	p=0.91
<b>Pre-operative KSS Function</b>	44.15 ± 15.71	45.51 ± 18.14	46.32 ± 15.33	p=0.14
<b>Pre-operative KSS Total</b>	95.45 ± 23.23	96.93 ± 29.25	98.52 ± 23.28	p=0.50
<b>1-3 yr KSS Pain</b>	46.53 ± 6.22	46.66 ± 5.21	46.18 ± 7.63	p=0.30
<b>1-3 yr KSS Function</b>	78.38 ± 22.20	76.45 ± 22.59	75.56 ± 24.30	p=0.44
<b>1-3 yr KSS Total</b>	171.37 ± 25.96	169.89 ± 24.98	169.55 ± 26.72	p=0.62
	<b>Decreased Anterior Patellar Offset (mean ± SD)</b>	<b>Maintained Anterior Patellar Offset (mean ± SD)</b>	<b>Increased Anterior Patellar Offset (mean ± SD)</b>	
<b>Pre-operative KSS Pain</b>	19.39 ± 8.63	20.60 ± 9.21	19.32 ± 9.53	p=0.29
<b>Pre-operative KSS Function</b>	44.86 ± 15.93	44.39 ± 16.41	50.00 ± 16.12	p=0.36
<b>Pre-operative KSS Total</b>	96.33 ± 24.13	96.74 ± 23.94	102.76 ± 27.08	p=0.53
<b>1-3 yr KSS Pain</b>	46.59 ± 6.05	46.08 ± 7.49	45.18 ± 10.35	p=0.54
<b>1-3 yr KSS Function</b>	77.78 ± 22.69	73.08 ± 23.64	74.20 ± 25.91	p=0.14
<b>1-3 yr KSS Total</b>	170.88 ± 25.84	167.64 ± 25.83	169.62 ± 28.72	p=0.61

**Table 2-3. Patient outcomes based on KSS for decreased, maintained, and increased anterior femoral offset, AP femoral size, and anterior patellar offset.**



## 2.4 Discussion

Patellofemoral complications remain some of the most challenging problems following TKA. The rate of anterior knee pain with modern designs and technique is between 10% - 23%.<sup>11,13</sup> Recent registry data suggests that up to 10% of TKA revision are secondary to patellofemoral pain alone.<sup>14</sup> Other complications are less frequent but present with significant morbidity.<sup>15</sup> It remains controversial whether changes in PFO lead to adverse outcomes in TKA.

In the current study, our primary outcome was the influence of changes in the patellofemoral offset (PFO) on clinical patient-reported outcomes, with secondary outcomes of range of motion and post-operative patellar tilt. Our results showed that there was no association between change in PFO and WOMAC or KSS scores, or ROM post-operatively. There was an association between increased post-operative PFO and increased post-operative patellar tilt. However, increased tilt was not correlated with adverse patient satisfaction scores.

Our findings are in line with previous investigations. Beldman<sup>10</sup> recently evaluated the effect of overstuffing the PFJ on clinical outcomes or anterior knee pain in total knee arthroplasty without patellar resurfacing. They found no association between overstuffing and anterior knee pain or patient reported outcomes. Importantly, the sample size was limited (193 knees) and the study may have lacked adequate power to detect subtle trends in outcomes. Pierson<sup>9</sup> conducted a retrospective review of the effect of overstuffing the PFJ in resurfaced knees with two different knee designs, finding no adverse effects associated with overstuffing. To our knowledge, this was the first clinical study to challenge the importance of overstuffing. While they were able to quantify percent change in post-operative stuffing, the absolute amount of overstuffing was not directly quantifiable. In the present study, the presence of calibration allowed us to draw conclusions based on directly quantifiable measures. Furthermore, the presence of a single knee design eliminated potential confounders.

Whereas clinical studies have not shown an association between changes in PFO and outcomes, biomechanical studies have demonstrated mixed results. In a cadaveric biomechanical study, Hsu<sup>6</sup> tested knee range of motion with three different patella thickness levels, finding that ROM was not significantly affected by patellar thickness. On the other hand, a more recent biomechanical study found that increasing the patellar thickness exponentially decreased knee flexion.<sup>4</sup> This decrease, however, may not be clinically significant.<sup>4</sup>

We found frequent changes in PFO post-operatively, with a tendency towards decreased PFO in our sample. The etiology for changes in PFO is multifactorial.<sup>4,6,16</sup> In the majority of knees, the magnitude of change in PFO was overall relatively small. Our findings are therefore likely only relevant for small changes and should not be extrapolated to extreme changes in PFO.

Increased PFO was associated with increased patellar tilt in this cohort of patients. Previous investigations indicated that patellar tilt may increase component wear.<sup>19</sup> In addition, increased tilt may also contribute to patellar maltracking.<sup>20</sup> Maltracking has been associated with various complications affecting the patellofemoral joint, such as anterior knee pain and range of motion limitation.<sup>21,22</sup> Our findings did not show an association between adverse outcomes and increased patellar tilt. Unlike the biomechanical studies showing increased loading and wear<sup>19</sup>, other clinical studies have also not shown an association between increased tilt and adverse patient outcomes.<sup>23</sup>

The limitations of the current study are as follows. The patient reported outcome scores are susceptible to a ceiling effect, which may affect the results of the study. In addition, our institution historically used the standard Skyline view of the patella as opposed to the patellofemoral axial weight bearing views, which have previously been shown to correlate with anterior knee pain.<sup>24</sup> All surgeons used an inlay technique for patellar resurfacing making the results potentially not generalizable for the onlay technique. Finally, while using a sample with a single knee design improves our internal validity, it may also limit the generalizability of our results to other designs.

In conclusion, this study quantified changes in PFO following TKA using a large sample size and calibrated measurements. Our findings highlight the difficulty of maintaining the PFO post-operatively but also show that small changes in PFO may not adversely affect clinical outcomes post TKA. Given the potential for increased contact forces at the PFJ, further studies are required to establish whether changes in PFO would lead to adverse implant wear implications.

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## Chapter 3

### 3 Do Changes in Patellofemoral Offset Lead to Increased Femoral Component Wear or Surface Damage? A Study of Radiographic and Surface Profilometry Findings

*Outline: The etiology of patellofemoral complications after total knee arthroplasty is controversial. Biomechanical studies have shown that changes in post-operative patellofemoral offset lead to increased patellofemoral contact forces. The objective of this chapter was to determine whether changes in patellofemoral offset are associated with increased surface damage and wear to the femoral component following total knee arthroplasty.*

#### 3.1 Introduction

Patellofemoral joint (PFJ) complications continue to be a substantial source of patient morbidity, causing anterior knee pain, instability, and dysfunction following total knee arthroplasty (TKA).<sup>1</sup> Rates of anterior knee pain following TKA are up to 23%.<sup>2</sup> As the volume and patient demands for TKA increase<sup>3</sup>, obtaining a greater understanding of the PFJ is important.

The patellofemoral offset (PFO) describes the AP geometry of the native patellofemoral joint. Following TKA, the PFO may be decreased, maintained, or increased. Changing the PFO results in a mismatch between the AP geometry of the host bones and the AP diameter of the femoral and patellar components. Computer-based modeling and in vitro studies demonstrate that increased post-operative PFO can decrease knee flexion, affect patellofemoral contact and shear forces, and contribute to abnormal patellofemoral motion.<sup>4,5</sup> Star<sup>6</sup> demonstrated substantially increased patellofemoral contact forces, particularly between 75° and 90° of flexion with increased patellar bone or implant thickness. Theoretically, this may result in early component loosening, increased wear, and anterior knee pain.

Whereas in vitro experiments showed adverse effects of increased PFO, clinical studies have not shown adverse outcomes.<sup>7,8</sup> It remains unclear whether increased PFO leads to abnormal loading of the patellofemoral compartment in vivo. The present study compared femoral component wear following TKA in implants with post-operative changes in PFO. The objective of this study was to determine if changes in PFO is a factor contributing to increased surface damage and wear in the patellofemoral joint.

## 3.2 Materials & Methods

### 3.2.1 Femoral Component Selection and Retrieval

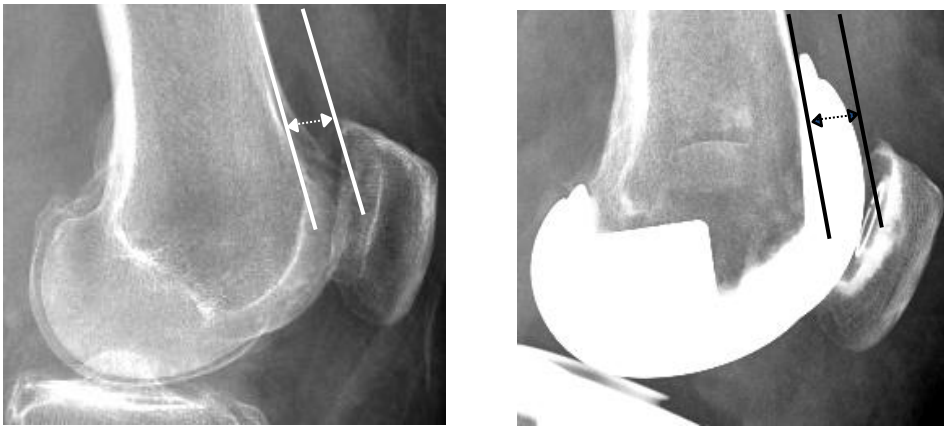
All Genesis II™ Cobalt Chromium femoral components (Smith & Nephew, Memphis, TN) in the LHSC Implant Retrieval Laboratory were reviewed. The Research Ethics Board provided approval for the implant and patient chart review. To be included, implants required to have pre-arthroplasty knee radiographs to allow for an assessment of changes in PFO. Implant information and patient medical records were reviewed, including revision diagnosis, time-in-vivo (TIV), and demographic data (age, sex, side, BMI). All implants were an identical design – cobalt-chromium, posterior stabilized, cemented components with fixed bearing design. The patella was resurfaced in all knees. All components were implanted between 2006 and 2010 by one of four arthroplasty surgeons. None of the components had an implantation time of less than one year.

### 3.2.2 Radiographic Measurements of Patellofemoral Offset

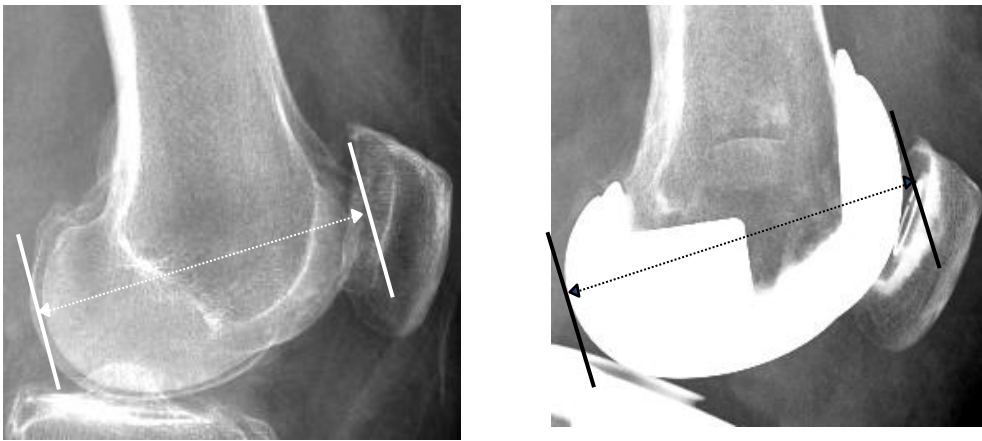
Lateral and skyline knee radiographs from standard preoperative and post-operative (1-3 years) visits were reviewed. Measurements were performed for the 10 retrieved implants. Anterior femoral offset and anteroposterior (AP) femoral size were measured on the lateral radiograph (Figures 3-1, 3-2).<sup>7,8</sup> The anterior femoral offset was measured as the distance between the anterior edge of the femoral cortex and the anterior aspect of the anterior femoral condyle. The AP femoral size was defined as the distance between the posterior condylar line and the anterior condylar line. Anterior patellar offset and patellar tilt were measured on the skyline radiographs (Figure 3-3). Anterior patellar offset was



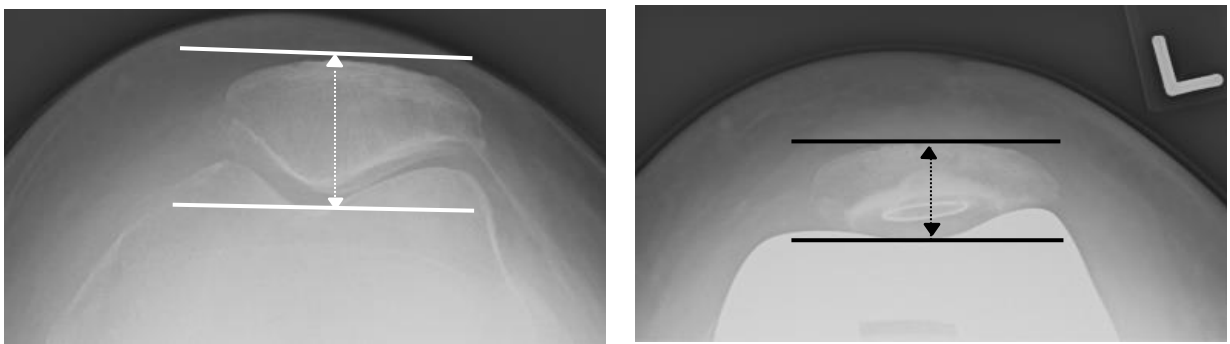
defined as the distance from the deepest part of the trochlear groove to the anterior cortex of the patella. Changes in PFO were quantified based on changes in the anterior femoral offset, AP femoral size, and anterior patellar offset. Calibration markers were not available for the radiographs and therefore percent change was used for each of the measurements. Implant with an increased (%) post-operative anterior femoral offset, AP patellar size, or anterior patellar offset were classified as having increased PFO. Other implants with no change (%) in the post-operative measurements were classified as maintained PFO. Finally, implants with decreased (%) measurements were classified as having decreased PFO.



**Figure 3-1. Measurement of Anterior Femoral Offset.**



**Figure 3-2. Measurement of AP Femoral Size.**



**Figure 3-3. Measurement of Anterior Patellar Offset.**

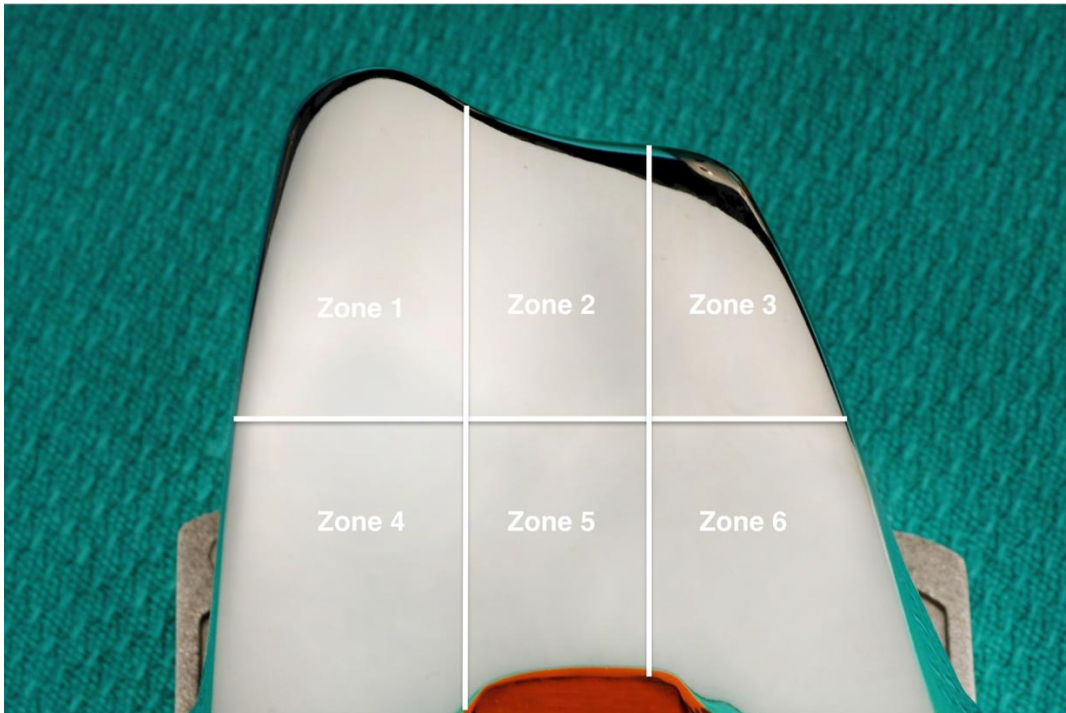
### 3.2.3 Surface Damage Quantification

In order to assess surface damage, the trochlea of each femoral component was divided into six zones in an identical pattern (Figure 3-4). These divisions were three zones in the coronal plane (lateral ridge, groove, and medial trochlea) for both the proximal and distal areas. Within each zone, the central area was outlined with a marker as a potential zone of patellofemoral contact, and the same areas were analyzed between components, in order to maintain consistency. The anterior-superior flange at the proximal end of the component was excluded due to possibility of inadvertent damage during extraction.

Visual inspection and low-magnification light microscopy were used for analysis. Both were carried out by two authors (JM and ZS). The scoring method utilized was previously outlined by Heyse<sup>9</sup>. Each zone was assigned a score of 0 or 1 based on the presence or absence of a particular damage feature. Identified damage modes included striations, scratches, pitting, and delamination. Striation consisted of very fine surface indentations. Scratches were defined as linear features that were slightly coarser than striations. Pitting was defined as cavity-like defect in the surface and delamination consisted of larger areas of damage where flat layers of metal were removed. A total damage score was calculated for each zone and each implant.

A non-contact light-profilometer (NT1100, WYKO Co., Tucson, AZ) was used to analyze the femoral components. In light profilometry, white light is used to produce a topographical image of the sample being analyzed.<sup>10, 11</sup> The system is equipped with a 10x objective and the vertical resolution of the system is less than 1nm. The reading length of each measurement was 238 $\mu$ m. The implants were cleaned with acetone before analysis. Parameters collected were  $R_a$ ,  $R_q$ ,  $R_p$ , and  $R_{sk}$ .<sup>12</sup>  $R_a$  is the gold standard to describe surface roughness. It represents the arithmetic mean of the surface profile, taking into account the absolute values of height deviation compared to a main line. As the average over one length, atypical peaks or valleys will be averaged out.<sup>13</sup> As such, lower  $R_a$  values represent a smoother surface.  $R_q$  is the root mean square deviation of the profile, another way to define surface roughness, and tends to be more affected by large

valleys or peaks.<sup>14</sup>  $R_p$  is the maximum profile peak height of the surface. Finally,  $R_{sk}$  is the skewness of the surface. It reflects the surface symmetry around a main line; a surface with positive skew has more peaks than valleys while a surface with a negative skew is the opposite<sup>15</sup>.



**Figure 3-4. The trochlea of each femoral component was divided into 6 zones in a consistent pattern. (Photograph taken at the LHSC Implant Retrieval laboratory)**

### 3.2.4 Statistical Analysis

The Mann-Whitney U test was used for comparing the visual damage scores between implants with increased PFO and implants with maintained or decreased PFO. Surface roughness scores based on profilometry in implants with increased PFO, and those with maintained or decreased PFO were also compared using the Mann-Whitney U test.

Finally, Spearman's correlation was used as an additional measure in order to assess for

an association between implant wear and PFJ offset changes. Statistical significance was considered for  $p < 0.05$ . The statistical analysis was carried out with IBM SPSS Version 23 (SPSS Inc., Chicago, IL).

### 3.3 Results

Ten implants were identified and used for the topographical analysis. Table 3-1 outlines the demographic profile of the ten retrieved femoral components, including TIV, age at revision, BMI, side, gender, and reason for revision.

The changes in post-operative compared to preoperative patellofemoral offset are outlined in Figure 3-5. The anterior femoral offset was increased in 4 implants ( $121.27\% \pm 47.02$ ), decreased in 5 implants ( $-35.33\% \pm 19.72$ ), and unchanged in 1 implant. The AP femoral size was increased in 4 implants ( $17.43\% \pm 12.14$ ), and decreased in 6 implants ( $-5.72\% \pm 4.17$ ). Anterior patellar offset was decreased in 9 implants ( $-19.77\% \pm 9.82$ ), and unchanged in 1. Across all components, the magnitude of change in anterior femoral offset, AP femoral size, anterior patellar offset, was, on average (SD),  $+7.72\%$  ( $57.59$ ),  $+3.54\%$  ( $14.20$ ), and  $-17.79\%$  ( $9.82$ ), respectively.

On visual inspection of the 10 retrieved femoral components, scratches (all 10 implants), pitting (9 implants), striations (10 implants), and delamination (5 implants) were observed. The total surface damage score for each implant is outlined in Figure 3-6. The average scores for scratching, striations, pitting, and delamination across all implants were:  $5.66 \pm 0.03$ ,  $2.20 \pm 0.16$ ,  $1.60 \pm 0.13$ ,  $0.50 \pm 0.08$ , respectively. Comparisons between visual damage scores and patellofemoral offset measurements were performed (Table 3-2). There was no significant association found between patellofemoral offset changes and total implant damage as determined by visual inspection (anterior femoral offset,  $p=0.803$ ; AP femoral size,  $p=0.517$ ). Furthermore, when subdivided into types of damage, no association was found in the rate of scratching ( $p=0.73$ ), striations ( $p=0.06$ ), pitting ( $p=0.28$ ), and delamination ( $p=0.41$ ) between implants with increased and maintained PFO.

**Table 3-1. Patient demographics.**

<b>TIV (years)</b>	2.8±1.5
<b>Age at revision (years)</b>	67.9±13.3
<b>BMI (kg/m<sup>2</sup>)</b>	40.4±13.2
<b>Gender</b>	6M 4F
<b>Side</b>	3 L, 7 R
<b>Reasons for revision</b>	Infection (6), Instability (2), Loosening (1), Fracture (1)

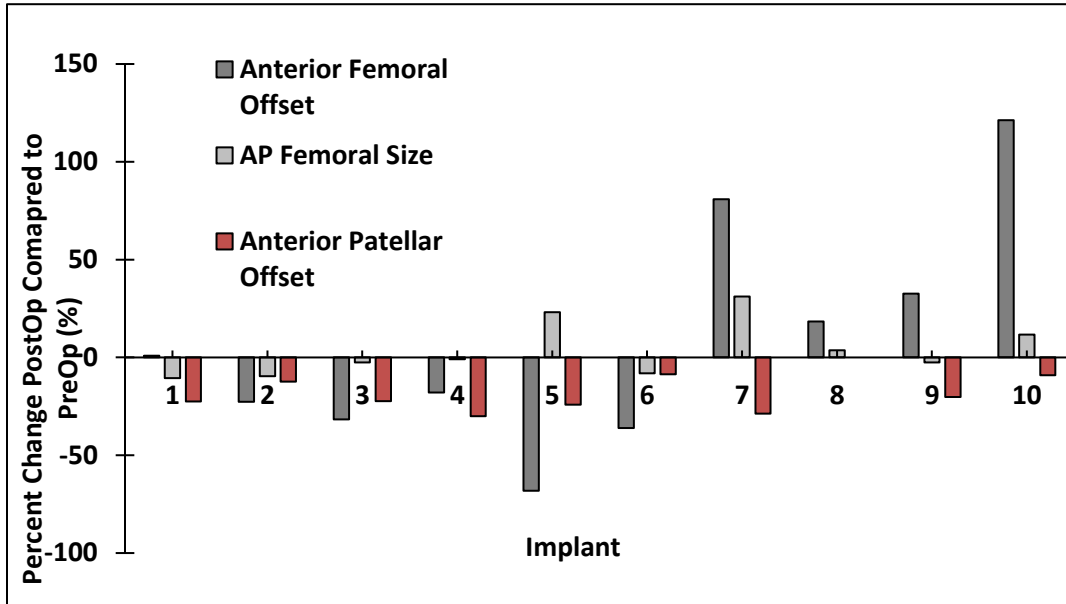


Figure 3-5. Changes in patellofemoral offset as based on anterior femoral offset, AP femoral size, and anterior patellar offset.

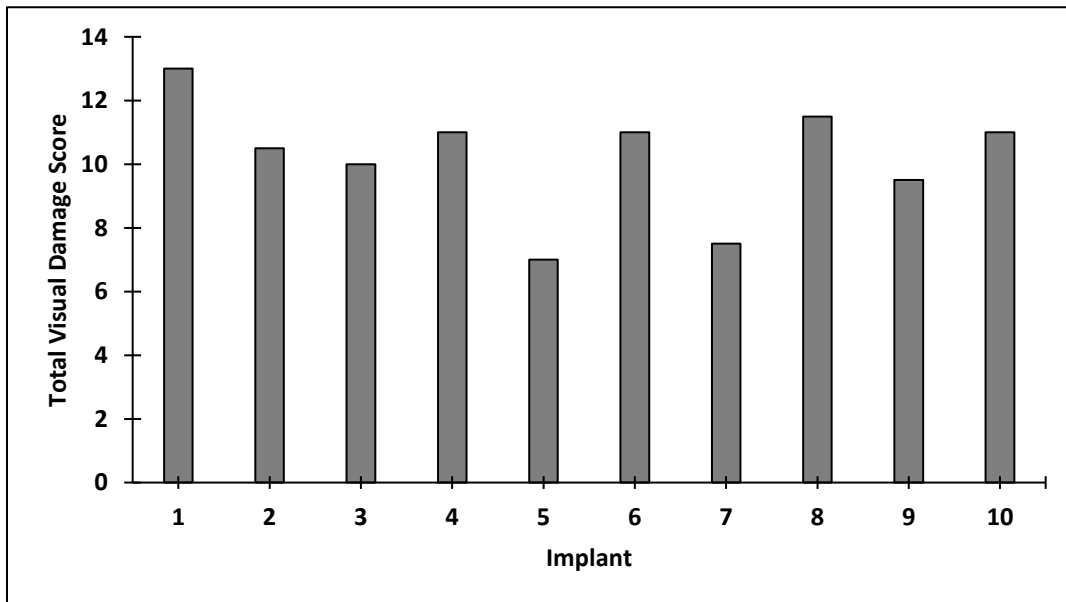


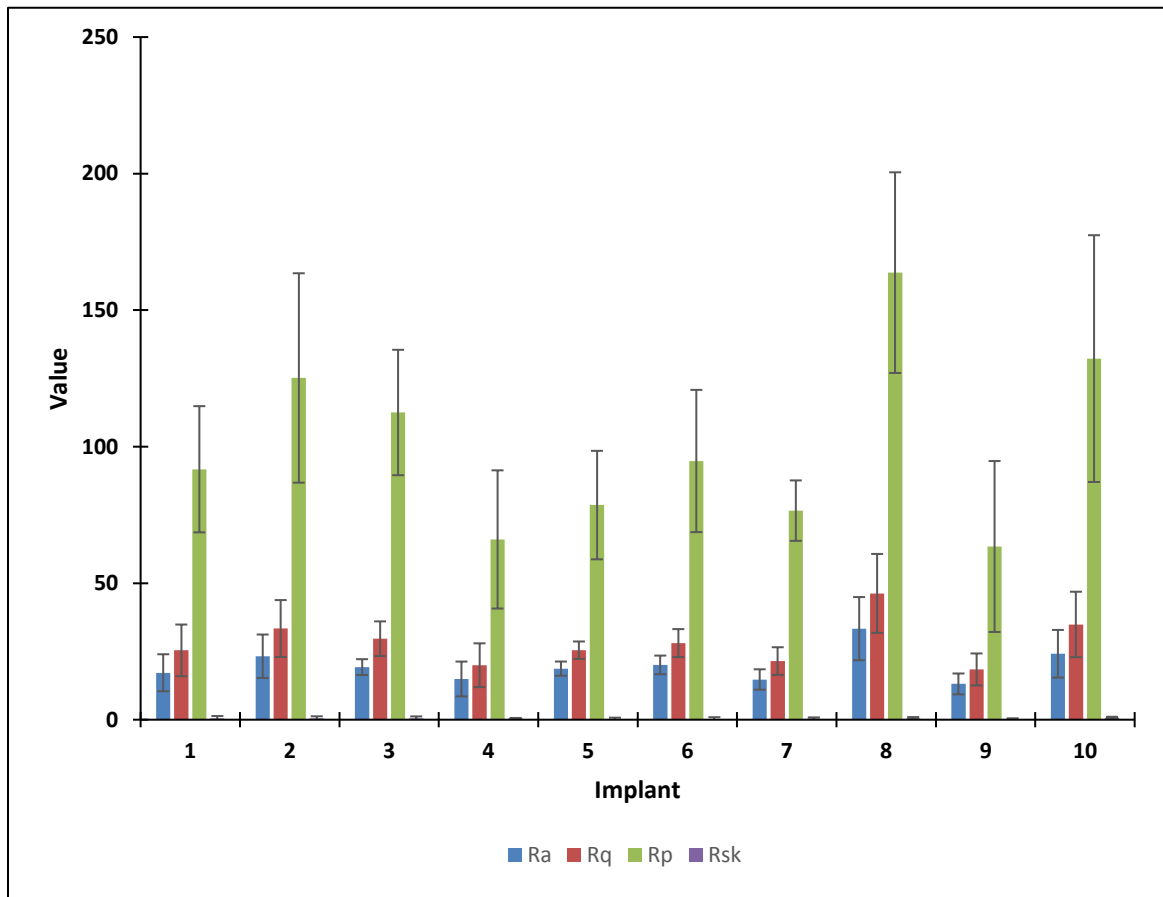
Figure 3-6. Total damage score based on visual assessment for each of the 10 retrieved implants.

**Table 3-2. Comparison of femoral component wear and surface damage based on visual assessment in implants with increased, maintained or decreased patellofemoral offset.**

<b><u>Parameters</u></b>	<b><u>Total Damage Score</u></b>	<b><u>p-value</u></b>
<b>Increased Anterior Femoral Offset</b>	5.25±1.79	NS p=0.803
<b>Maintained or Decreased Anterior Femoral Offset</b>	4.8±1.67	
<b>Increased AP Femoral Size</b>	4.75±2.32	NS p=0.517
<b>Maintained or Decreased AP Femoral Size</b>	6.0±1.21	
<b>Increased Anterior Patellar Displacement</b>	N/A	N/A
<b>Maintained or Decreased Anterior Patellar Displacement</b>	10.20±1.81	N/A



The roughness parameters ( $R_a$ ,  $R_q$ ,  $R_p$ ,  $R_{sk}$ ) for each of the implants are outlined in Figure 7. Comparisons of profilometry-based wear scores with PFO measurements are outlined in Table 3-3. Implants with increased patellofemoral offset, based on anterior femoral offset and AP femoral size, did not demonstrate increased wear rates compared to other implants ( $R_a$ ,  $p=0.90$  and  $p=0.39$ , respectively). Similarly, no significant correlations were found between anterior femoral offset changes ( $R_a$ ,  $r=-0.10$ ,  $p=0.77$ ;  $R_q$ ,  $r=-0.04$ ,  $p=0.90$ ;  $R_p$ ,  $r=0.01$ ,  $p=0.96$ ;  $R_{sk}$ ,  $r=0.40$ ,  $p=0.24$ ) or AP femoral size ( $R_a$ ,  $r=0.13$ ,  $p=0.70$ ;  $R_q$ ,  $r=0.09$ ,  $p=0.80$ ;  $R_p$ ,  $r=-0.38$ ,  $p=0.27$ ;  $R_{sk}$ ,  $r=-0.39$ ,  $p=0.26$ ) and wear rates.



**Figure 3-7. Surface roughness based on profilometry for each of the 10 retrieved implants.**

**Table 3-3. Comparison of femoral component wear based on profilometry in implants with increased, maintained, or decreased patellofemoral offset.**

<b><u>Parameters</u></b>	<b>R<sub>a</sub></b>	<b>R<sub>q</sub></b>	<b>R<sub>p</sub></b>	<b>R<sub>sk</sub></b>
<b>Increased Anterior Femoral Offset</b>	21.32±9.37	30.24±12.84	108.99±47.13	0.46±0.23
<b>Maintained or Decreased Anterior Femoral Offset</b>	18.89±2.80	26.98±4.55	94.79±21.61	0.38±0.15
<b>p-value</b>	p=0.90	p=0.83	p=0.83	p=0.67
<b>Increased AP Femoral Size</b>	22.72±8.06	32.01±11.02	45.29±24.40	0.45±.25
<b>Maintained or Decreased AP Femoral Size</b>	17.95±3.67	25.80±5.77	73.64±43.99	0.39±0.13
<b>p-value</b>	p=0.39	p=0.28	p=0.39	p=0.83
<b>Increased Anterior Patellar Displacement</b>	N/A	N/A	N/A	N/A
<b>Maintained or Decreased Anterior Patellar Displacement</b>	19.86±5.93	28.28±8.32	62.30±38.57	0.42±0.18
<b>p-value</b>	N/A	N/A	N/A	N/A

### 3.4 Discussion

Patellofemoral complications remain some of the most challenging problems following TKA. The rate of anterior knee pain with modern designs and technique is between 10% - 23%.<sup>2, 16</sup> Recent registry data suggests that up to 10% of TKA revisions are secondary to patellofemoral pain alone.<sup>17</sup> Abnormal loading or force distribution in the patellofemoral joint may contribute to adverse outcomes<sup>18</sup>, and evidence exists that changes in PFO can contribute to increased patellofemoral forces.<sup>19</sup> In the current study, we quantified the wear of the trochlea of retrieved Genesis II™ femoral components. In addition, we measured PFO changes based on pre- and post-operative radiographs. Our primary outcome was the influence of changes in the PFO on the visual surface damage and wear ratings and light profilometry readings of retrieved femoral components. Our analysis showed that there was no significant association between changes in PFO and implant wear or surface damage based on surface profilometry or visual assessment.

The consequences of changes in PFO have been previously studied with mixed findings.<sup>7, 8, 20-22</sup> Some, primarily cadaveric biomechanical studies, reported a marked effect of patellar thickness on patellofemoral joint compressive and shear forces.<sup>19-21</sup> Hsu<sup>20</sup> demonstrated in a cadaveric model that compared to knees with a neutral-sized patella, a thicker patella (2 mm) led to a substantial increase in patellofemoral contact force (174%). This finding was only significant in higher flexion angles. Kawahara<sup>19</sup> performed intra-operative measurements of patellofemoral joint contact forces in deep-flexion and found that upsized femoral components lead to increased mean patellofemoral forces. Both of these studies suggest that the greatest changes occur in deep flexion. On the other hand, Oishi<sup>21</sup> in a cadaveric modelling study found significantly increased patellofemoral shear and contact forces with 4 mm increased patellar thickness in as early as 45° of flexion. In the present study, wear was measured in the femoral trochlea, which articulates with the patella in low to mid-flexion angles.<sup>23</sup> In deeper flexion, the patella articulates mostly with the femoral condyles.<sup>23</sup> Based on the above studies, it is possible that the greatest difference in patellofemoral contact occur in deep-flexion and may explain the absence of changes in wear or surface damage in other

areas. Of note, the above studies used components of different designs, and it is possible that the design of the trochlea affected the particular angle and magnitude of the compressive and shear forces at the patellofemoral joint.

Only a few studies previously looked at retrieved femoral component roughness.<sup>9, 15, 24</sup> The  $R_a$  measurement is the standard for reporting surface roughness and represents the arithmetic mean. The roughness values range from 20 nm for new components and up to 190nm after in vivo use of cobalt-chromium metal components in the hip and knee.<sup>25-27</sup> Previous studies that examined the surface wear characteristics of retrieved femoral components focused on the femoral condyles.<sup>9, 24, 25</sup> In a comparative study of cobalt-chromium and oxidized-zirconium femoral components, Brandt<sup>24</sup> found a mean  $R_a$  of 14nm for new cobalt-chromium components and 26 nm for used cobalt-chromium components. With respect to the patellofemoral joint, we report mean  $R_a$  values of 20 nm for retrieved components, close to the values previously reported for the tibiofemoral joint. We are unaware of previous reports of trochlear wear.

The majority of the knees in our sample had a change in the PFO post-operatively. The majority had femoral-sided increases in PFO. Interestingly, in all but one knee, the anterior patellar offset was decreased post-operatively. It is possible that positive changes in femoral offset can be offset by negative changes in patellar offset. The inability to calibrate the images precluded us from being able to calculate a total PFO for each knee. Furthermore, it is possible that the amount of change in patellofemoral offset was not large enough to cause substantial forces to promote surface change to the femoral components. Ghosh<sup>22</sup>, in a cadaveric model, demonstrated that excess patellar thickness (4 mm) can lead to increased soft tissue tension of the extensor retinaculum. However, increases of patellar thickness up to 2 mm did not appear to make a difference, suggesting that it is likely possible to increase offset without substantial adverse effects on soft tissue tension and patellofemoral force.

Our study has a number of limitations. The visual damage rating system that was used is based on binary rating (0 or 1) for the presence or absence of each damage feature in each

zone. This rating system was previously described by Heyse<sup>9</sup> to quantify femoral component damage and has commonly been used in the literature. Although the sensitivity of the visual findings could be improved by use of a more detailed system, we did prove good reliability with this tool and have results that we could easily compare to the available literature. Secondly, when analysing trochlear zones by profilometry, readings were taken from small areas in each zone to represent the surface roughness of the entire zone. This was secondary to cost and feasibility restrictions that made it impossible to analyze the entire zone. Sampling areas within a zone has been previously done by other investigators.<sup>9,15,24</sup> While this is a limitation, the same areas were examined in each zone between components, adding to the consistency of the analysis. Furthermore, this drawback is balanced by the high precision of the analysis by profilometry.<sup>28</sup> The major strengths of this study are the homogenous group of implants and the availability of pre- and post-operative radiographs to allow the measurement of changes in PFO.

In conclusion, this study quantified patellofemoral joint surface damage following TKA in relation to changes in PFO. After short term follow-up, some wear was visually apparent throughout the trochlea, without a specific pattern. Our findings did not demonstrate an increase in surface wear in joints where PFO was increased. However, the majority of increases in PFO were femoral-sided only, and may have been offset by a decreased patellar offset. These findings highlight the difficulty of maintaining the PFO post-operatively but also show that small changes in PFO may not adversely affect patellofemoral contact post TKA.

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## Chapter 4

### 4 Patellofemoral Joint Surface Damage and Wear in Retrieved Femoral Components of a Single Design

*Outline: Optimizing the function of the patellofemoral joint in total knee arthroplasty requires an understanding of factors affecting joint kinematics. The design of the trochlea of the femoral component has been implicated as one of the factors. The goal of this chapter study was to obtain evidence regarding patellofemoral contact mechanics by studying surface damage and wear in the trochlea of femoral components of a single design.*

#### 4.1 Introduction

Despite significant advances in surgical technique, component design, and perioperative management, complications related to the patellofemoral joint continue to be a substantial source of patient morbidity following total knee arthroplasty (TKA).<sup>1</sup> Anterior knee pain affects up to 23% of knee replacements.<sup>2</sup> The etiology of anterior knee pain is likely multifactorial<sup>3</sup>, however, abnormal loading of the patellofemoral compartment may be contributory to adverse patient outcomes.<sup>4</sup>

Patellofemoral kinematics can be influenced by a number of factors.<sup>3</sup> One of the main factors is trochlear design.<sup>5</sup> Trochlear design has played a substantial role in TKA improvement over the past two decades and certain design modifications have been termed “patella-friendly”.<sup>1</sup> In many modern designs, the trochlea was extended proximally to ensure that the patella enters the trochlear groove properly.<sup>5</sup> The trochlear groove depth was increased and the lateral flange was raised to minimize tracking abnormalities.<sup>6-8</sup> Overall, a balance is sought between conformity and the freedom of the patella to align itself in the groove.

Since abnormal kinematics likely contribute to anterior knee pain and other patellofemoral complications<sup>9</sup>, understanding which features of trochlear design can

contribute to increased patellofemoral loading and subsequent wear remains important. The objective of the present study was to examine patellofemoral joint contact by analyzing areas of joint wear, with focus on retrieved femoral components of a single design.

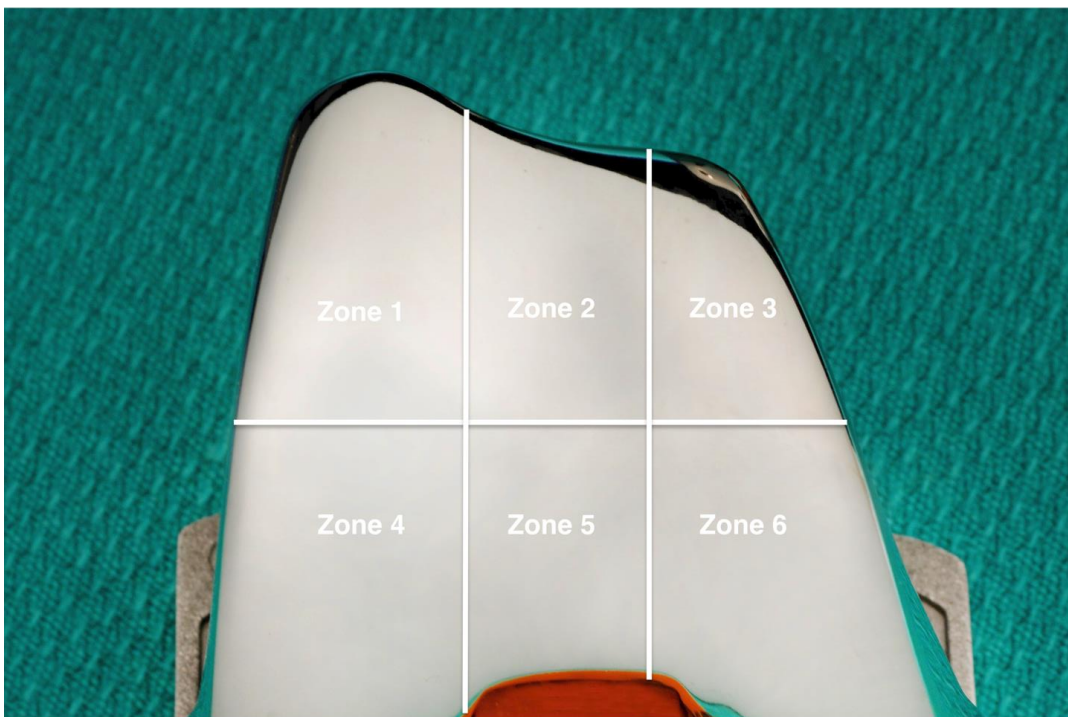
## 4.2 Materials & Methods

A retrospective review of all Genesis II™ Cobalt Chromium femoral components (Smith & Nephew, Memphis, TN) at the LHSC Implant Retrieval Laboratory was performed. Approval for the implant and patient chart review was obtained from the Research Ethics Board. All selected implants were with an identical design – cobalt-chrome, posterior stabilized, cemented components with fixed bearing design that articulated against a resurfaced patella. None of the implants had an implantation time of less than one year. Components were implanted between 2006 and 2010 by one of four arthroplasty surgeons. Patient medical records were reviewed, including revision diagnosis, time-in-vivo, and demographic data (age, sex, side, BMI).

For the purposes of analysis, the trochlea of each femoral component was divided into six zones in a consistent pattern (Figure 4-1). These divided the trochlea into the lateral ridge zone, the trochlear groove, and the medial trochlea. These zones were then subdivided into proximal and distal areas. This allowed to quantify whether the lateral flange area experiences more wear compared to a deeper recessed zone, such as the central area, as well as compare proximal and distal surface damage and wear. Within each zone, to ensure consistency between components, the central area was outlined as a potential area of patellofemoral contact. As such, the same areas were analyzed in each implant in order maintain consistency between components. The anterior-superior flange at the proximal end of the component was excluded due to possibility of inadvertent damage during explanation and given its decreased patellofemoral contact

The retrieved implants were inspected visually as well as using light microscopy. The visual inspection was carried out by two authors (JM and ZS) utilized a scoring method outlined by Heyse.<sup>10</sup> Identified damage modes included striations, scratches, pitting, and

delamination. Striation consisted of very fine indentations in the surface of the component. Scratches were defined as linear features that were coarser than striations. Pitting was defined as cavity-like defect in the surface of the component. Finally, delamination consisted of larger areas of damage where layers of metal were removed. Each zone was assigned a score of 0 or 1 based on the presence or absence of the particular damage feature. A total damage score was calculated for each zone.



**Figure 4-1. The trochlea of each femoral component was divided into 6 zones in a consistent pattern. (Photograph taken at the LHSC Implant Retrieval Laboratory)**

To establish an accurate assessment of the implant surface roughness, three dimensional light profilometry was utilized. A non-contact light-profilometer (NT1100, WYKO Co., Tucson, AZ) was used to analyze each of the femoral components. Light profilometry uses white light to produce a topographical image of the sample being analyzed.<sup>11, 12</sup> The system is equipped with a 10x objective. The vertical resolution of the system is less than 1nm. The reading length of each measurement was 238 $\mu$ m. The implants were cleaned with acetone before analysis. Parameters collected were  $R_a$ ,  $R_q$ ,  $R_p$ , and  $R_{sk}$ .<sup>13</sup>  $R_a$  represents the arithmetic mean of the surface profile. It takes into account the absolute values of height deviation compared to a main line. It is the average over one length, and atypical peaks or valleys will be averaged out.<sup>14</sup> As such, lower  $R_a$  values represent a smoother surface.  $R_q$  is the root mean square deviation of the profile, another way to define surface roughness, and is more affected by large valleys or peaks.<sup>15</sup>  $R_p$  is the average maximum profile peak height of the surface. Finally,  $R_{sk}$  is the skewness of the surface. It reflects the surface symmetry around a main line; a surface with positive skew has more peaks than valleys while a surface with a negative skew is the opposite.<sup>16</sup> A new, unused, CoCr Genesis II™ femoral component (Smith & Nephew, Memphis, TN) was used for reference measurements. One or two measurements were taken in each zone outlined on the trochlea.

The statistical analysis was carried out with IBM SPSS Version 23 (SPSS Inc., Chicago, IL). The Kruskal-Wallis test was used to compare the surface damage scores on visual assessment between the various zones of the trochlea. The Mann-Whitney U test was used to assess for differences in surface roughness between the reference and retrieved femoral components. Finally, the Kruskal-Wallis test was also used to compare the surface roughness scores in the various zones of the trochlea based on surface profilometry. Statistical significance was considered for  $p < 0.05$ .

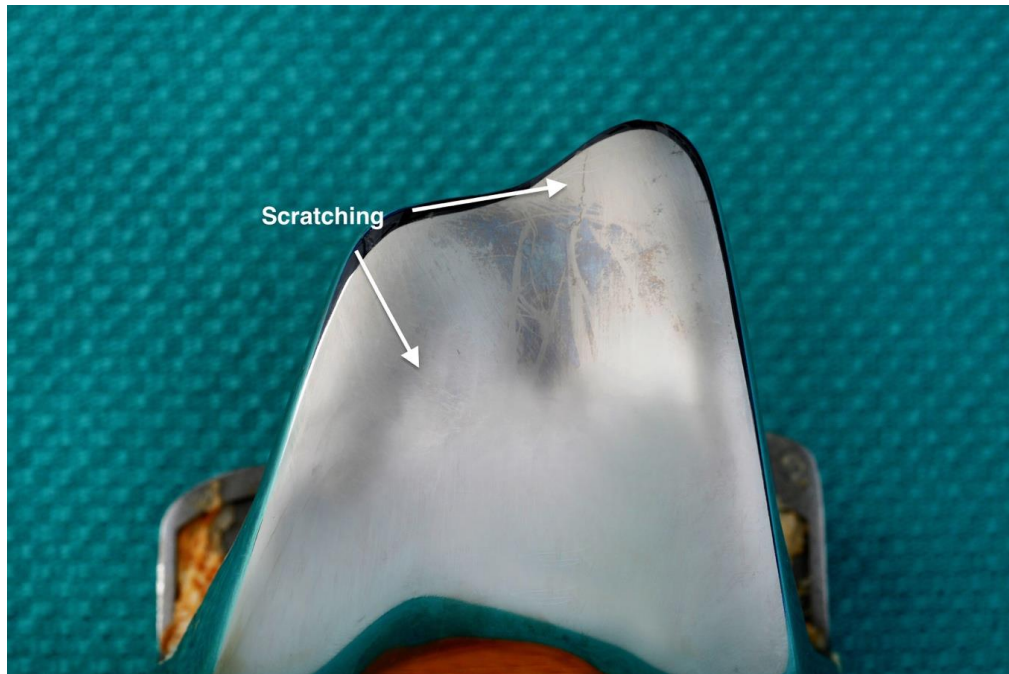
### 4.3 Results

Ten implants were selected for analysis. Patient demographics, including time-in-vivo, BMI, patient age, side, and gender are outlined in Table 4-1. Revision diagnosis across the implants were infection (n=6), instability (n=2), loosening (n=1), and fracture (n=1).

**Table 4-1. Patient demographics.**

<b>TIV (years)</b>	2.8±1.5
<b>Age at revision (years)</b>	67.9±13.3
<b>BMI (kg/m<sup>2</sup>)</b>	40.4±13.2
<b>Gender</b>	6M 4F
<b>Side</b>	3 L, 7 R
<b>Reasons for revision</b>	Infection (6), Instability (2), Loosening (1), Fracture (1)

On visual inspection of the retrieved femoral components, scratches were the principal form of damage seen in all implants (100% of zones), followed by striations and pitting (65% and 43% of zones examined). The scratches were seen in multiple directions (Figure 4-2). Only one component showed extensive evidence of delamination (Figure 4-3). On average, across all zones, there was significantly more scratching than delamination ( $p=0.001$ ) or pitting ( $p=0.047$ ). Specifically, within zone 1, there were significantly more scratches than delamination ( $p=0.001$ ). Within zones 2, 3, 5, and 6 there were significantly more scratches than striations ( $p=0.016$ ), pitting ( $p=0.002$ ), or delamination ( $p=0.001$ ). In zone 4, scratches were more common than pitting ( $p=0.002$ ) or delamination ( $p=0.001$ ). Overall, there was no evidence of any particular zone having more scratching ( $p=0.74$ ), striations ( $p=0.74$ ), pitting ( $p=0.18$ ), or delamination ( $p=0.27$ ) than the other zones.



**Figure 4-2. Damage notable on the trochlear surface of retrieved femoral components. (Photograph taken at the LHSC Implant Retrieval Laboratory)**



**Figure 4-3. Damage notable on the trochlear surface of retrieved femoral components. (Photograph taken at the LHSC Implant Retrieval Laboratory)**

Table 4-2 contains the total damage scores for the different zones of the trochlea of retrieved femoral components. The average total surface damage score was  $2.15 \pm 0.44$  for zone 1,  $1.85 \pm 0.39$  for zone 2,  $1.7 \pm 0.43$  for zone 3,  $1.7 \pm 0.44$  for zone 4,  $1.06 \pm 0.41$  for zone 5, and  $1.5 \pm 0.42$  for zone 6 for all retrieved components. Zone 1, which includes the raised lateral flange, tended to have more damage but this was statistically non-significant ( $p=0.63$ ). Overall, there were no statistical differences between zones with respect to overall damage ( $p=0.63$ ). When grouped into lateral, central, and medial zones, there was no clear difference with respect to medio-lateral asymmetry in wear ( $p=0.57$ ). Furthermore, when grouped into proximal and distal zones, no significant differences in total damage were noted ( $p=0.17$ ).

**Table 4-2. Visual assessment scores of damage modes in each zone of the trochlea of retrieved femoral components.**

<b>Parameter</b>	<b>Zone 1</b>	<b>Zone 2</b>	<b>Zone 3</b>	<b>Zone 4</b>	<b>Zone 5</b>	<b>Zone 6</b>
<b>Scratches</b>	1±0	0.95±1.18	0.95±0.15	0.95±0.16	0.91±0.21	0.9±0.21
<b>Delamination</b>	0.1±0.21	0.2±0.34	0.15±0.33	0.05±0.35	0±0.21	0±0.35
<b>Pitting</b>	0.5±0.40	0.3±0.25	0.2±0.34	0.25±0.35	0.1±0.21	0.25±0.35
<b>Striations</b>	0.55±0.43	0.4±0.31	0.4±0.31	0.45±0.36	0.05±0.34	0.35±0.33
<b>Total Score*</b>	2.15±0.44	1.85±0.39	1.7±0.43	1.7±0.44	1.06±0.41	1.5±0.42

**\* No statistical differences were noted between the individual zones of the trochlea ( $p=0.63$ ).**

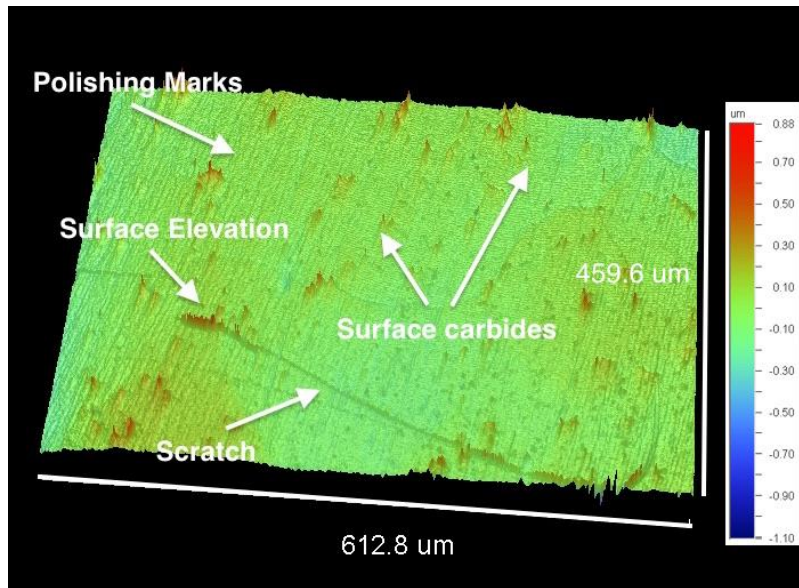
Using light profilometry, we compared the surface roughness values between the trochlea of the reference and retrieved femoral components (Table 4-3). Residual polishing marks, carbide peaks, and scratching were notable on the surface of the new component (Figure 4-4). There was evidence of wear and scratching on the surface of the retrieved components (Figure 4-5). No statistically significant differences were seen in  $R_a$  ( $p=0.18$ ),  $R_q$  ( $p=0.74$ ),  $R_p$  ( $p=0.09$ ), or  $R_{sk}$  ( $p=0.06$ ) of the trochlea of retrieved components when compared with the same areas in the reference implants.

Surface roughness measurements based on light profilometry of retrieved femoral components are outlined in Table 4-4. Light profilometry of retrieved femoral components revealed no significant differences in the roughness parameters between the individual zones of the trochlea ( $R_a$ ,  $p=0.46$ ;  $R_q$ ,  $p=0.43$ ;  $R_p$ ,  $p=0.60$ ,  $R_{sk}$ ,  $p=0.18$ ). Comparisons of the lateral flange area, the recessed central zone, and the medial zones of the trochlea did not show significant differences in the measured roughness parameters ( $R_a$ ,  $p=0.14$ ;  $R_q$ ,  $p=0.16$ ;  $R_p$ ,  $p=0.36$ ;  $R_{sk}$ ,  $p=0.13$ ). Additionally, no significant differences ( $R_a$ ,  $p=0.77$ ;  $R_q$ ,  $p=0.67$ ;  $R_p$ ,  $p=0.89$ ;  $R_{sk}$ ,  $p=0.08$ ) were found between proximal and distal wear.

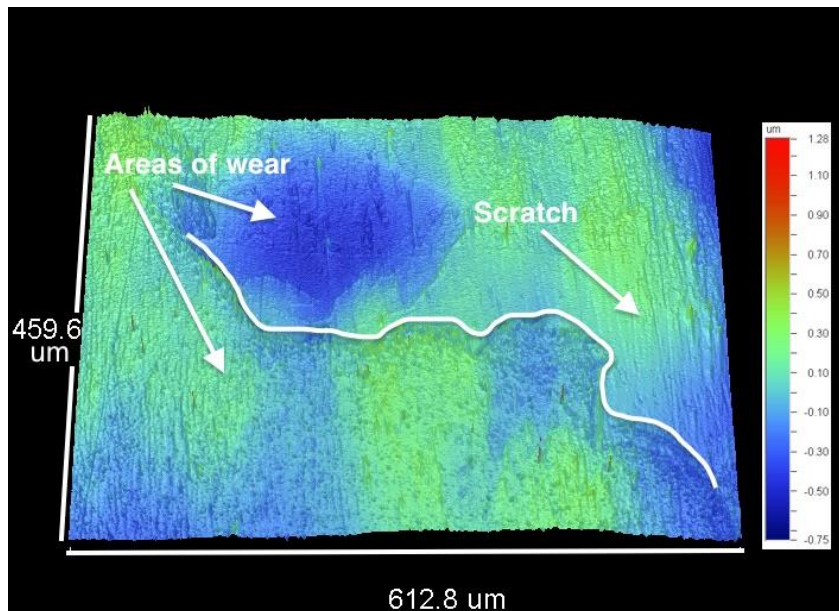
**Table 4-3. Comparison of surface roughness parameters between the reference and retrieved femoral components.**

	<u>Surface Parameter</u>			
	$R_a$ (nm)	$R_q$ (nm)	$R_p$ (nm)	$R_{sk}$
<b>Reference Component</b>	19.22±3.37	102.15±20.56	26.92±4.43	0.87±0.31
<b>Retrieved Components</b>	18.65±2.23	94.80±12.70	26.76±3.21	0.41±0.37
<b>p-value</b>	NS $p=0.52$	NS $p=0.74$	NS $p=0.42$	NS $p=0.06$





**Figure 4-4. Surface profile of the trochlea of a new Genesis II™ femoral component. A scratch is notable on the surface. The direction of surface polishing and surface carbides are visible.**



**Figure 4-5. Surface profile of the trochlea of a retrieved Genesis II™ femoral component. Notable surface features are substantial wear in the lower zone of the image and scratching.**

**Table 4-4. Comparison of surface roughness parameters between trochlear zones in retrieved femoral components.**

<b>Surface Parameter</b>	<b>Zone 1</b>	<b>Zone 2</b>	<b>Zone 3</b>	<b>Zone 4</b>	<b>Zone 5</b>	<b>Zone 6</b>	<b>p-value</b>
<b>R<sub>a</sub>(nm)</b>	22.46±7.58	19.15±10.04	18.59±7.22	21.25±7.39	20.73±10.57	16.98±6.53	NS 0.46
<b>R<sub>q</sub>(nm)</b>	32.87±11.12	26.72±13.04	26.74±9.82	30.34±10.63	29.02±13.63	24.02±9.49	NS 0.43
<b>R<sub>p</sub>(nm)</b>	114.54±48.90	89.71±44.22	99.76±38.72	109.40±38.55	101.74±41.45	87.65±38.78	NS 0.60
<b>R<sub>sk</sub></b>	0.03±0.72	0.18±0.56	0.58±0.56	0.51±0.33	0.49±0.47	0.70±0.29	NS 0.18

## 4.4 Discussion

Following TKA, the patellofemoral joint consists of an articulation between the trochlea of the femoral component and either a native or resurfaced patella. The trochlea of the femoral component articulates with the patella in low to mid flexion angles, which encompasses most day-to-day activities.<sup>17</sup> The design of the prosthetic patella and trochlea can therefore have a significant effect on tracking, loading, and overall biomechanics of the patellofemoral joint. Trochlear design has evolved substantially<sup>18</sup>, with present designs attempting to obtain an equilibrium between patellofemoral conformity and the freedom of the patella to align itself.<sup>18</sup> Features of the prosthetic trochlea that have been included in modern designs are a raised lateral flange, deepened trochlear groove, proximal extension of the trochlea, and a gradual transition at the superior end of the box.<sup>5-8</sup>

Previous studies used profilometry to examine the surface wear characteristics of the femoral condyles of retrieved femoral components. With respect to the patellofemoral joint, while the patterns of patellar polyethylene wear were previously reported<sup>24</sup>, we are unaware of previous reports specific to trochlear wear. In the present study, we found that after short term use (average TIV 33.6 months), the trochlear roughness is not significantly different than in its new state. However, some damage was noted, primarily in the form of scratches. We did not find any significant differences in patellofemoral wear between the different zones of the trochlea. From a surface wear standpoint, this study did not reveal any particularly adverse wear or damage with the current design, and prominent areas, such as over the lateral flange, did not appear particularly damaged.

In the Genesis II™ prosthesis, trochlear design features include a raised lateral flange and a deepened and lateralized trochlear groove.<sup>19</sup> From a theoretical standpoint, while increasing the conformity between the patella and trochlea may increase surface area and improve tracking<sup>20</sup>, the downside may be increased shear forces, wear, and pain.<sup>21, 22</sup> Furthermore, deepening the trochlear groove to increase conformity must be balanced against the possibility of decreasing the moment arm of the quadriceps or creating

instability.<sup>21</sup> The majority of the evidence suggests that a certain degree of increased conformity is beneficial. Yoshii<sup>6</sup> performed an in vitro comparison of various trochlear designs and found that a deepened trochlear groove and a raised lateral ridge allowed the patellar button to be constrained in the groove and minimized tracking abnormalities. Petersilge<sup>7</sup> found that increased conformity did not result in increased shear forces, and instead, decreased total shear forces were found with a deeper, more congruent trochlea. This was attributed to decreased tension on the lateral retinaculum as well as the more uniform shape of the deeper trochlea. Using a finite element model of the knee, D'Lima<sup>23</sup> found that compared to a 0° trochlea, introducing a 7° valgus angle to the trochlea reduced the lateral shear forces at <20°, but forces were essentially the same at 90° of flexion. Likely the ideal design is a compromise between conformity and the ability of the patella to align itself in the groove.

Although the femoral component is substantially harder than the patellar polyethylene surface it articulates with, some damage of the trochlea was still visually notable. Visual analysis of the retrieved femoral components showed that the damage pattern is multidirectional, likely secondary to the nonlinear pattern of movements of the patella. Indeed, previous studies of patellar tracking have demonstrated an exaggerated rotational and translational movement of the patella following TKA<sup>25-27</sup>, likely contributing to multidirectional wear.

This study did not find any significant differences between the reference component roughness and the retrieved component roughness, in fact, the reference component roughness parameters tended to be slightly higher than the retrieved components ( $R_a$ ,  $R_q$ , and  $R_p$  non-statistically significant). This suggests that the surface finish of the trochlea did not appear to substantially deteriorate after in-vivo use, and furthermore, the trochlea in retrieved components may experience polishing during in-vivo use.

This study has a number of limitations. Firstly, the retrieved components were compared to a single reference component. This analysis relied on the assumption that the reference component that was used for comparison was a truly representative sample. Given that

this was an unused, new component, this assumption was felt to be reasonable. Secondly, the visual damage rating system used, previously utilized by Heyse<sup>10</sup>, was based on a binary score (0 or 1) for the presence or absence of each damage feature in each zone. This rating system has commonly been used in the literature. Although the sensitivity of the visual findings could be improved by use of a more detailed system, we did prove good reliability with this tool and have results that we could easily compare to the available literature. Thirdly, surface profilometry was carried out in a sample area within each zone to characterize the surface roughness of the entire zone. This limitation was secondary to cost and feasibility restrictions and is offset by the consistent sampling of areas between samples and the high precision of the analysis by profilometry.<sup>28</sup> Finally, our wear findings are specific to the design of the Genesis II™ implant and cannot be extrapolated to other designs. The major strength of the present study was our ability to examine patellofemoral joint surface damage in a homogeneous group of components with similar patient demographics.

Patellofemoral complications, particularly anterior knee pain<sup>1, 2</sup>, are prevalent after TKA. Abnormal loading or force distribution affecting the patellofemoral joint may contribute to adverse outcomes.<sup>9</sup> The kinematics of the patellofemoral joint are influenced by multiple parameters<sup>18</sup>. One of the most important factors is trochlear design<sup>5</sup>. Although modern components have benefitted from substantial design improvements, the optimal design for the trochlea to optimize function is still undetermined. Nevertheless, the features of this specific design did not appear to compromise tribology, while offering theoretical advantages to the patellofemoral joint.

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## Chapter 5

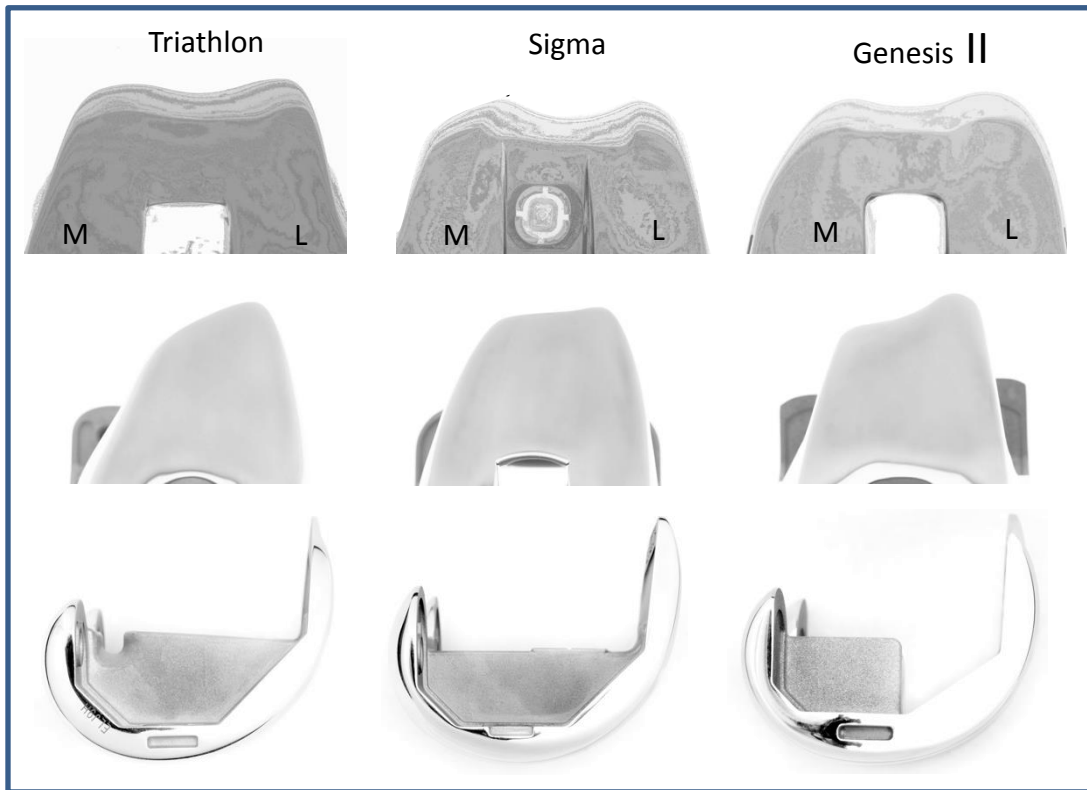
# 5 Differences in Trochlear Surface Damage and Wear Between Three Different Total Knee Arthroplasty Designs

*Outline: Trochlear design plays a role in patellofemoral kinematics. The optimal design is currently unknown, and modern implants have a wide variety of geometries. The purpose of this chapter was to study the association between trochlear design and patellofemoral contact by analyzing areas of joint surface damage and wear, with a focus on retrieved femoral components of three modern designs.*

### 5.1 Introduction

The most effective treatment of debilitating knee pain associated with degenerative joint disease is total knee arthroplasty (TKA).<sup>1</sup> Despite significant advances in surgical technique, component design, and perioperative management, complications related to the patellofemoral joint continue to be a substantial source of patient morbidity, causing anterior knee pain, instability, and dysfunction following TKA.<sup>2</sup> As such, insights into the mechanisms and causes of patellofemoral complications are critical to improving the outcomes of TKA.

Patellofemoral kinematics can be influenced by a number of factors.<sup>3</sup> One of the principle factors is trochlear design.<sup>4</sup> Modern implants incorporate “patella-friendly” design elements (Figure 5-1). For example, the Triathlon® (Stryker, Mahwah, NJ) features an asymmetric trochlear design with a raised lateral flange and approximately 6° of valgus built in the trochlear axis.<sup>5</sup> The trochlea of the Sigma® (Johnson & Johnson, Raynham, Massachusetts) features a femoral component with a deepened and extended trochlear groove and a raised lateral epicondylar ridge for improved patellar tracking.<sup>6</sup> Similarly, the Genesis II™ (Smith & Nephew, Memphis, TN) trochlea also features an asymmetric trochlea with valgus orientation and increased depth in order to reproduce the height of the native trochlea.<sup>7</sup>



**Figure 5-1. AP, axial, and sagittal photographs of Triathlon® (Stryker, Mahwah, NJ), Sigma® (DePuy, Warsaw, IN), and Genesis II™ (Smith & Nephew, Memphis, TN) femoral components. Modern components share common features, such as proximal extension of the trochlea, raised lateral trochlear flange, lateralized groove, and deepened trochlea. M = medial, and L= lateral. (Photograph taken at the LHSC Implant Retrieval Laboratory)**

While similarities in the design features exist, the exact geometry varies between implants and the optimal trochlear design has not been established.<sup>4</sup> For example, while some studies showed that an asymmetric trochlea is beneficial for reducing medial-lateral shear forces<sup>8</sup>, a more recent cadaveric modeling study found that an asymmetric trochlea, designed to more closely reproduce native anatomy, did not improve kinematics and stability compared to a symmetric trochlea<sup>5</sup>. Aside from the design of the trochlea itself, factors such as the radius of the component may significantly affect patellofemoral kinematics. The Triathlon® is single radius of curvature implant while the Sigma® and Genesis II™ are multi-radius implants. Some *in vitro* biomechanical studies showed use of a single radius of curvature design leads to lower patellofemoral and quadriceps forces, primarily by shifting the center of rotation more posteriorly.<sup>9</sup> While there are some theoretical benefits to single-radius designs, these have not been proven in practice.<sup>10, 11</sup>

Understanding the implications of trochlear design on patellofemoral contact and wear remains important and may provide insights for design optimization. The objective of the present study was to study patellofemoral joint contact by analyzing areas of joint wear and surface damage, with focus on retrieved femoral component of three different modern designs.

## 5.2 Materials & Methods

### 5.2.1 Femoral Component Retrieval

A review of all retrieved Triathlon® (Stryker, Mahwah, NJ), Sigma® (DePuy, Warsaw, IN), and Genesis II™ (Smith & Nephew, Memphis, TN) femoral components in the LHSC Implant Retrieval Laboratory was performed. Approval for the implant and patient chart review was obtained from the Research Ethics Board. The implants were matched based on time-in-vivo (TIV), BMI, patient age and gender. All implants were cobalt-chromium, posterior stabilized, cemented components with a fixed bearing design. The patella was resurfaced in all knees. None of the implants had an implantation time of less

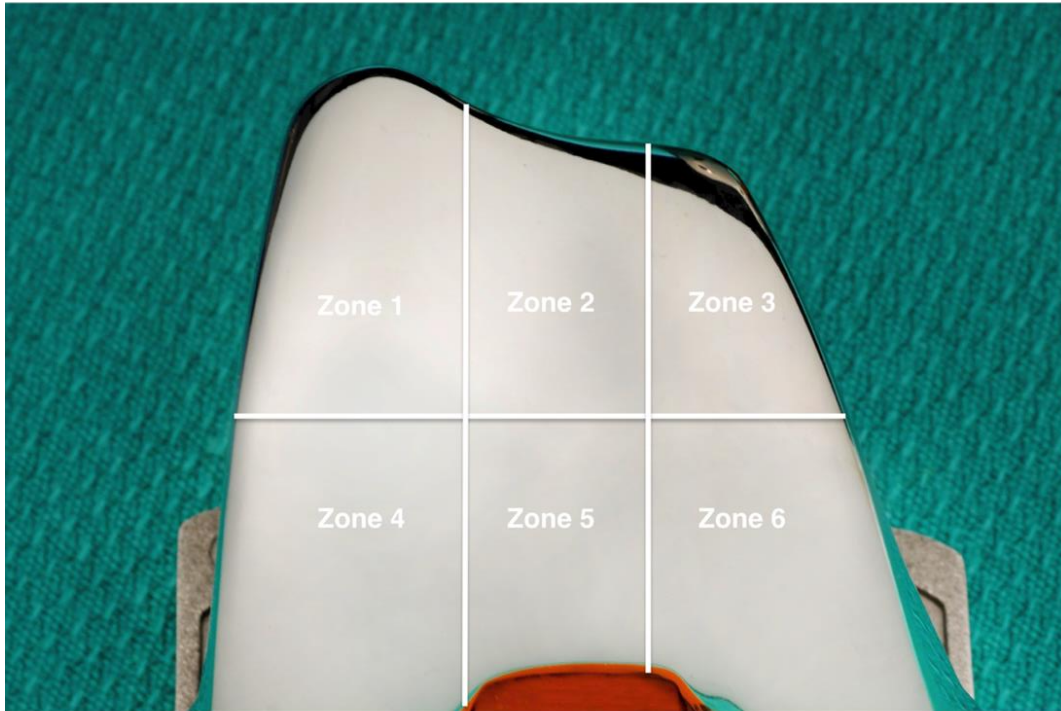
than one year. Components were implanted between 2006 and 2014 by one of eight fellowship trained arthroplasty surgeons.

## 5.2.2 Surface Damage and Wear Quantification

The retrieved implants were inspected visually and analyzed with surface profilometry. In order to examine the trochlea systematically, the trochlea of each femoral component was divided into six zones in a consistent pattern (Figure 5-2). There were three zones in the medial-lateral direction and a proximal and distal zone. The zones in the medial-lateral direction were chosen to separate the lateral prominence, the groove, and medial trochlea. The distinction in proximal and distal zones was created to allow a comparison of wear and surface damage in early flexion (proximal) and mid-deep flexion (distal). Within each zone, a pre-set area was outlined with a marker to identify a zone of patellofemoral contact. Approximately the same areas were analyzed in order maintain consistency between components. The anterior-superior flange at the proximal-lateral end of the component was excluded due to possibility of inadvertent damage during explantation.

Visual inspection of the components was carried out by two authors (JM and ZS). We utilized a scoring method outlined by Heyse.<sup>12</sup> Identified damage modes included striations, scratches, pitting, and delamination. Striation consisted of very fine indentations in the surface of the component. Scratches were defined as linear features that were coarser than striations. Pitting was defined as cavity-like defect in the surface of the component. Finally, delamination consisted of larger areas of damage where layers of metal were removed. Each zone was assigned a score of 0 or 1 based on the presence of absence of the particular damage feature. A total damage score was calculated for each zone as well as each component.

Surface roughness of each femoral component was assessed using a light profilometer (NT1100, WYKO Co., Tucson, AZ). Light profilometry uses white light to produce a topographical image of the sample being analyzed.<sup>13, 14</sup> The system has a 10x objective and has a vertical resolution of less than 1nm. The reading length of each measurement was set to 238 $\mu$ m. Four surface roughness parameters were collected:  $R_a$ ,  $R_q$ ,  $R_p$ , and



**Figure 5-2. The trochlea of each femoral component was divided into 6 zones in a consistent pattern. (Photograph taken at the LHSC Implant Retrieval Laboratory)**

$R_{sk}$ .<sup>15</sup> In surface topography,  $R_a$  is the “gold standard” and represents the arithmetic mean of the surface profile. In determining  $R_a$ , the absolute values of height deviation compared to a main line are calculated and an average is produced over one length.<sup>16</sup> Therefore, lower  $R_a$  values correspond to a smoother surface.  $R_q$  is the root mean square average of the profile height.  $R_q$  is more susceptible than  $R_a$  to be affected by peaks or valleys and therefore provides useful information regarding the surface profile in addition to  $R_a$ .<sup>17</sup>  $R_p$  is the maximum peak height in the roughness profile of the evaluated surface.  $R_{sk}$  is the skewness of the surface and it reflects the surface symmetry around a main line. A surface with positive skew has more peaks while a surface with a negative skew is the opposite.<sup>18</sup> Between one and two measurements were taken in each zone outlined on the trochlea. New unused, CoCr Triathlon®, Sigma®, and Genesis II™ femoral components were used for reference measurements.

### 5.2.3 Statistical Analysis

The statistical analysis was carried out with IBM SPSS Version 23 (SPSS Inc., Chicago, IL). Demographic characteristics between groups were compared using a one-way ANOVA. The Kruskal-Wallis test was used to compare visual damage scores between groups. The Mann-Whitney U test was used to compare differences in wear and surface damage parameters between retrieved and reference components. Surface roughness values in retrieved components were compared using the Kruskal-Wallis test. To conduct pair-wise comparisons between groups, the Kruskal-Wallis test was followed by post hoc testing with a Dunn-Bonferroni correction. Statistical significance was considered for  $p < 0.05$ .

### 5.3 Results

Six implants from each group were successfully matched and were used for the topographical analysis. The demographic profile of the retrieved femoral components is outlined in Table 5-1. Infection was the most common reason for revision ( $n=13$ ) followed by femoral-tibial instability ( $n=3$ ). There were no significant differences in TIV ( $p=0.36$ ), age ( $p=0.82$ ), and BMI ( $p=0.58$ ) between the groups of components.

On visual inspection of the retrieved femoral components, scratches were the principal form of damage seen in all implants (93% of zones), followed by pitting and striations (42% and 40% of zones examined respectively). The average total surface damage score was  $9.80 \pm 1.25$ ,  $10.00 \pm 1.87$ , and  $10.50 \pm 2.00$  for the Triathlon®, Sigma®, and Genesis II™ components, respectively. Overall, visual analysis did not reveal any significant differences between the groups with respect to total surface damage ( $p=0.68$ ). With respect to specific damage modes, no significant differences between the groups were noted in scratches ( $p=0.06$ ), striations ( $p=0.50$ ), pitting ( $p=0.97$ ), and delamination ( $p=0.99$ ) (Table 5-2). In all groups, scratches were most prevalent and significantly more common than delamination (Triathlon® and Genesis II™,  $p=0.001$ ; Sigma®,  $p=0.002$ ). Table 5-3 contains the total wear scores for the different zones of the trochlea for each

group of retrieved femoral components. No differences were found between the three groups with respect to wear in zones 1 through 6.

**Table 5-1. Implant and patient demographics.**

<u>Parameter</u>	<u>Triathlon®</u>	<u>Sigma®</u>	<u>Genesis II™</u>	<u>p-value</u>
<b>TIV</b>	2.04±0.78	3.18±1.69	2.37±1.08	NS 0.36
<b>Age at revision</b>	70.0±6.44	72.66±14.17	72.33±13.92	NS 0.82
<b>BMI</b>	31.60±6.6	31.66±4.06	36.32±10.13	NS 0.58
<b>Side</b>	2L, 4R	1L, 5R	1L, 5R	N/A
<b>Sex</b>	4M 2F	2M 4F	4M 2F	N/A
<b>Reason for revision</b>	Infection (4), Instability (2)	Infection (5), Loosening (1)	Infection (5), Instability (1)	

**Table 5-2. Visual assessment scores of damage modes in each zone of the trochlea of retrieved femoral components.**

<u>Parameter</u>	<u>Triathlon®</u>	<u>Sigma®</u>	<u>Genesis II™</u>	<u>p-value</u>
<b>Scratches</b>	4.90±0.74	5.20±0.75	5.83±0.25	NS 0.06
<b>Delamination</b>	0.50±0.70	0.40±0.41	0.50±0.77	NS 0.99
<b>Pitting</b>	1.90±1.24	1.90±0.41	2.08±1.39	NS 0.97
<b>Striations</b>	2.50±0.70	2.50±1.0	2.08±1.31	NS 0.50
<b>p-value</b>	<b>Sig 0.001</b>	<b>Sig 0.002</b>	<b>Sig 0.001</b>	

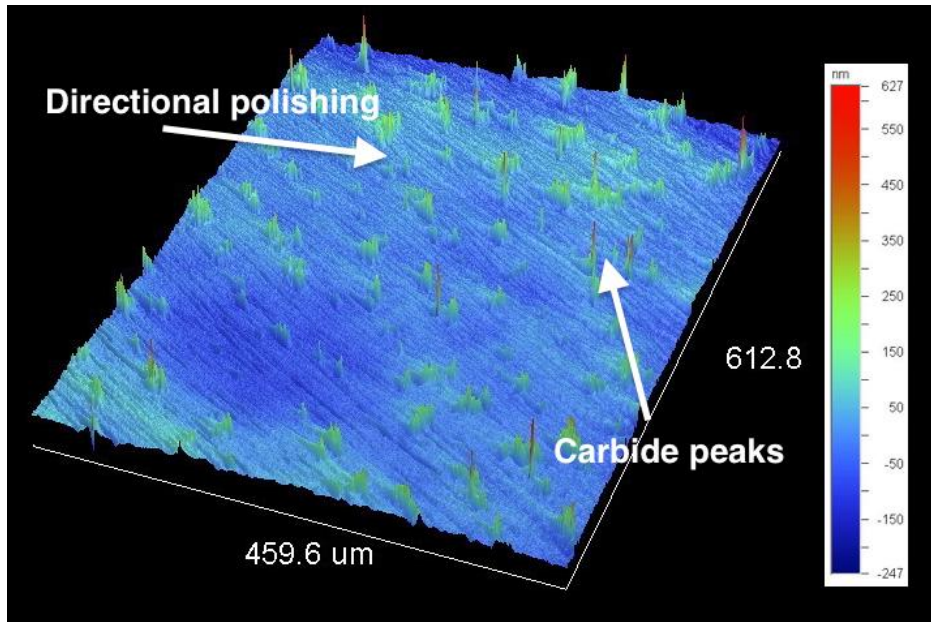
**Table 5-3. Visual assessment scores of damage in each zone in Triathlon®, Sigma®, and Genesis II™ components.**

<b>Zone</b>	<b>Triathlon®</b>	<b>Sigma®</b>	<b>Genesis II™</b>	<b>p-value</b>
<b>1</b>	1.67±0.51	1.75±0.68	2.25±0.41	NS 0.11
<b>2</b>	1.91±0.20	2.00±0.54	1.83±0.68	NS 0.73
<b>3</b>	1.83±0.60	1.83±0.60	1.83±0.87	NS 0.92
<b>4</b>	2.08±0.49	1.75±0.61	1.83±0.51	NS 0.50
<b>5</b>	1.00±00	1.33±0.60	1.25±0.27	NS 0.27
<b>6</b>	1.75±0.27	1.75±0.61	1.41±0.58	NS 0.56

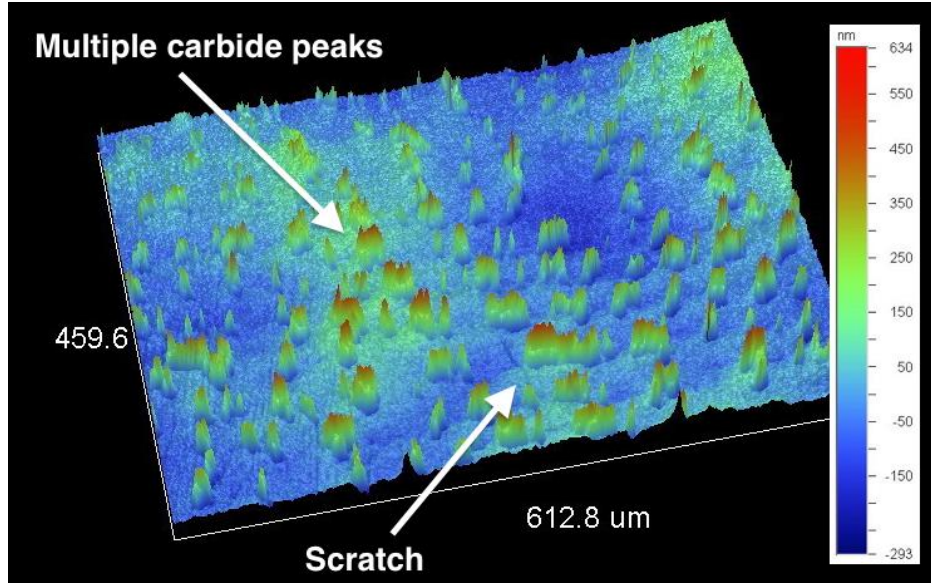
Using light profilometry, we compared the surface roughness values between the three groups of retrieved components and new, unused components of the same type. Residual polishing marks, carbide peaks, and scratching were notable on the surface of new Triathlon®, Sigma®, and Genesis II™ components (Figures 5-3, 5-4, 5-5). There was evidence of wear and scratching on the surface of the retrieved components (Figure 5-6, 5-7, 5-8).

Surface profilometry allowed for a quantitative comparison of the surface roughness between the retrieved components to the respective reference components (Table 5-4). The retrieved Triathlon® implants were significantly more rough than the reference components ( $R_a$ ,  $p=0.004$ ;  $R_q$ ,  $p=0.004$ ;  $R_p$ ,  $p=0.004$ ;  $R_{sk}$ ,  $p=0.01$ ). Similarly, the retrieved Sigma® components were significantly rougher than the reference components in all parameters except for  $R_p$  ( $R_a$ ,  $p=0.009$ ;  $R_q$ ,  $p=0.02$ ;  $R_p$ ,  $p=0.48$ ;  $R_{sk}$ ,  $p=0.02$ ). For the Genesis II™ components, no significant differences were found between the reference and retrieved genesis components ( $R_a$ ,  $p=0.48$ ;  $R_q$ ,  $p=0.58$ ;  $R_p$ ,  $p=0.99$ ; and  $R_{sk}$ ,  $p=0.093$ ).

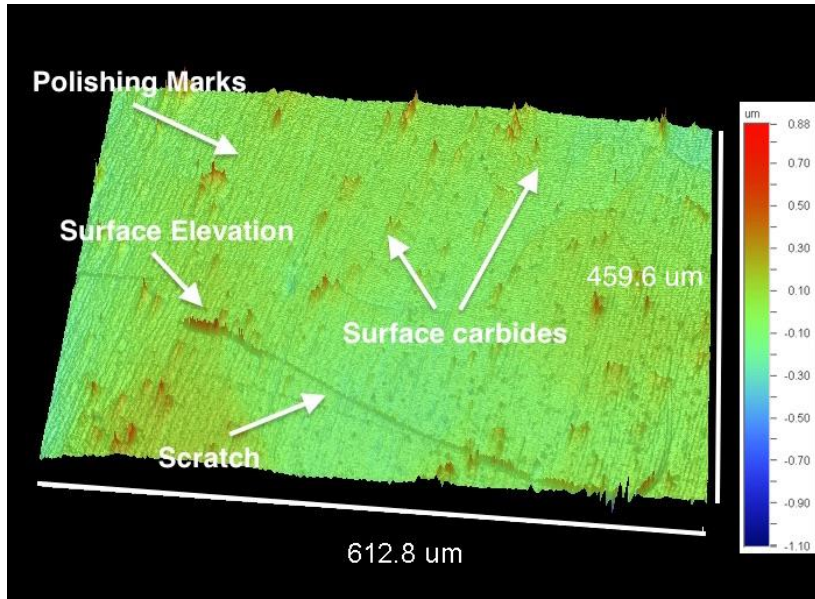




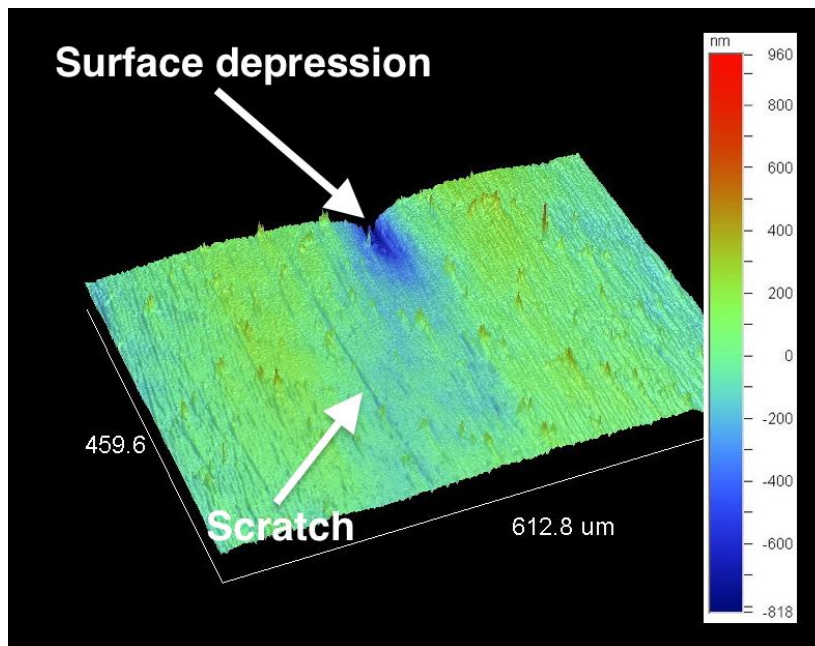
**Figure 5-3. Surface profilometry image of a reference Triathlon® component. There is evidence of directional polishing likely used during the manufacturing process. Peaks are present that likely represent surface carbides.**



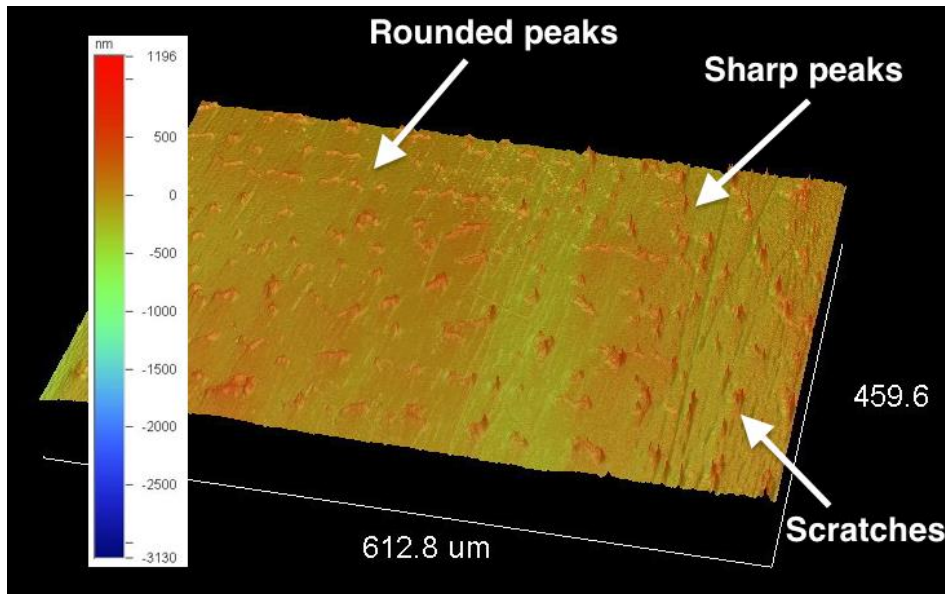
**Figure 5-4. Surface profilometry image of a reference Sigma® component. Multiple surface peaks are present, which may represent surface carbides. A fine scratch is visible. There is no evidence of directional polishing.**



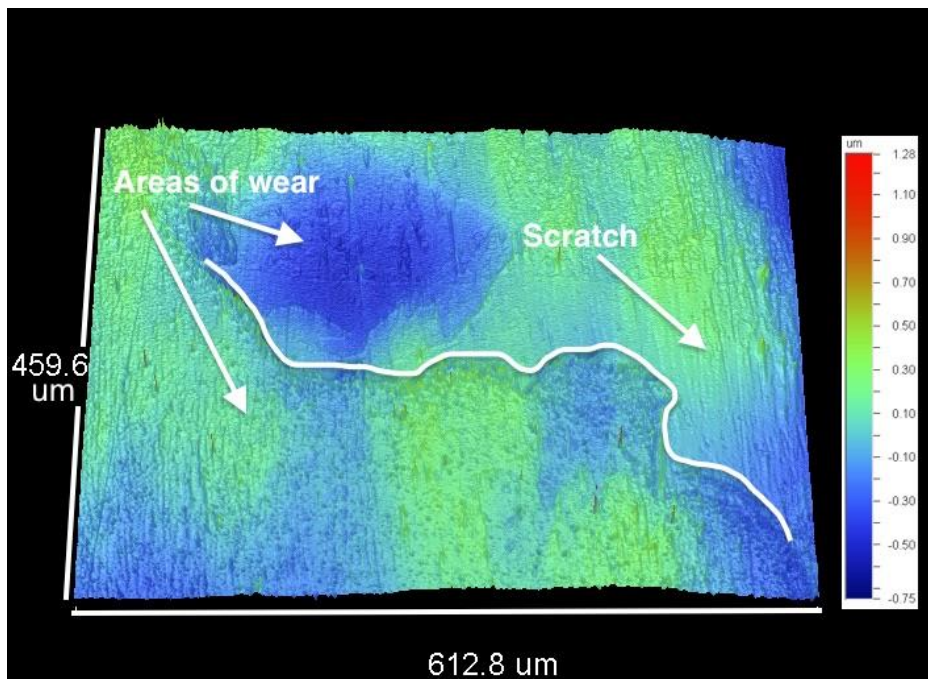
**Figure 5-5. Surface profile of the trochlea of a reference Genesis II™ femoral component. A scratch is notable on the surface. The direction of surface polishing and surface carbides are visible.**



**Figure 5-6. Surface profilometry image of a retrieved Triathlon® component. There is a scratch present which may be secondary to a handling mark or wear. A groove is present in the surface, which may represent localized surface wear.**



**Figure 5-7. Surface profilometry image of a retrieved Sigma® component. There is evidence of wear as noted by the sharp surface peaks in one part of the surface and rounded peaks in the other part. Scratches are visible on the surface as well.**



**Figure 5-8. Surface profile of the trochlea of a retrieved Genesis II™ femoral component. Notable surface features are substantial wear in the lower zone of the image and scratching.**

**Table 5-4. Comparison of surface roughness parameters between the reference and retrieved femoral components.**

	<u>Surface Parameter</u>			
	<u>R<sub>a</sub>(nm)</u>	<u>R<sub>q</sub>(nm)</u>	<u>R<sub>p</sub>(nm)</u>	<u>R<sub>sk</sub></u>
<b><u>Triathlon®</u></b>				
Reference Component	10.62±1.29	15.97±1.62	71.63±7.01	1.16±0.28
Retrieved Components	23.05±5.36	33.09±6.84	118.05±10.89	0.63±0.29
p-value	<b>Sig p=0.002</b>	<b>Sig p=0.002</b>	<b>Sig p=0.002</b>	<b>Sig p=0.009</b>
<b><u>Sigma®</u></b>				
Reference Component	21.85±2.67	33.81±5.23	144.41±33.19	1.43±0.61
Retrieved Components	33.36±8.04	45.47±9.61	150.27±22.52	0.48±0.40
p-value	<b>Sig p=0.009</b>	<b>Sig p=0.02</b>	NS p=0.48	<b>Sig p=0.02</b>
<b><u>Genesis II™</u></b>				
Reference Component	19.45±4.35	27.04±5.84	101.68±22.94	0.88±0.52
Retrieved Components	18.65±2.23	26.76±3.21	94.80±12.70	0.41±0.37
p-value	NS p=0.48	NS p=0.58	NS p=0.99	NS p=0.093

The roughness parameters of the reference components across the three groups were compared (Table 5-5). Overall, the reference Triathlon® component exhibited lower  $R_a$  than both the Genesis II™ ( $p=0.03$ ) and the Sigma® ( $p=0.004$ ). As well, Triathlon® reference  $R_p$  and  $R_q$  values were significantly lower than Sigma® ( $p=0.001$  and  $p=0.002$ , respectively). No differences were noted in  $R_{sk}$  ( $p=0.35$ ) across the implants.

We compared the surface roughness between the three groups of retrieved implants (Table 5-6). Statistical analysis showed that the Sigma® components had significantly higher overall  $R_a$  ( $p=0.001$ ),  $R_q$  ( $p=0.003$ ), and  $R_p$  ( $p=0.007$ ) compared to the Triathlon® and Genesis II™ components.  $R_{sk}$  ( $p=0.90$ ) values were not significantly different across the components. Differences in wear were also analyzed in each zone between the three groups (Tables 5-7, 5-8, 5-9, 5-10). In zone 2, the wear parameters in the Sigma® were higher than the Genesis II™ ( $R_a$ ,  $p=0.04$ ). In zone 3, the wear parameters in the Sigma® were higher than the Triathlon® ( $R_a$ ,  $p=0.02$ ) and the Genesis II ( $R_q$ ,  $p=0.01$ ;  $R_p$ ,  $p=0.02$ ). Finally, we also made comparisons within each group of components (Tables 5-7, 5-8, 5-9, 5-10). There was no evidence of asymmetric trochlear wear in any of the groups.

**Table 5-5. Comparison of surface roughness parameters between the reference components in all three groups.**

Reference Component	Surface Parameter			
	R <sub>a</sub> (nm)	R <sub>q</sub> (nm)	R <sub>p</sub> (nm)	R <sub>sk</sub>
Triathlon®	10.62±1.29	15.97±1.62	71.63±7.01	1.16±0.28
Sigma®	21.85±2.67	33.81±5.23	144.41±33.19	1.43±0.61
Genesis II™	19.45±4.35	27.04±5.84	101.68±22.94	0.88±0.52
p-value	<b>Sig p=0.004</b>	<b>Sig p=0.001</b>	<b>Sig p=0.002</b>	NS p=0.35

**Table 5-6. Comparison of surface roughness parameters between the retrieved components in all three groups.**

Retrieved Component	Surface Parameter			
	R <sub>a</sub> (nm)	R <sub>q</sub> (nm)	R <sub>p</sub> (nm)	R <sub>sk</sub>
Triathlon®	23.05±5.36	33.09±6.84	118.05±10.89	0.63±0.29
Sigma®	33.36±8.04	45.47±9.61	150.27±22.52	0.48±0.40
Genesis II™	18.65±2.23	26.76±3.21	94.80±12.70	0.41±0.37
p-value	<b>Sig p=0.001</b>	<b>Sig p=0.003</b>	<b>Sig p=0.007</b>	<b>NS p=0.90</b>

**Table 5-7. Comparison of  $R_a$  in each zone of the 3 groups of components.**

	<u>Trochlear Zone</u>						<b>p-value</b>
	<b>Zone 1</b>	<b>Zone 2</b>	<b>Zone 3</b>	<b>Zone 4</b>	<b>Zone 5</b>	<b>Zone 6</b>	
<b>Triathlon®</b>	24.09±20.6	27.39±17.63	16.77±3.63	19.98±5.11	27.66±22.28	23.43±10.45	NS p=0.79
<b>Sigma®</b>	41.47±33.4	57.94±47.84	34.96±12.54	29.10±12.13	27.85±17.02	28.53±6.56	NS p=0.42
<b>Genesis II™</b>	18.93±6.40	19.25±7.73	21.54±7.98	29.10±12.13	18.22±5.56	33.33±11.56	NS p=0.11
<b>p-value</b>	NS p=0.30	<b>Sig p=0.04</b>	<b>Sig p=0.02</b>	NS p=0.32	NS p=0.54	NS p=0.19	

**Table 5-8. Comparison of  $R_q$  in each zone of the 3 groups of components.**

	<u>Trochlear Zone</u>						<b>p-value</b>
	<b>Zone 1</b>	<b>Zone 2</b>	<b>Zone 3</b>	<b>Zone 4</b>	<b>Zone 5</b>	<b>Zone 6</b>	
<b>Triathlon®</b>	32.92±23.60	39.43±25.59	24.97±4.47	40.68±26.84	36.75±15.15	36.75±15.15	NS p=0.56
<b>Sigma®</b>	53.92±41.40	57.94±47.84	49.02±16.64	39.87±15.43	38.45±22.72	40.04±10.21	NS p=0.84
<b>Genesis II™</b>	28.12±10.43	26.88±9.84	31.24±11.48	23.97±5.81	25.39±8.19	46.24±14.46	NS p=0.70
<b>p-value</b>	NS p=0.35	NS p=0.25	<b>Sig p=0.01</b>	NS p=0.55	NS p=0.32	NS p=0.52	

**Table 5-9. Comparison of  $R_p$  in each zone of the 3 groups of components.**

	Trochlear Zone						p-value
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	
<b>Triathlon®</b>	114.13±45.22	134.19±83.76	103.86±22.47	125.74±35.72	135.38±36.36	135.38±36.36	NS p=0.36
<b>Sigma®</b>	163.88±113.05	175.05±119.49	166.58±39.02	139.55±41.64	136.53±71.74	137.82±47.19	NS p=0.36
<b>Genesis II™</b>	103.78±39.93	89.03±37.25	114.95±39.15	90.04±16.06	87.72±39.54	163.73±36.74	NS p=0.86
<b>p-value</b>	NS p=0.55	NS p=0.16	<b>Sig p=0.02</b>	NS p=0.057	NS p=0.10	NS p=0.56	

**Table 5-10. Comparison of  $R_{sk}$  in each zone of the 3 groups of components.**

	Trochlear Zone						p-value
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	
<b>Triathlon®</b>	0.72±0.64	0.37±0.51	0.83±0.68	0.30±0.84	0.57±0.97	0.25±0.68	NS p=0.62
<b>Sigma®</b>	0.27±0.46	0.31±0.22	0.45±0.71	0.76±0.50	0.55±0.49	0.64±0.83	NS p=0.62
<b>Genesis II™</b>	0.36±0.79	0.18±0.61	0.59±0.51	0.68±0.22	0.56±0.60	0.53±0.41	NS p=0.75
<b>p-value</b>	NS p=0.41	NS p=0.93	NS p=0.63	NS p=0.80	NS p=0.94	NS p=0.48	



## 5.4 Discussion

The outcome of a TKA is influenced by a complex interplay of patient factors, surgical technique, and implant design.<sup>19</sup> Over the last several decades, there have been substantial efforts to optimize implant design<sup>20</sup>, and considerable improvements have been achieved. In particular, while patellofemoral complications were some of the most prevalent causes of revision<sup>21,22</sup>, improvements in design and technique have decreased this significantly.<sup>23</sup> Nevertheless, anterior knee pain is still prevalent in up to 20%<sup>24</sup> of patients and is a cause of dissatisfaction following TKA.<sup>25</sup> The prevalence of anterior knee pain is observed equally in resurfaced and unresurfaced patellae<sup>26</sup>, and therefore patellar arthritis is unlikely to be the only cause. Abnormal patellofemoral kinematics, which may be influenced by trochlear design, is likely an important factor.<sup>4</sup>

Abnormal biomechanics following joint arthroplasty can lead to component surface changes, such as plastic deformation, damage, and wear.<sup>27-29</sup> The mechanisms are varied and may relate to increased compressive<sup>30</sup>, rotational<sup>31</sup>, and shear forces.<sup>27,29</sup> The main purpose of the present study was to evaluate patellofemoral surface damage and wear, with focus on the femoral trochlea, in three different modern implants. Comparison of new, unused reference components from each group revealed increased roughness of the Sigma® components compared to the Triathlon® components, but no difference between the Sigma® and the Genesis II™ components. The retrieved Sigma® and Triathlon® components were significantly rougher than the new components, but this was not the case for the Genesis II™ components. Finally, in retrieved implants, we found increased patellofemoral joint wear in Sigma® components compared with Triathlon® and Genesis II™ components.

When analyzed according to the various zones of the trochlea, differences in wear were significant in zones 2 and 3, which correspond to the proximal trochlear groove and the medial trochlea. The Sigma® group exhibited more wear than the Triathlon® or Genesis II™ in both zones. Zone 2, corresponding to the proximal trochlear groove, is susceptible to wear as the patella engages into the trochlea. Previous studies suggested that the

amount of proximal extension of the trochlear groove can play a role in the wear in this zone.<sup>4, 8</sup> Trochlear designs where this zone extends more proximally allow the patella to engage and theoretically improve tracking.<sup>4, 32</sup> The finding of increased medial wear in the trochlea in Sigma® components compared to Triathlon® and Genesis II™ components is interesting. This may occur due to a more abrupt angle at the medial ridge of the trochlea, and may predispose the component to more wear as the patella moves medial to lateral through the flexion cycle.<sup>33</sup> In addition, it is likely that the specific areas of wear depend on the rotational profile of the trochlea and well as the rotational alignment achieved intra-operatively. Meijerink<sup>34</sup> demonstrated that the coronal plane orientation of the native and prosthetic trochlea varies, and in general, the sulcus of the prosthetic trochlea is oriented more medially. The orientation of the groove has been shown to affect patellar tilt<sup>35</sup> and therefore may affect patellofemoral contact.

The exact geometry of the prosthetic trochlea varies significantly between components of different manufacturers. In a review of 14 femoral components, Dejour<sup>36</sup> found significant variation in lateral facet height, with some components having less than 5mm lateral facet height. In contrast, previous cadaveric anatomical studies reported a lateral facet height of  $6.6 \pm 1.8$ mm.<sup>37</sup> Reduced height may predispose to lateral patellar subluxation or dislocation, whereas too steep of a lateral ridge may lead to increased laterally-directed forces.<sup>37, 38</sup> In addition, the exact depth of the trochlear groove varies between components, and on average, is 3mm less than native knees.<sup>38</sup> Finally, prosthetic trochlea position varies in the coronal plane and in general, rests 0.8–2.5 mm more medial than in the normal knee.<sup>38, 36</sup> Since information about the specifics of how prosthetic trochlear design compares with native trochlear anatomy is still relatively limited, identifying an optimal trochlear design remains challenging.

In addition to cadaveric biomechanical studies, clinical studies<sup>39, 40</sup> offer insights regarding the functional outcomes of different trochlear designs. Support exists for “patella-friendly” features intended to support the patella and reduce contact pressures. Whiteside<sup>39</sup> retrospectively examined the outcomes of patients with short, narrow, and shallow trochlear grooves to those with a wider, deeper, and longer groove (“patella

friendly”), and found significantly better outcomes with the latter group. Andriacchi<sup>40</sup> evaluated stair climbing function in two design groups that differed in the shape and curvature of the femoral flange. The group with the non-anatomic trochlea, where the trochlea is smaller radius, experienced an increase in knee flexion in late stance, resulting in a substantial increase in quadriceps forces. It was hypothesized that the design of the non-anatomic femoral trochlea causes the patella to track more anteriorly and inferiorly, bringing about adverse biomechanical adaptations. These and other clinical studies help clarify desirable features in trochlear design, but the optimal design is still unknown.

This study has a number of limitations. Firstly, while the groups were well matched based on TIV, age, and BMI, there was a higher proportion of males in the Triathlon® and Genesis II™ groups compared to the Sigma® group. While the effect of gender on femoral component wear, to our knowledge, has not been explored, previous evidence exists that male sex leads to higher damage scores on tibial polyethylene inserts.<sup>41</sup> In the context of this study, the retrieved Sigma® components exhibited more wear, and therefore this was unlikely to be a significant factor affecting the results. Secondly, in all three groups, the retrieved components were compared to one reference component. This analysis relied on the assumption that the individual reference components were a truly representative sample. Since new, unused femoral components were used for reference, this assumption was felt to be warranted. Another limitation is that while the surface damage and wear on the femoral components was examined, having information regarding the wear on both surfaces of the bearing couple (the patellar button), may provide useful information regarding wear patterns. Particularly, since the patellar polyethylene is a softer surface, any differences in wear would be expected to be greater and more discernible. The strengths of this study is that this is the first to compare trochlear wear between three modern femoral component designs. Furthermore, this was done in an overall well matched sample, eliminating sources of bias. As such, this study provides important information for improving our understanding of trochlear wear.

Despite modern TKA techniques and design, complications related to the patellofemoral joint continue to be problematic.<sup>42</sup> Physiologic patellofemoral kinematics are difficult to

achieve and both surgical technique and implant design can potentially be limiting factors. In the present study, we used the tribological characteristics of the patellofemoral articulation to provide some evidence regarding contact mechanics. After short term follow-up, some trochlear designs exhibited more wear than others. The etiology of increased wear requires further investigation. Additionally, longer term retrieval studies may provide further details on patellofemoral mechanics and wear patterns.

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## Chapter 6

### 6 Discussion

Total knee arthroplasty (TKA) has proven to be a highly successful surgical procedure<sup>1</sup> for the treatment of advanced osteoarthritis, and its demand has been increasing.<sup>2</sup> However, complications involving the patellofemoral joint, particularly anterior knee pain, maltracking, and instability continue to be problematic.<sup>3</sup> Resurfacing the patella has not been the answer to address these complications.<sup>4</sup> Other etiologies for patellofemoral complications, such as abnormal patellofemoral loads or kinematics, and changes in patellofemoral offset (PFO) may play important roles in these complications.

Traditionally, changes in patellofemoral offset (PFO) have been implicated as a potential cause of adverse outcomes following TKA. Despite previous clinical<sup>5, 6</sup> and biomechanical<sup>7, 8</sup> studies, this issue remains controversial among arthroplasty surgeons. Chapter 2 examined the differences in patient-reported outcomes in knees with and without post-operative changes in patellofemoral offset (PFO). We retrospectively studied a large cohort of patients and used calibrated imaging to obtain absolute values of change in PFO. This study found that in a large proportion of patients, the PFO is changed post-operatively, however, most changes in our sample were small. These changes did not have a significant effect on patient-reported outcomes. This study suggests that there is some forgiveness with respect to post-operative patellofemoral offset changes. Our results are in line with findings reported by Pierson<sup>5</sup> and Beldman<sup>5</sup>.

While the implications of changes in PFO were previously studied in terms of clinical outcomes and modelled in cadaveric specimens, the effects on the tribology of the patellofemoral joint following *in vivo* use has not been assessed. Specifically, it remains unclear whether increased PFO leads to abnormal loading of the patellofemoral compartment *in vivo*. Abnormal biomechanics following joint arthroplasty can lead to component surface changes, such as plastic deformation, damage, and wear.<sup>9-11</sup> To assess for this possibility, in Chapter 3, we investigated the effect of changes in PFO on the

tribology of the patellofemoral joint. Retrieved femoral components were examined visually and by surface profilometry. We did not find any adverse effects on surface damage or wear in knees with changed post-operative PFO compared to knees with maintained or decreased PFO. This raises the possibility that the extensor mechanism allows for some elasticity without a substantial effect on compressive forces, in agreement with a previous modelling study<sup>12</sup> showing that up to 2 mm of increased offset did not increase extensor mechanism tension. The other possibility is that the small changes in PFO in this study were not enough to cause wear on the hard surface of the femoral component.

Despite improvements in component design, evidence shows that the prosthetic knee continues to be a different kinematic environment than the native knee, and in general, is subject to greater forces.<sup>13</sup> Some argue that trochlear design plays a key part in TKA kinematics.<sup>14</sup> Since abnormal patellofemoral kinematics may contribute to anterior knee pain and other patellofemoral complications<sup>15</sup>, understanding which features of trochlear design can contribute to increased patellofemoral loading and subsequent wear remains important. In Chapter 4, we investigated the surface damage and wear characteristics of a single trochlear design in both new and retrieved components to identify patterns of surface damage and wear. This was done through visual analysis and profilometry of retrieved femoral components. Interestingly, we found that even the surface of new, unused femoral components, exhibits some minor surface markings. All retrieved components showed visual evidence of surface damage. Surface topography through profilometry did not reveal any asymmetrical wear or any zones that are particularly loaded compared to other areas. Clearly, the results of this study are limited to the particular trochlear design that was studied and generalizability to other designs is limited. Nevertheless, the features of the present design appear to offer theoretical advantages to the patellofemoral articulation without compromising the tribology.

Trochlear design has evolved substantially over time and certain features have been termed “patella-friendly” based on improved outcomes.<sup>14, 16</sup> Nevertheless, the exact geometry of the trochlea varies between commonly used implants and the optimal design

for *in vivo* use is still undetermined. Understanding the implications of trochlear design on patellofemoral contact and wear remains important and may provide insights for design optimization. The objective of Chapter 5 was to study patellofemoral joint contact by analysing areas of joint wear and surface damage, with focus on retrieved femoral component of three different modern designs. We found significantly increased wear in the proximal and medial areas of the trochlea in one of the designs compared to the others. This may relate to specific differences in design, such as the proximal extent of the groove and the acuity of the angle of the medial ridge. It is likely that trochlear design influences contact mechanics, which subsequently affects surface wear, and may have an overall impact on long-term patient outcomes. The exact mechanisms of how this takes place still require further investigation.

## 6.1 Future Directions

This thesis reported the wear and surface damage characteristics of the trochlea of retrieved cobalt-chromium femoral components. While other studies previously evaluated the femoral condyles<sup>17, 18</sup>, we are not aware of previous studies evaluating the trochlea. Therefore, this information is an important starting point and advances our understanding of patellofemoral contact following *in vivo* use. This thesis, consistent with the trend in previous studies<sup>17-20</sup>, studied one element of the bearing surface in isolation. While such studies are beneficial, future topographical studies should attempt to address and analyze both bearing surfaces of the patellofemoral joint as a system. Such analysis may provide more detailed information on the interaction between surface changes, component design, and kinematics. In addition, further work should be aimed at obtaining more specimens and extending the time-*in-vivo* period in order to reflect long-term changes over the life-span of the implant. Finally, as alternative metal alloys and ceramics are increasingly used for femoral components<sup>21</sup>, future research should be directed at evaluating the tribology of these surfaces.

We demonstrated that the post-operative patient-reported outcome scores used in our studies were not adversely affected by post-operative changes in PFO. However, it is possible that the sensitivity of these outcome scores may be the limiting factor in establishing a correlation. This is termed as a “ceiling effect” and it has been described in the past for patient-reported outcome scores.<sup>22</sup> As such, functional outcome measurements with improved resolution may be of importance for future clinical research. Furthermore, while global assessment tools, such as the WOMAC or KSS, are beneficial in giving information about the overall function of a knee, a more specific patellofemoral outcomes score may be required to elucidate differences between patients.

Finally, in this thesis, we compared surface changes following in vivo use across different femoral component designs. While such comparisons are beneficial, basic information is still lacking regarding differences in the anatomy and kinematics of the TKA trochlea and that of the native knee<sup>23</sup>. Therefore, another important line of research is to continue investigating and clarifying the differences between native patellofemoral kinematics to prosthetic kinematics.

## 6.2 Conclusions

The results from this thesis will contribute to our understanding of the patellofemoral joint in TKA. We demonstrated that surgeons have some leeway with respect to patellofemoral joint offset both in terms of patient clinical outcomes as well as the tribology of the patellofemoral joint. The retrieval studies showed that with modern femoral components, the tribology of the patellofemoral joint is affected by trochlear design. The clinical implications of these findings require further investigation.

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# Appendix A: Western Ontario and McMaster Universities Arthritis Index

## WOMAC Osteoarthritis Index LK3.1 (IK)

### Section A

### PAIN

Think about the pain you felt during the last 48 hours caused by the arthritis in your knee to be injected.

(Please mark your answers with an "X".)

QUESTION: <b>How much pain have you had . . .</b>	Study Coordinator Use Only
1. when walking on a flat surface? none <input type="checkbox"/> mild <input type="checkbox"/> moderate <input type="checkbox"/> severe <input type="checkbox"/> extreme <input type="checkbox"/>	PAIN1 _____
2. when going up or down stairs? none <input type="checkbox"/> mild <input type="checkbox"/> moderate <input type="checkbox"/> severe <input type="checkbox"/> extreme <input type="checkbox"/>	PAIN2 _____
3. at night while in bed? (that is - pain that disturbs your sleep) none <input type="checkbox"/> mild <input type="checkbox"/> moderate <input type="checkbox"/> severe <input type="checkbox"/> extreme <input type="checkbox"/>	PAIN3 _____
4. while sitting or lying down? none <input type="checkbox"/> mild <input type="checkbox"/> moderate <input type="checkbox"/> severe <input type="checkbox"/> extreme <input type="checkbox"/>	PAIN4 _____
5. while standing? none <input type="checkbox"/> mild <input type="checkbox"/> moderate <input type="checkbox"/> severe <input type="checkbox"/> extreme <input type="checkbox"/>	PAIN5 _____

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V3 - English for USA  
(at baseline)

## WOMAC Osteoarthritis Index LK3.1 (IK)

### Section B

## STIFFNESS

Think about the stiffness (not pain) you felt during the last 48 hours caused by the arthritis in your knee to be injected.

Stiffness is a sensation of **decreased** ease in moving your joint.

(Please mark your answers with an "X".)

<p>6. How <b>severe</b> has your stiffness been <b>after you first woke up</b> in the morning?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>7. How <b>severe</b> has your stiffness been after sitting or lying down or while resting <b>later in the day</b>?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p>	<p>Study Coordinator Use Only</p> <p>STIFF6    _____</p> <p>STIFF7    _____</p>
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V3 - English for USA  
(at baseline)



# WOMAC Osteoarthritis Index LK3.1 (IK)

## Section C

### DIFFICULTY PERFORMING DAILY ACTIVITIES

Think about the difficulty you had in doing the following daily physical activities during the last 48 hours caused by the arthritis in your knee to be injected. By this we mean **your ability to move around and take care of yourself**.

(Please mark your answers with an "X".)

QUESTION: How much difficulty have you had . . .					Study Coordinator Use Only	
8. when going down the stairs?	none	mild	moderate	severe	extreme	PFTN8 _____
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
9. when going up the stairs?	none	mild	moderate	severe	extreme	PFTN9 _____
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
10. when getting up from a sitting position?	none	mild	moderate	severe	extreme	PFTN10 _____
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
11. while standing?	none	mild	moderate	severe	extreme	PFTN11 _____
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
12. when bending to the floor?	none	mild	moderate	severe	extreme	PFTN12 _____
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
13. when walking on a flat surface?	none	mild	moderate	severe	extreme	PFTN13 _____
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	

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**WOMAC Osteoarthritis Index LK3.1 (IK)**

**DIFFICULTY PERFORMING DAILY ACTIVITIES**

Think about the difficulty you had in doing the following daily physical activities during the last 48 hours caused by the arthritis in your knee to be injected. By this we mean **your ability to move around and take care of yourself**.

(Please mark your answers with an "X".)

<p>QUESTION: <b>How much difficulty have you had . . .</b></p> <p>14. getting in or out of a car, or getting on or off a bus?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>15. while going shopping?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>16. when putting on your socks or panty hose or stockings?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>17. when getting out of bed?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>18. when taking off your socks or panty hose or stockings?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>19. while lying in bed?</p> <p>none      mild      moderate      severe      extreme</p> <p><input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p>	<p>Study Coordinator Use Only</p> <p>PFTN14 _____</p> <p>PFTN15 _____</p> <p>PFTN16 _____</p> <p>PFTN17 _____</p> <p>PFTN18 _____</p> <p>PFTN19 _____</p>
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**WOMAC Osteoarthritis Index LK3.1 (IK)**

**DIFFICULTY PERFORMING DAILY ACTIVITIES**

Think about the difficulty you had in doing the following daily physical activities during the last 48 hours caused by the arthritis in your knee to be injected. By this we mean **your ability to move around and take care of yourself**.

(Please mark your answers with an "X".)

<p><b>QUESTION: How much difficulty have you had . . .</b></p> <p>20. when getting in or out of the bathtub?          none      mild      moderate      severe      extreme  <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>21. while sitting?          none      mild      moderate      severe      extreme  <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>22. when getting on or off the toilet?          none      mild      moderate      severe      extreme  <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>23. while doing heavy household chores?          none      mild      moderate      severe      extreme  <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p> <p>24. while doing light household chores?          none      mild      moderate      severe      extreme  <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/>      <input type="checkbox"/></p>	<p>Study Coordinator Use Only</p> <p>PFTN20 _____</p> <p>PFTN21 _____</p> <p>PFTN22 _____</p> <p>PFTN23 _____</p> <p>PFTN24 _____</p>
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# Appendix B: Knee Society Score

## KNEE SOCIETY SCORE

•to be completed by staff

PAIN	Right	Left			
None	50	50			
Mild or Occasional	45	45			
Stairs Only	40	40			
Walking and Stairs	30	30			
Moderate Occasional	20	20			
Moderate Continual	10	10			
Severe	0	0			
Range of Motion	Right	Left			
Start of Flexion (Degrees)- Extension					
End of Flexion (Degrees)					
Anterior/ Posterior Instability: Measured at 90°					
	R	L			
None					
Moderate <5mm					
Severe >5mm					
Medial/ Lateral Instability: Measured in Full Extension					
	R	L			
None					
Little <5mm					
Moderate 5mm					
Severe >5mm					
Flexion Contracture					
	R	L			
1-5°					
6-10°					
11-15°					
>15°					
Extension Lag					
	R	L			
<10°					
10-20°					
>20°					
Walking	Right	Left			
Unlimited	50	50			
>10 blocks	40	40			
5-10 blocks	30	30			
<5 blocks	20	20			
House Bound	10	10			
Unable	0	0			
Stairs	Right	Left			
Normal Up and Down	50	50			
Normal Up; Down with Rail	40	40			
Up and Down with Rail	30	30			
Up with Rail; Unable Down	15	15			
Unable	0	0			
Support	Right	Left			
None	0	0			
Cane	-5	-5			
Two Crutches	-10	-10			
Crutches or Walker	-20	-20			

Charnley Functional Classification					
A	B1	B2	C1	C2	C3
A: Unilateral Knee Arthritis					
B1: Unilateral TKA, Opposite Knee Arthritic					
B2: Bilateral TKA					
C1: TKA, but remote arthritis affecting ambulation					
C2: TKA, but medical condition affecting ambulation					
C3: Unilateral or Bilateral TKA with Unilateral or bilateral THA					
RADIOGRAPHIC FINDINGS					
Alignment: Measured on AP Xray					
	R	L			
Neutral: 2-10° valgus					
Varus: <2° Valgus					
Valgus: >10° Valgus					
Comments: _____					
_____					
Examiner: _____					

# Appendix C: Ethics Approval



Western  
Research

Research Ethics

## Western University Health Science Research Ethics Board HSREB Delegated Initial Approval Notice

**Principal Investigator:** Dr. Brent Lanting

**Department & Institution:** Schulich School of Medicine and Dentistry\Orthopaedic Surgery, London Health Sciences Centre

**Review Type:** Expedited

**HSREB File Number:** 106766

**Study Title:** Does Overstuffing the Patellofemoral Joint Lead to Adverse Outcomes in Total Knee Arthroplasty? A Radiographic Review

**Sponsor:**

**HSREB Initial Approval Date:** July 17, 2015

**HSREB Expiry Date:** July 17, 2016

### Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Data Collection Form/Case Report Form	Data Collection Form	2015/06/01
Western University Protocol	Received July 6/15	

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.

Ethics Officer to Contact for Further Information

*This is an official document. Please retain the original in your files.*

Western University, Research, Support Services Bldg., Rm. 5150  
London, ON, Canada N6G 1G9 t. 519.661.3036 f. 519.850.2466 www.uwo.ca/research/ethics



**Western University Health Science Research Ethics Board  
HSREB Delegated Initial Approval Notice**

**Principal Investigator:** Dr. Brent Lanting  
**Department & Institution:** Schulich School of Medicine and Dentistry\Orthopaedic Surgery,London Health Sciences Centre

**Review Type:** Delegated  
**HSREB File Number:** 106933

**HSREB Initial Approval Date:** October 06, 2015  
**HSREB Expiry Date:** October 01, 2016

**Documents Approved and/or Received for Information:**

Document Name	Comments	Version Date
Data Collection Form/Case Report Form	Data Form Retrieval Study	2015/07/13
Revised Western University Protocol		2015/09/29

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.

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The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number

Ethics Officer to Contact for Further Information

*This is an official document. Please retain the original in your files.*

# Curriculum Vitae

## JACOB MATZ

### EDUCATION

- 2015 – present **Master's of Science in Surgery (Candidate)**  
Supervisors: Drs. Brent Lanting, James Howard, Matthew Teeter  
University of Western Ontario, London, Ontario, Canada
- 2013 – present **Residency in Orthopedic Surgery**  
Class of 2018, University of Western Ontario, London, Ontario,  
Canada
- 2009 – 2013 **Medical School**  
Dalhousie University, Halifax, Nova Scotia, Canada
- 2005 – 2009 **Bachelor of Science (Honours in Neuroscience)**  
Dalhousie University, Halifax, Nova Scotia, Canada

### HONOURS AND AWARDS

- 2016 **COFAS Resident Scholar** – awarded to 2 Orthopedic residents in Canada to attend the annual Canadian Orthopedic Foot and Ankle Society meeting (\$1,000)
- 2015 **American Orthopaedic Foot & Ankle Society (AOFAS) Resident Scholar** – awarded to Orthopaedic residents exploring the foot and ankle specialty to attend the annual meeting.
- 2015 **Resident Research Grant (RRG)** – awarded on a competitive basis to a resident pursuing research at London Health Sciences Centre (\$5,000)
- 2015 **Ontario Graduate Scholarship (OGS)** - awarded on a competitive basis to students pursuing graduate research (\$15,000)
- 2011 **Faculty of Medicine Murray McNeil Summer Research Studentship** - Awarded a studentship (\$5,000) to pursue summer research at the Dalhousie Medical School.
- 2011 **1<sup>st</sup> Place Poster Award** - Dalhousie Health Trainee Research Day.
- 2005-2011 **Dean's List** – Awarded to the top 10% of students in the Bachelor of Science program.

- 2010      **DMRF Kohler Summer Research Studentship in Neuroscience**  
 –studentship to pursue Summer research (\$5,000).
- 2008      **NSERC Undergraduate Student Research Award (Neuroscience)**  
 –awarded to students interested in obtaining research experience (\$5,000).

## PUBLICATIONS

Howard JL, Lanting BA, **Matz J**. Understanding the Patellofemoral Joint in Total Knee Arthroplasty: An Unresolved Issue. Submitted for publication in JAAOS, under review (May 2016).

**Matz J**, Howard JL, Morden DJ, MacDonald SJ, Teeter MG, Lanting BA. Do Changes in Patellofemoral Joint Offset Lead to Adverse Outcomes in Total Knee Arthroplasty with Patellar Resurfacing? A Radiographic Review. Submitted for publication in Journal of Arthroplasty, under review (May 2016)

Weeks CA, Preston S, Howard JL, Vasarhelyi EM, **Matz J**, Lanting BA (2016). Preoperative Pelvic Tilt Analysis Reduces Fluoroscopy Time in Direct Anterior Total Hip Arthroplasty. *Orthopedics* 23:1-5.

Al Khudairy A, Gauthier L, Heflin J, Fletcher N, **Matz J**, Soroceanu A, El-Hawary R (2014). Reliability of Proximal Junctional Kyphosis Measurements for Young Children with Scoliosis. *Spine Deformity* 2(6):448-453.

**Matz J**, Abdollel M, Nasser J (2014). A Systematic Review and Meta-Analysis of Palpation Versus Ultrasound-Guided Fine Needle Aspiration of the Thyroid Gland. *Dalhousie Medical Journal* 41(1): 14-21.

Molinari M, **Matz J**, DeCoutere S, El-Tawil K, Abu-Wasel B, Keough V (2013). Live liver donors' risk thresholds: risking a life to save a life. *HPB* 16(6):560-74.

**Matz J**, Matz A (2012). Use of a SILS Port in Transanal Endoscopic Microsurgery in the Setting of a Community Hospital. *Journal of Laparoendoscopic & Advanced Surgical Techniques*. 22(1):93-6.

**Matz J**, Kolar A, McCarvill T, Krueger SR (2010). Rapid synapse-specific structural changes of active zone cytomatrix regulate neurotransmitter release. *Proceedings of the National Academy of Sciences* 107(19):8836-8841.

## PODIUM PRESENTATIONS

**Matz J**, Morden D, Teeter M, Howard J, Lanting B (2016). Does Overstuffing the Patellofemoral Joint Lead to Adverse Outcomes in Total Knee Arthroplasty? Canadian Orthopedic Association Meeting, Quebec.