The influence of knee position and sex on ultrasound imaging of femoral cartilage characteristics

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Abstract

The purpose was to examine (1) the effect of measurement position and sex on femoral cartilage outcomes, and (2) the association between gait biomechanics and cartilage outcomes. Fifty individuals participated (25 males, 25 females; Age=20.62±1.80 years). Ultrasound measured femoral cartilage thickness and echo-intensity (EI) at 90°, 115°, and 140° of knee flexion. Gait outcomes included the external knee adduction and knee flexion moments. Cartilage outcomes were compared using 2(sex) x 3(position) repeated measures ANOVA. Gait and cartilage associations were assessed using stepwise regression. Cartilage was thicker when measured at 90° compared with 140°, but mainly in males. Males had thicker cartilage than females in all positions. EI was lower at 90° than 140° in the central and lateral regions. No association was found between gait and cartilage outcomes. Imaging position and sex influences cartilage outcomes and should be considered in study designs and clinical evaluation.

Key words: Ultrasound, Cartilage, Sex, Gait
Summary for Lay Audience

Articular knee cartilage is the substance within the knee joint that allows the thigh to move over the shin and kneecap without pain. Thinner cartilage can contribute to diseases such as osteoarthritis which can reduce mobility and cause pain in the knee joint. Thus, assessing knee cartilage thickness is important when assessing knee health.

Ultrasound is a cost effective, accessible method of viewing cartilage about the femur. However, it is only able to view a portion of the joint due to the size of the ultrasound probe. Knee cartilage characteristics are not homogeneous throughout the joint. Thus, manipulating probe placement or the joint position during imaging may change the viewable region of cartilage.

Cartilage is affected by compressive forces within the knee during tasks like walking. Males and females have different walking patterns, which may have unique effects on knee cartilage characteristics.

This study had two aims. 1) evaluate the effect of sex (males and females) and knee position during imaging on femoral cartilage thickness and composition and 2) assess associations between walking patterns and these cartilage characteristics. We found thicker cartilage was observed when viewing the knee in a more extended position. Cartilage composition was also affected by measurement position. Next, we found that males had thicker cartilage than females across all measurement positions. We did not find any relationship between walking patterns and cartilage outcomes.

The findings from this study show that sex and knee position during ultrasound imaging influence knee cartilage measurements. Both variables should be considered by researchers and clinicians who use ultrasound to assess joint health.
Co-Authorship Statement

A version of this Thesis is being prepared for manuscript submission. The lead author was Harry Battersby who assisted with development of the research question and protocol design as well as led data collection, processing and writing the report. Dr. Derek Pamukoff is a coauthor who led the development of the research question and protocol and assisted with data processing and critical writing revision. Ryan Evans is a co-author who assisted in data processing. Iwi Eghobamien is a co-author who assisted in data collection.
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Chapter 1

1 Introduction

Knee osteoarthritis (KOA) is the most common form of OA accounting for approximately 42.8% of cases.\(^1\) Features of KOA include thickening of the subchondral bone, osteophyte formation and articular cartilage thinning that contribute to impaired mobility and knee pain.\(^2\) Femoral cartilage is often thinner with worsening grades of KOA.\(^3,4\) Therefore, assessing knee cartilage is important to assess KOA disease state and as a component of joint health.

Radiography is used to measure joint space between adjacent bones. However, joint space narrowing is only a surrogate of cartilage thinning, and is imprecise when measuring cartilage features that are indicative of early stage KOA.\(^5\) Magnetic resonance imaging (MRI) is a gold standard for measuring cartilage morphology in clinical and research settings.\(^6\) However, MRI has drawbacks due to its cost and inaccessibility.\(^7,8\) Ultrasound is a cost-effective an portable way to assess cartilage morphology,\(^9\) and is reliable and reproducible when measuring distal femoral cartilage thickness.\(^10\) However, ultrasound provides an image that is limited by the width of the acoustic window and depends on joint anatomy. Therefore, probe placement and anatomical position should be consistent when measuring between individuals and within individuals at separate time points.

Previous literature has commonly used maximum knee flexion during ultrasound imaging because it provides an unimpeded view of the distal anterior femur that is load bearing during gait.\(^11\) However, cartilage structure and composition are not uniform across
the distal femur. For instance, cartilage thickness differs throughout the femoral trochlea when viewed with ultrasound. Furthermore, thicker cartilage is found in areas that experience higher compressive forces, such as the posterior femur that articulates with tibial plateau and the anterior portion that articulates with the patella. These areas also exhibit the greatest thinning in individuals with KOA compared to controls. As such, imaging multiple regions of the knee is needed to comprehensively evaluate cartilage morphology.

Ultrasound also measures hyperechoic and anechoic substances via greyscale image analysis to differentiate cartilage from other forms of tissue, which refers to echointensity (EI). Healthy cartilage appears hypoechoic while cartilage in the early stages of KOA appears hyperechoic. Changes in cartilage MRI T2 relaxation times, a measure assessing the integrity of collagen fibers and cartilage water content, may occur before cartilage thinning. As such quantitative assessment of cartilage ultrasound EI may be a useful supplemental measurement to cartilage thickness that provides a surrogate of tissue composition, but studies evaluating cartilage EI are sparse.

Only a small portion of cartilage relative to the entire surface area of the femur can be viewed when using ultrasound imaging. Therefore, the ultrasound probe must be placed at various positions to comprehensively view regional variation in cartilage features (e.g., thickness and composition) across the femur. One way this may be achieved is by positioning the knee joint at various degrees of flexion. The patella translates inferiorly over the femur during knee flexion. Thus, an anterior perspective of the femur may be exposed at lower degrees of knee flexion assuming a suprapatellar probe placement. However, the influence of measurement position during ultrasound imaging on femoral cartilage features remains unclear.
Repeated chondrocyte loading is important to growth and maintenance of articular cartilage.\textsuperscript{18} Gait is a common movement where the knee joint experiences weight bearing load, and gait patterns influence cartilage thickness.\textsuperscript{14} For example, the external knee adduction moment (KAM) is a surrogate for dynamic medial knee load and contributes to medial KOA progression.\textsuperscript{19} However, a larger KAM has been associated with a larger mediolateral thickness ratio across the femur in individuals without OA.\textsuperscript{20} Similarly, a larger knee flexion moment (KFM) has been associated with thicker medial and lateral cartilage.\textsuperscript{21} Overall, evidence suggests that greater loading during gait may be beneficial to cartilage in controls without KOA.

Females have a larger prevalence of KOA and are also more susceptible to KOA at earlier ages,\textsuperscript{22,23} which may be partly due to gait patterns. For example, females have a smaller absolute peak KFM during gait compared with males.\textsuperscript{24} However, sex-specific associations between gait patterns and cartilage thickness within control populations are unclear. Smaller compressive forces during gait may contribute to thinner cartilage in females compared with males and contribute to this discrepancy of KOA prevalence. Furthermore, sex comparisons of cartilage features using ultrasound are sparse in control populations.

The purpose of this study was to compare femoral cartilage thickness and EI when measured at 90°, 115° and 140° of knee flexion, and between sexes in a young control cohort. We hypothesized that cartilage would be thicker when measured at 90° than at 115° and 140° of knee flexion, and thicker in males compared to females. We also hypothesized that EI would be greater at 140° than at 115° and 90°. A second purpose was to examine the associations between gait biomechanics and cartilage outcomes from both positions. We hypothesized that a larger KFM would be associated with thicker cartilage
and lower EI at all measurement positions in both males and females, but that there would be a stronger association with images obtained from 90° of knee flexion.
Chapter 2

2  Literature Review

2.1  Knee Osteoarthritis

Knee osteoarthritis (KOA) is a chronic disease that affects nearly 10% of adults over the age of 55 years\(^{25}\). It is the most prevalent knee joint disease worldwide and the most common form of osteoarthritis (OA), and approximately 42.8% of OA cases being KOA.\(^{1}\) Additionally, patients with OA are at greater risk of cardiovascular disease, hypertension, and diabetes compared to matched controls.\(^{1}\) Further data from the United Kingdom suggest that one in four people over 55 years have a significant episode of knee pain at least once a year, with at least half of those individuals reporting some kneerelated disability\(^{26}\). Knee osteoarthritis also incurs a considerable financial burden. For example, 20% of patients with KOA had a minimum of one primary joint arthroplasty, 2% had arthrodesis, and 1% had joint revision arthroplasty, with the average cost of total knee arthroplasty being $17,433.\(^{1}\)

Individuals diagnosed with KOA often have irreparable damage to their articular cartilage by the time they become symptomatic.\(^{27}\) Further research indicates that KOA is likely to rise within the coming years due to an ageing population.\(^{28}\) As there is no cure for KOA, outlining potential risk factors and mediators for the disease before diagnosis should be of great importance. Age is one of the prevailing risk factors in developing KOA. A longitudinal study in the United States involving 2262 participants showed that the incidence and progression rate of KOA increased with age in men and women.\(^{23}\) However, the American population has shown that over 2 million of the 14 million people within the United States diagnosed with symptomatic KOA were under 45 years of age.\(^{29}\)
Knee osteoarthritis also affects younger adults, and thus, other risk factors are important to consider when assessing and screening for KOA. For instance, females with obesity (BMI >30) are at 4 times the risk of KOA compared to those with a BMI under 25, whereas males are at 5 times the risk within the same BMI categories. Another risk factor is previous injury. The reported incidence of posttraumatic knee osteoarthritis within either limb, following ACL injury has been seen to be as high as 87%. Sex also seems to play a role in the risk of OA. Females have a higher prevalence of KOA than males throughout the population, particularly in individuals aged over 55 years.

Numerous pathological changes occur within a joint for OA to be determined, and OA affects all joint structures. For instance, degradation of the articular cartilage and ligaments, thickening of the subchondral bone, osteophyte formation, and synovial inflammation are all symptoms associated with the disease. Thinner knee cartilage is a prominent characteristic within individuals with KOA. One study using magnetic resonance imaging (MRI) assessed femorotibial cartilage thickness at 12-month intervals between participants with KOA (n=194) and a control population (n=406). They found that the KOA group exhibited 0.2mm more medial femorotibial cartilage loss at 12 months post-baseline than the control group. This study is in line with previous research where tibiofemoral joint thickness decreased in the lateral and medial compartments in participants with increasing grades of KOA. The same is true within the patellofemoral joint. Within males, patellar cartilage was 18% thinner in those experiencing patellofemoral pain compared to a control group. Within individuals 5 years post ACL reconstruction, a group at high risk of contracting KOA, patellofemoral cartilage had
thinned by 58µm within the injured limb. Most scales that evaluate KOA use cartilage thickness as a measurement. For instance, the Whole-Organ Magnetic Resonance Imaging Score (WORMS) utilizes MRI to assess knee joint cartilage damage. The WORMS cartilage scale ranges from 0 – 6, where 0 = normal cartilage morphology; and 6=a greater than 75% region of whole cartilage thickness loss.

2.2 Cartilage Response to Mechanical Loading

Within the knee joint, both hyaline cartilage and fibrocartilage facilitate smooth movement. Hyaline cartilage forms at the end of the patella, femur, and tibia. This is known as articular cartilage, which provides a low friction coefficient for articulating bones to maintain smooth knee joint movement at the tibiofemoral and patellofemoral joints. Articular cartilage is also designed to bear and distribute loads across these joints. Type II collagen fibres make up 60% of cartilage weight, and their orientation within the extracellular matrix allows for high mechanical loads to be spread across the joint's surface. Chondrocytes are metabolically active cells responsible for the synthetization of collagen within cartilage. Therefore, chondrocyte activation is responsible for cartilage’s ability to adapt to mechanical load. The typical response of connective tissue within the body once damaged will be to repair itself through a cascade of necrosis, inflammation, repair, and scar remodeling. However, hyaline cartilage cannot perform these repairs due to its avascular nature. Therefore, cartilage efforts should be made to strengthen articular cartilage to avoid initial damage.

Multiple studies have shown that isolated chondrocytes respond to mechanical stimulation. However, these have been mainly produced on bovine chondrocytes. An in vitro study in human knee articular cartilage showed that Type II collagen mRNA
signal levels were positively correlated with increased hydrostatic pressure up to 10MPa at 1Hz for 4 hours over 4 days. An increase in these signal levels allows for differentiation within the chondrocyte to promote cartilage growth. Furthermore, in vitro studies have shown that aggrecan (a proteoglycan that helps pull fluid into cartilage) messenger RNA increases after one hour of cyclic pressure-induced strain to human chondrocytes. A systematic review showed that applying intermittent hydrostatic pressure increased both aggrecan and type II collagen fibres in healthy and osteoarthritic individuals. More prolonged pressure on cartilage from physical activity may yield similar results. Knee cartilage morphology is influenced by consistent, repetitive loading such as running and cycling than short-term loading such as weightlifting. For instance, 186 individuals undertook a physical activity questionnaire and a series of fitness tests including long jump, handgrip strength, and a PWC170 cycle test. Results showed a positive correlation between higher test scores and thicker tibiofemoral and patella articular cartilage. This study also found a positive correlation between cartilage thickness and participants' lean mass, implying that physical fitness influences knee cartilage thickness over time. This would concur with previous studies that found that participants with more walking and total physical activity minutes per week had greater tibial cartilage volume over a 5-year period.

Conversely, a lack of mechanical loading also results in knee cartilage loss. Participants who suffered spinal cord injuries and thus had immobilized lower limbs lost between 5-7% of total knee cartilage thickness within the first 6 months of injury. This aligns with the theory that the lack of a pumping action within cartilage results in a decreased nutrient supply to the tissue, which ultimately results in reduced proteoglycan
content, matrix fibrillation, and erosion of articular cartilage.\textsuperscript{48} Although animal studies have highlighted the ability of cartilage to return to its original volume following immobilization,\textsuperscript{49} little research has been done to see if these hypotheses are confirmed in human subjects.\textsuperscript{36} Moderate exercise increases glycosaminoglycans activity (these bond to proteins to form new proteins and are responsible for cell repair and proliferation within cartilage) in those at risk of OA due to meniscal injuries.\textsuperscript{50} However, the lack of knowledge around cartilage recovery highlights the need for further studies on predisposing factors for KOA.

2.3 Cartilage Imaging Methods

There are several methods of imaging articular cartilage to assess morphology. Radiography has been used to evaluate KOA severity by viewing joint space narrowing, osteophytes, subchondral sclerosis, cyst formation, and bony deformities within the knee joint. Assessing joint space narrowing is effective to evaluate KOA disease state,\textsuperscript{51} and has helped outline the Kellgren-Lawrence Classification of Osteoarthritis which is still used to define and categorize KOA severity.\textsuperscript{52} However, there are several disadvantages in using joint space narrowing as an assessment of articular cartilage. The distance between the femur and tibia is representative of both articular cartilage and the meniscus. Therefore, in some instances progression of joint space narrowing could reflect meniscal extrusion rather than true cartilage loss. Radiography is also unable to accurately assess cartilage morphology and unable to view early damage to cartilaginous structures.\textsuperscript{53} Thus, other methods to view cartilage have been implemented by practitioners in order to more accurately assess cartilage composition. Magnetic resonance imaging has been used to assess cartilage composition and morphology. Various anatomical structures within the
body are made of water molecules, each containing a hydrogen atom. Protons within hydrogen atoms are affected by short magnetic pulses, which moves them out of alignment and then realigns them when the signal is removed. As these protons are realigning, they provide a radio signal that provides a basis for MRI. As different structures within the body have different water compositions, their protons realign at different rates and with different positions thus giving off unique signals. This allows MRI to accurately obtain and distinguish images of cartilage from other tissues within the body.

Magnetic resonance imaging is the gold standard of imaging for articular cartilage. Compared to radiography, MRI can measure cartilage characteristics and highlight osteophytes with superior accuracy. Radiography only assesses joint space narrowing and is unable to measure early cartilage compositional changes that occur before cartilage thinning in cases of KOA. Moreover, MRI has strong accuracy against cadaver measurements of cartilage, with one in vitro study showing that MRI can detect cartilage lesions with 78.3% accuracy. Magnetic resonance imaging costs between 5-22 times that of standard radiography tests, and therefore, it is seldom used for evaluating KOA given the prevalence of the disease. Furthermore, Canada has 1.5 MRI machines fewer per million people compared to the median for countries within the Organisation for Economic Co-operation and Development, which indicates the lack of availability. The increased cost and lack of available machinery highlight the need for novel methods to measure cartilage for health screening, disease state or progression, or assessment of the effectiveness of interventions.
Ultrasonography may be an effective alternative. Radiography has been previously discussed as less expensive than MRI, but ultrasound can be more accessible with emerging technology costing as low as $1.5-3k per device.\textsuperscript{58} Ultrasound obtains an image of bodily tissues by sending sound waves and recording the resulting echoes when they contact different surfaces. Due to the high-water content in cartilage, it appears as a homogeneous anechoic band situated between the bony cortex and the soft tissues of two more echoic surfaces. There is a significant correlation between ultrasonographic measurements of femoral cartilage thickness and MRI at measured lengths upon dissection at the medial and lateral condyles as well as the intercondylar notch.\textsuperscript{10} Furthermore, ultrasound is valid for femoral articular cartilage thickness in normal and moderately damaged cartilage, with greater than 70% agreement between ultrasound and cadaver measures.\textsuperscript{10} This is supported by research that found a significant positive correlation between MRI and ultrasonography measures of cartilage thickness when measuring the anterior and midpoint of the medial femoral condyle.\textsuperscript{59}

Further research may elucidate the benefits of ultrasonography compared to MRI. Underfunded hospitals as well as rural areas where lack of access to an MRI becomes a problem, would greatly benefit from the low cost and increased mobility of ultrasound technology. Patients can often have negative perceptions and experiences with MRI testing due to perceived danger from unfamiliarity with the procedure and physical discomfort from factors such as claustrophobia.\textsuperscript{60} This may be counteracted using ultrasonography due to its less invasive nature.
2.4 Assessing Cartilage Using Ultrasonography

Maximum knee flexion has been used during imaging in much of the literature involving ultrasound images of femoral cartilage\textsuperscript{10,11,61–63} due to the notion that it exposes a significant portion of the weight bearing femoral condyles.\textsuperscript{11} Studies show that distal femoral cartilage is thickest in the anterior portion of the femoral trochlea and the posterior weight-bearing regions of the femoral condyles because these areas are in contact with the patella and tibia during gait, respectively.\textsuperscript{64} In the medial and lateral compartments of the knee, tibial and femoral cartilage are thicker in the posterior weightbearing regions.\textsuperscript{64} If the probe is placed superior to the patella, portions of articular cartilage such as the posterior portion of the tibiofemoral joint are obstructed from view when the knee is maximally flexed.\textsuperscript{10} This is a distinct limitation of ultrasound as the posterior portion of the tibiofemoral joint experiences significant weight bearing during gait.\textsuperscript{65} Therefore, femoral cartilage viewed in maximal knee flexion from a suprapatellar probe placement may provide a view of the central or anterior portion of the distal femur. Studies have been able to view a more posterior part of the medial femoral cartilage by placing the probe transversely over the medial femoral condyle.\textsuperscript{59} However, this limits the view to one aspect of the bone surface and does not provide a comprehensive assessment of femoral cartilage.

Cartilage thickness across the distal femur varies. For example, MRI has revealed that cartilage thickness can vary by up to 3mm across the bone surface with the thickest portions of cartilage found in the posterior portions of the medial and femoral condyles and the intercondylar notch.\textsuperscript{13} When viewing individuals with patellofemoral OA, areas of greatest thickness are consistent between individuals, but thickness measurements can
vary across the joint by more than 5mm. When viewing just the anterior distal femur, cartilage thickness varies by over 1mm throughout the bone surface suggesting considerable variation between adjacent areas of cartilage. Ultrasound visualization of the articular cartilage is limited by the width of the acoustic windows that depends on the anatomy of the joint. Most ultrasound probes measuring femoral cartilage range in length from 4-7cm with a width of 1cm. The distal femur has an approximate surface area of 5478mm² in females and 6554mm² in males. This means the probe can only view an approximate 11% of the female femur and 8% of the male femur at a time. Given the variation in cartilage morphology across the bone surface, it is important to ensure consistent measurement position and probe placement in longitudinal studies or those drawing comparisons across groups or conditions.

Altered cartilage composition occurs before cartilage thinning in individuals with OA. Moreover, cartilage lesions that occur before cartilage thinning are associated with increased risk of rapid cartilage loss. Previous research using MRI has shown that longer T2 relaxation times are longer compared with controls and those with mild KOA, which may represent reduced structural integrity of the collagen matrix and increased cartilage water content. Ultrasound detects hyperechoic and anechoic fluids to differentiate cartilage from other connective tissues in the knee joint with a loss of anechoic fluid being an early predictor of KOA. This is known as ultrasound echointensity (EI). Increased water content occurs before cartilage thickness changes in those with knee OA or joint injury. Water is hypo-echoic and an increase in cartilage EI has been associated with an increased risk of having medial femoral arthroscopic cartilage damage. Echo-intensity has also been shown to increase in individuals with early-stage OA compared with
controls prior to cartilage thinning when measured using ultrasound. Given that an increased cartilage water content can occur before cartilage thinning and that EI has been associated with compositional features in other soft tissues, assessing cartilage EI may provide a complementary assessment to thickness to comprehensively evaluate cartilage health. Central portions of the distal femur experience a greater number of lesions in individuals with patellofemoral OA. These portions along with the more posterior medial condyle experience the greatest thinning compared with other joint regions in individuals with KOA. Studies also indicate that the sensitivity of ultrasound to analyze fluid within a joint is altered by knee position during measurement. The cartilage in the central femoral region is more prone to structural integrity loss and thinning, and the sensitivity of fluid detection within the knee joint is altered depending on knee position. Therefore, cartilage EI values may differ if the position of the knee and probe placement are not consistent.

2.5 Sex Differences in Knee Cartilage Morphology

Studies have shown differing KOA prevalence between males and females. Females have a higher susceptibility to KOA compared with males in the general population. A recent meta-analysis found that across 3.5 million participants over the age of 40 years, KOA was found in 21.7% of women compared to only 11.9% of males. Similarly, studies dating back as far as 1987 show that 11% of females compared to 7% of males suffer symptomatic KOA within Americans over the age of 63 years. Males also have a reduced risk of KOA incidence and prevalence compared with especially, in ages over 55 years.
Cartilage in the patellofemoral joint is also greater in males than females in both individuals with patellofemoral pain and healthy controls. A four-year longitudinal study in controls without OA showed that females had thinner cartilage in their tibia and patella at baseline, and greater cartilage degeneration over 4 years compared with males. Moreover, females had thinner cartilage compared with males at the anterior, central, and posterior portions of the femur when measured using both MRI and ultrasound. As a result, females may have an increased risk of tibiofemoral and patellofemoral cartilage loss.

The discrepancy in cartilage morphology could be due to biological differences between sexes. For instance, greater adipose tissue has been linked to higher levels of systemic inflammation and dyslipidemia (an excess of plasma cholesterol or triglycerides within the bloodstream that causes plaque build-up within the arteries), both of which have been associated with an increase in collagen degradation. Studies have shown that females have a significantly higher body fat percentage than males, which may contribute to why females are at a higher risk of KOA than males.

Females have weaker quadriceps strength than males relative to body size. Secondly, quadriceps dysfunction contributes to joint space narrowing within the knee before clinical symptoms of KOA have been diagnosed. In participants with ACL reconstruction, peak quadriceps strength was positively correlated with greater femoral cartilage cross sectional area. When assessed using MRI, isolated quadriceps strength was associated with thicker cartilage within individuals with no radiographical KOA. Thirdly, females may have thinner cartilage because of their unique knee joint anatomy. Across the subchondral bone, females have a smaller femoral surface area of
4.15cm²-4.93cm² compared to males. This was coupled with smaller cartilage of 0.420.49mm across the same area compared to males. A high peak bone mass is known to be protective of cartilage within adolescents. Cartilage may be damaged by high compressive forces not being adequately dispersed over a joint surface. Females have a higher external knee adduction moment (KAM) during gait compared with males when scaled to body size, and a similar absolute KAM compared with males despite smaller body size. The KAM is a surrogate of medial knee joint loading and this inability to disperse large forces over the knee joint due to small knee size may contribute to why females have thinner cartilage and a greater likelihood of KOA.

2.6 Association between Gait and Knee Cartilage Morphology

Gait is a common activity of daily living and a major contributor to habitual joint loading. Therefore, cartilage morphology may be influenced by the joint loading environment that is partially determined by gait biomechanics. Regional variation of cartilage morphology is important and may be influenced by gait kinetics and kinematics. For instance, the KAM is an accurate surrogate of medial compartment loading within the knee, explaining 63% of the variance in medial compartment force. This relationship has also been seen in slow and fast walking speeds where the KAM has been positively correlated with an increase in medial compartment contact force. The KFM is also a contributor to medial knee loading. The addition of KFM to a multiple regression model explained an additional 22% of variance, and their linear combination predicted 85% of the variance in medial knee compartment force. However, whereas the KAM may be able to predict disproportion compartmental forces within the knee joint, the KFM may be a better predictor of overall compressive force within the knee. The KFM is
the external moment acting in the sagittal plane to flex the knee joint.\textsuperscript{89} The quadriceps contract in response to the external moment during the stance phase of gait (i.e., internal knee extensor moment). As such, an increase in KFM may be equivalent to a higher quadriceps force. Patellofemoral reaction force is the resultant force of quadriceps force and patellar tendon force. As such an increase in KFM contributes to a higher PFJ reaction force and stress.\textsuperscript{90,91} Both KAM and KFM are reasonable surrogates of loading within the knee joint, and therefore, may have associations with knee cartilage features.

The KAM during gait has been identified as a contributor to cartilage morphology. In one study, 54 patients with medial tibiofemoral KOA were assessed for their KAM in relation to joint space thinning between the tibia and femur. For every 1.0 unit increase in KAM, there was a 0.63mm increase in medial joint space thinning.\textsuperscript{92} Similar findings occur in females post ACL reconstruction, where a larger KAM is associated with thinner medial femoral cartilage when measured using ultrasound.\textsuperscript{93} However, within healthy populations the KAM may have an opposite effect due to the anabolic response to mechanical loading. Studies have shown that a larger KAM is associated with a greater medial to lateral cartilage thickness ratio in the femur and tibia.\textsuperscript{20,94} However, this anabolic effect is lost in individuals at risk of OA (e.g., obesity, older adults).\textsuperscript{93} However, further studies are needed to evaluate the influence of KAM on individuals without injury or disease.

In individuals with early and end stage KOA, a larger KFM has been associated with thicker cartilage across the tibia.\textsuperscript{95,96} Moreover, there is a positive association between thicker femoral cartilage and knee flexion impulse (equating to the area under the KFM curve when graphed over a gait cycle) in individuals with ACL reconstruction.\textsuperscript{93}
There is also a similar relationship between peak knee flexion angle and knee flexion excursion and cartilage thickness. Other studies indicate that a larger KFM has been associated with thicker medial femoral cartilage in healthy individuals when measured using ultrasound. However, research has also shown no relationship between the KFM and individuals without injury, whilst studies in individuals with patellofemoral pain find that thinner cartilage is associated with a larger KFM.

During a gait cycle, the knee flexes between 0-60° of knee flexion under typical conditions without pathology. The peak knee flexion moment (KFM) is during the first 20-30% of the gait cycle when the knee is flexed between 0-10°. The KAM has two distinct peaks with the first occurring commonly between 20-30% of a gait cycle and the second occurring later at approximately 75% of gait. When using MRI, studies have identified that the portion of the femoral trochlea that is in contact with the patella during the first 20-30% of the gait cycle has the thickest cartilage of the distal femur in both old and young adults. This portion of the anterior distal femur is estimated to contact the patella when the knee is flexed between 0-10° and thus is in line with the peak KFM during gait and where peak patellofemoral contact occurs. The next thickest portions of cartilage among healthy individuals are at the weight bearing femoral condyles. These portions contact the tibia during 0-10° of flexion again coinciding with a peak KFM and KAM during the early stance phase of gait. Areas in between regions that experience consistent compressive loads during gait have thinner cartilage and may be more susceptible to cartilage lesions due to their inability to adequately disperse compressive force when needed.
Knee kinematics are affected by age and injury. At 3-5 months post ACL surgery, there are deficits of 4 degrees in knee flexion angle range of motion.\textsuperscript{105} This decrease in knee flexion during gait also exists 3 years after surgery.\textsuperscript{106} Following initial ground contact the knee rapidly flexes and eccentric knee extensor control is needed to slow the body’s progress over the stance limb. Individuals with ACL reconstruction have decreased shank angular velocity in the injured limb.\textsuperscript{107} This coupled with the reduced knee flexion ROM suggested altered gait kinematics following injury. Contact stress within the knee joint may be shifted during gait to areas of cartilage that are thinner and have not previously received large amounts of compressive force. This may explain why individuals who sustain injuries that manipulate gait patterns are more susceptible to cartilage thinning and KOA.\textsuperscript{108}

Sex-specific regional differences in the mean and maximal cartilage thickness have also been examined but results are conflicting. Within the patellofemoral joint, regional differences between sexes were insignificant when imaged using MRI.\textsuperscript{12} Literature has also shown no significant differences in the tibiofemoral joint between sexes.\textsuperscript{68} However, females had a larger reduction in femoral and patellar cartilage thickness compared to males, while males had a larger change in tibial cartilage thickness four years after ACL reconstruction.\textsuperscript{109} This may suggest that females are more prone to cartilage damage within the patellofemoral joint whilst males are more vulnerable within the tibiofemoral joint. However further investigation is needed into regional differences in cartilage thickness across healthy males and females and their potential causes.
2.7  Sex Differences in Gait

One potential contributor to differences in cartilage morphology between sexes is gait biomechanics. A higher quadriceps angle has been associated with a higher KAM and knee adduction angle (KAA) during gait and this has been found to increase the prevalence of patellofemoral OA within an elderly population.\textsuperscript{110} This higher quadriceps angle is also more prevalent in females.\textsuperscript{111} Females exhibit a larger KAM than males when normalized to body weight and height.\textsuperscript{112} More recent literature has also found that females walk with a 34\% greater KAM than males when normalized with no difference between males and females in absolute KAM.\textsuperscript{24} This study also found that females had a 25.7\% higher knee varus velocity (KVV) than males during gait. In a study of 236 individuals, it was found that those with increased KVV had both increased peak knee varus angle and peak knee varus angular velocity.\textsuperscript{113} This would contribute to an increase in medial knee load during each stance phase of a gait cycle.

Elderly females have a higher KAM than males, which was driven by narrow step width and greater pelvic width to height ratio. It may be that there is a positive association between KAM and cartilage morphology in young females\textsuperscript{94}, but the opposite is true for older adults. Frontal plane loading during gait differs between males and females, which may contribute to alterations in cartilage thickness across the femur. Further research is needed to highlight if frontal plane loading is detrimental for cartilage health in young adults without OA.

There are also differences between males and females in sagittal plane knee mechanics during gait. Females use less knee flexion when preparing for the weight bearing stage of gait.\textsuperscript{114} The knee flexion angle (KFA) at ground contact is associated
with variations in the portions of cartilage that are thickest across the femur. This suggests that knee kinematics and surface contact points of cartilage differ between sexes, which may contribute to regional variation of femoral cartilage that differs between males and females. Additionally, females have lower ranges of flexion and extension during the stance phase compared with males. Individuals with KOA also have lower peak knee flexion and knee flexion excursion (the difference between peak knee flexion angle and the knee flexion angle at initial heel contact) during gait. Females have higher KFM during specific time points of gait when normalized to body weight and height. The results of these studies could indicate that females would have thicker cartilage in the patellofemoral joint than males. However, these studies normalized kinetic outcomes to body weight and height and may not have considered other anatomical factors such as femoral size that affect the dispersion of compressive forces. Furthermore, another study has shown that healthy females have lower peak KFM when normalized to body weight and height than males, but not in individuals with obesity. This study also found that males have greater absolute peak KFM and other literature has shown that males have greater absolute total joint forces in the knee during gait. This may provide some understanding as to why most literature shows that males have thicker cartilage than females in the knee joint.

2.8 Summary

Articular cartilage is important for knee function and activities of daily living. Ultrasound imaging is a cost-effective alternative to MRI for measuring cartilage thickness. However, knee position during imaging may influence cartilage measurements. As the knee flexes the patella moves inferiorly exposing a different portion of the femur to the ultrasound probe. Thickness across the distal femur is not uniform. Contact area and
mechanical stress differ as the knee flexes during gait, which may contribute to regional
differences in cartilage thickness. Unique vantage points of differing areas of femoral
cartilage may be observed if ultrasound imaging is taken at different testing positions to
provide a comprehensive evaluation of the joint. Knee biomechanics differ between males
and females, which may contribute to regional cartilage morphology differences across
the femur.

Chapter 3

3 Methodology

3.1 Participants

Twenty-five male and 25 female Western University students were recruited and
matched on age (± 2 years) and BMI (± 2 BMI points). Participant characteristics can be
found in Table 1. Estimations of associations between predictor variables and cartilage
characteristics and effect size between groups and cartilage characteristics from previous
studies were used to estimate sample size. Previous literature using MRI found that
posterior femoral cartilage was significantly different in thickness compared to anterior
femoral cartilage with an effect size of 0.91. Studies assessing sex differences in
cartilage thickness using ultrasound have found that males have significantly thicker
cartilage than females in the lateral and medial condyles with an effect size of 0.67. A
priori sample size estimation (G*power Version 3.1, Dusseldorf Germany) indicated that
21 participants were needed to achieve a power 0.80 (assuming effect size of 0.8, α=0.05,
β=0.20). We oversampled to account for methodological differences compared to previous
studies that the effect size for our priori sample estimation was based on.
Participants were included if they were (1) between 18-30 years old, (2) BMI between 18.5-30.0, (3) self-reported participation in exercise 3 or more times a week. Participants were excluded for: (1) lower extremity injury within the preceding 6 months of participation, (2) history of lower extremity surgery or knee OA, (3) lower extremity pain.

3.2 Ultrasound Imaging

All participants were instructed to not undertake exercise immediately prior to the investigation to not limit compression of articular cartilage. Participants rested in a nonweight bearing supine position prior to ultrasound imaging, with their knees fully extended for 30 minutes to unload femoral cartilage. A Logiq E ultrasound device with a 12-5MHz linear array transducer were used to image femoral cartilage (frequency: 12 Hz, depth: 4.0cm, gain: 50). While supine participants had their knees position at 140°, 115° and 90° of flexion using a handheld goniometer by positioning it upon the centre of the knee joint and creating an angle between the lateral malleolus and the greater trochanter (Figure 1). Limb and knee position were tested in a block-randomized order using a random number generator. The probe was placed in the transverse plane superior to the patella over the medial and lateral condyles of the femur. Three images were obtained from both knees by a single technician who was trained by an expert with more than 10 years of musculoskeletal ultrasound imaging experience. 140° and 90° of knee flexion were chosen as 1) they are the most cited positions within the literature and 2) they expose the load bearing portion of distal anterior femoral articular cartilage with limited obstruction from surrounding soft tissue. 115° was selected as an intermediate position that provided sufficient difference to exceed measurement error in handheld goniometry.
3.3 Gait Biomechanics

Three-dimensional gait biomechanics were collected as participants completed five overground walking trials at a self-selected speed along a 10m walkway. All participants wore laboratory standard neutral cushion footwear and tight-fitting shorts to minimize marker motion on clothing. Marker position and force plate data were acquired using an 8-camera motion capture system (Qualisys, Göteborg, Sweden) and two force platforms (AMTI, Germantown MD) sampling at 200Hz (marker data) and 2000 Hz (force data). Walking speed was maintained within ±5% of self-selected speed and monitored using infrared timing gates (Tractronix, Belton, MO) placed 2m apart surrounding the force plates. Bilateral calibration markers were placed on the anterior superior iliac spine (ASIS), greater trochanters, medial and lateral femoral condyles, malleoli, calcaneus, and first and fifth metatarsal heads. Rigid clusters of 4 non-collinear markers were firmly affixed on the sacrum, and bilaterally on the thigh, shank, and foot segments (Figure 2).
Calibration markers were removed after a standing static trial, and only cluster markers remained for dynamic trials. Five practice trials were collected and averaged to obtain self-selected walking speed and confirm participants could strike the force plate without visibly altering their gait. Participants were instructed to continue walking after contacting the force plate to avoid deceleration. Trials were deemed acceptable if (1) the entire foot contacted the force platform, (2) participants did not exhibit visible gait deviations, and (3) walking speed was within ±5% of self-selected pace.

**Figure 2:** Marker placement upon an individual (Anterior view on the left, Posterior view in the centre) and identification of marker set on Qualisys (Right).

### 3.4 Data Reduction

Marker position and force plate data were exported to Visual 3D (C-Motion Inc., Germantown, MD; Figure 3) for model construction and low-pass filtered at 6Hz using a 4th order zero-phase lag digital Butterworth filter based on residual analysis. Ankle and knee joint centres were estimated as the midpoints between the medial and lateral malleoli and femoral epicondyles. The hip joint centre was estimated using the Davis method. A joint coordinate system was used to derive knee angles defined as motion...
of the shank relative to the thigh. Knee joint moments were calculated using inverse dynamics and resolved in the tibial coordinate system (reported as external). Stance phase was identified as between when vertical GRF exceeded 20N and fell below 20N. As we were primarily interested in outcomes that contribute to joint loading, we assessed the peak KFM and peak KAM. Ensemble average waveforms for the average KFM and KAM for males and females were time-normalized to 101 data point and plotted for visualization purposes (Figure 5). An average of ten trials were used for analyses per participant (five from each limb).

Ultrasound images were analyzed using a custom MATLAB program by an investigator that was blinded to sex and measurement position, and intra- and inter-rater reliability was assessed during pilot testing in 5 individuals. The Euclidian distance from the hyperechoic cartilage-bone interface to the synovial space-cartilage interface between 300 evenly spaced data points was used to measure thickness, and the average thickness from data points 1-100, 101-200, and 201-300 represented thickness of the medial, central, and lateral regions of the anterior distal femur (Figure 4). Echo-intensity was assessed via tracing the cartilage cross-sectional area from the same portions of cartilage. Each pixel in the traced image received a value based on brightness on a scale of 0 (darkest) to 255 (brightest), with the average representing EI.
3.5 Statistical Analyses
Statistical analyses were completed using SPSS Version 28 (IBM, Armonk, NY).
Data were inspected for normality using a Shapiro-Wilk test and assessed for outliers.
using box plots. Intrarater and interrater reliability of ultrasound measures were assessed using intraclass correlation (ICC\(^{3,1}\)), and ICCs were classified as low (< 0.5), moderate (0.5-0.69), and good (> 0.7) in 5 participants prior to the start of the study.

Cartilage outcomes were compared between imaging positions and sex using a three (Position: \(90^\circ, 115^\circ, 140^\circ\)) by two (Sex: Male, Female) repeated measures ANOVA (\(\alpha= 0.05\)). Post hoc comparisons were conducted using independent and dependent samples t-tests using a Bonferroni correction.

Separate stepwise linear regression models were used to evaluate the unique associations between gait biomechanics and cartilage factors for males and females. Covariates included gait speed and BMI, which were entered first and followed by gait kinetics using stepwise entry. Body mass index is associated with gait biomechanics and cartilage thickness\(^ {119}\) and gait speed influences gait kinetics and is also related to cartilage metabolism.\(^ {123}\)

Chapter 4

4 Results

Descriptive statistics for participant variables are outlined in Table 1. All data were normally distributed and treated as such. Good to excellent intrarater reliability was found for all ultrasound-derived outcomes (Table 2). All data were normally distributed and treated as such.
Table 1: Descriptive Statistics for Participants

<table>
<thead>
<tr>
<th></th>
<th>Female (n=25)</th>
<th>Male (n=25)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>20.60±1.84</td>
<td>20.64±1.75</td>
<td>0.46</td>
</tr>
<tr>
<td>BMI</td>
<td>23.25±2.91</td>
<td>23.52±2.67</td>
<td>0.36</td>
</tr>
<tr>
<td>Gait speed (m/s)</td>
<td>1.40±1.11</td>
<td>1.48±1.56</td>
<td>0.06</td>
</tr>
<tr>
<td>Peak KFM</td>
<td>56.34±11.87</td>
<td>69.54±13.77</td>
<td>0.01</td>
</tr>
<tr>
<td>Peak KAM</td>
<td>30.11±6.98</td>
<td>37.82±9.33</td>
<td>0.03</td>
</tr>
<tr>
<td>Peak KFM (Bw*Ht)</td>
<td>0.06±0.02</td>
<td>0.06±0.02</td>
<td>0.37</td>
</tr>
<tr>
<td>Peak KAM (Bw*Ht)</td>
<td>0.03±0.01</td>
<td>0.02±0.01</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 2: Intra- and inter-rater reliability analyses from preliminary data (n=5 participants; 3 images per participant from 2 raters). Intraclass correlation and 95% confidence interval were calculated within raters from 3 images (ICC_{3,1}), and between raters from the average of 3 images per rater (ICC_{3,k}).

<table>
<thead>
<tr>
<th></th>
<th>Intra rater (ICC_{3,1})</th>
<th>Inter rater (ICC_{3,k})</th>
</tr>
</thead>
<tbody>
<tr>
<td>140°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial thickness</td>
<td>0.858 (0.485, 0.983)</td>
<td>0.920 (0.235, 0.992)</td>
</tr>
<tr>
<td>Central thickness</td>
<td>0.736 (0.221, 0.965)</td>
<td>0.940 (0.425, 0.994)</td>
</tr>
<tr>
<td>Lateral thickness</td>
<td>0.844 (0.447, 0.981)</td>
<td>0.971 (0.724, 0.997)</td>
</tr>
<tr>
<td>Medial Echo-intensity</td>
<td>0.839 (0.187, 0.982)</td>
<td>0.847 (0.191, 0.969)</td>
</tr>
<tr>
<td>Central Echo-intensity</td>
<td>0.760 (0.190, 0.974)</td>
<td>0.660 (0.168, 0.965)</td>
</tr>
<tr>
<td>Lateral Echo-intensity</td>
<td>0.700 (0.122, 0.966)</td>
<td>0.864 (0.310, 0.986)</td>
</tr>
<tr>
<td>115°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial thickness</td>
<td>0.945 (0.782, 0.994)</td>
<td>0.941 (0.433, 0.994)</td>
</tr>
<tr>
<td>Central thickness</td>
<td>0.869 (0.547, 0.984)</td>
<td>0.985 (0.858, 0.998)</td>
</tr>
<tr>
<td>Lateral thickness</td>
<td>0.905 (0.651, 0.989)</td>
<td>0.832 (0.281, 0.947)</td>
</tr>
<tr>
<td>Medial Echo-intensity</td>
<td>0.864 (0.508, 0.984)</td>
<td>0.976 (0.769, 0.997)</td>
</tr>
<tr>
<td>Central Echo-intensity</td>
<td>0.671 (0.108, 0.955)</td>
<td>0.755 (0.181, 0.905)</td>
</tr>
<tr>
<td>Lateral Echo-intensity</td>
<td>0.739 (0.346, 0.971)</td>
<td>0.776 (0.200, 0.916)</td>
</tr>
<tr>
<td>90°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial thickness</td>
<td>0.811 (0.407, 0.976)</td>
<td>0.938 (0.252, 0.987)</td>
</tr>
<tr>
<td>Central thickness</td>
<td>0.729 (0.207, 0.964)</td>
<td>0.899 (0.030, 0.989)</td>
</tr>
<tr>
<td>Lateral thickness</td>
<td>0.854 (0.220, 0.984)</td>
<td>0.976 (0.766, 0.997)</td>
</tr>
<tr>
<td>Medial Echo-intensity</td>
<td>0.892 (0.543, 0.987)</td>
<td>0.838 (0.218, 0.967)</td>
</tr>
<tr>
<td>Central Echo-intensity</td>
<td>0.942 (0.741, 0.984)</td>
<td>0.664 (0.159, 0.945)</td>
</tr>
<tr>
<td>Lateral Echo-intensity</td>
<td>0.648 (0.094, 0.934)</td>
<td>0.753 (0.179, 0.926)</td>
</tr>
</tbody>
</table>
4.1 Intersex Cartilage Thickness Comparison

**Medial Region**

There was a significant sex by position interaction effect ($F_{2.96} = 6.11$, $p<0.01$) (Figure 6). Females had no significant difference between cartilage thickness at any measurement position, but males had significantly thicker cartilage when measured at 90° than at 115° ($p=0.02$) and 140° ($p<0.01$) and at 115° than at 140° ($p=0.03$). Females also had thinner cartilage compared with males when measured at 90° ($p<0.01$), 115° ($p<0.01$), and 140° ($p<0.01$). (Table 3).

There was a significant main effect of position ($F_{2.96} = 7.78$, $p<0.01$). Thicker cartilage was found when measured at 90° compared to 140° ($p<0.01$), (2.14mm [95% CI: 2.06mm, 2.23mm] vs 2.00mm [95% CI: 1.92mm, 2.09mm]).

There was a significant main effect of sex ($F_{1.48} = 23.70$, $p<0.01$). Females had thinner cartilage than males (1.88mm [95% CI: 1.77mm, 1.99mm] vs 2.26mm [2.15mm, 2.37mm]).

**Central Region**

There was a significant sex by position interaction ($F_{2.96} = 9.73$, $p<0.01$) (Figure 7). Females had thicker cartilage when measured at 90° compared to 140° ($p<0.01$) and 115° compared to 140° ($p<0.01$), while males had significantly thicker cartilage at 90° compared to 115° ($p=0.01$) and 140° ($p<0.01$) as well as at 115° compared to at 140° ($p<0.01$). Females had thinner cartilage than males at 90° ($p<0.01$), 115° ($p<0.01$), and 140° ($p<0.01$). (Table 3).
There was a significant main effect of position ($F_{2.96}=88.45, p<0.01$). Thicker cartilage was found at 90° compared to 115° ($p=0.02$) and 140°, ($p<0.01$) and at 115° compared to 140° ($p<0.01$) in the central compartment (3.13mm [95% CI: 2.99mm, 3.27mm] vs 3.00mm [95% CI: 2.88mm, 3.13mm] vs 2.54mm [95% CI: 2.42mm, 2.66mm]).

There was a significant main effect of sex ($F_{1.48}=13.29, p<0.01$) Females had thinner cartilage than males (2.68mm [95% CI: 2.52mm, 2.85mm] vs 3.10mm [95% CI: 2.94mm, 3.26mm]).

**Lateral Region**

There was no significant interaction effect between sex by position (Figure 8). There was a significant main effect of position ($F_{2.96}=38.72, p<0.01$). Thicker cartilage was found at 90° compared to 115° ($p<0.01$) and 140° ($p<0.01$), (2.22mm [95% CI: 2.14mm, 2.31mm] vs 2.13mm [95% CI: 2.04mm, 2.21mm) vs 2.12mm [95% CI: 2.04mm, 2.19mm]).

There was a significant main effect of sex ($F_{1.48}=29.73, p<0.01$). Females had thinner cartilage than males (1.95mm [95% CI: 1.85mm, 2.25mm] vs 2.36mm [95% CI: 2.25mm, 2.46mm]).

**4.2 Intersex Cartilage Echo-intensity Comparison**

**Medial Region**

There was a significant sex by position interaction effect ($F_{2.96}=72.14, p<0.01$). (Figure 9). Females had higher EI values at 90° than males ($p=0.02$). (Table 3).
Central Region

There was not a significant interaction effect between sex by position (Figure 10). There was a significant effect of position ($F_{2.96}=36.04$, $p<0.01$). Cartilage EI was lower at 90° than at 115° ($p<0.01$) and 140° ($p<0.01$) and was lower at 115° compared to 140° ($p<0.01$), (63.94 [95% CI: 58.78, 69.10] vs 72.87 [95% CI: 68.02, 77.73] vs 80.63 [95% CI: 76.37, 84.90]).

Lateral Region

There was not a significant interaction effect between sex by position (Figure 11). There was a significant effect of position ($F_{2.96}=38.72$, $p<0.01$). Cartilage EI was lower at 90° than at 115° ($p<0.01$) and 140° ($p<0.01$) and was lower at 115° compared to 140° ($p<0.01$), (12.31 [95% CI: 10.41, 14.21] vs 16.61 [95% CI: 15.05, 18.16] vs 20.11 [95% CI: 18.29, 21.92]).

4.3 Associations Between Gait and Cartilage Features

Co-variates explained 2-28% of variance for cartilage thickness and EI. A summary of covariate contributions can be found in Appendix D (Tables 4-8). A larger KFM was associated with thicker medial cartilage in males when measured at 115° ($\Delta R^2=0.245$, $p=0.03$). However, while the addition of the KFM produced a significant increase in the coefficient of variation ($R^2$), the overall regression model was not significant ($F_{2.24}=2.44$, $p=0.09$). Therefore, we interpret the association as negligible.
Table 3: Cartilage thickness and Echo-Intensity measurements in both males and females at all positions.  
(Mean, 95% confidence interval)

<table>
<thead>
<tr>
<th>Sex</th>
<th>Position</th>
<th>90°</th>
<th>115°</th>
<th>140°</th>
<th>90°</th>
<th>115°</th>
<th>140°</th>
<th>P-value</th>
<th>Sex</th>
<th>Position</th>
<th>Sex X Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td></td>
<td>1.89 (1.78-2.01)</td>
<td>1.86 (1.75-1.98)</td>
<td>1.88 (1.78-1.98)</td>
<td>2.40 (2.25-2.54)</td>
<td>2.26 (2.10-2.41)</td>
<td>2.13 (1.99-2.27)</td>
<td>0.001</td>
<td>0.004</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td></td>
<td>2.82 (2.68-2.96)</td>
<td>2.79 (2.65-2.94)</td>
<td>2.43 (2.26-2.61)</td>
<td>3.44 (3.21-3.68)</td>
<td>3.21 (3.00-3.43)</td>
<td>2.65 (2.47-2.82)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td></td>
<td>2.02 (1.92-2.12)</td>
<td>1.92 (1.82-2.02)</td>
<td>1.92 (1.84-2.01)</td>
<td>2.43 (2.28-2.57)</td>
<td>2.34 (2.20-2.48)</td>
<td>2.31 (2.18-2.43)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.763</td>
<td></td>
</tr>
<tr>
<td>Cartilage thickness (mm)</td>
<td></td>
<td>83.89 (77.30-90.49)</td>
<td>79.08 (71.69-86.47)</td>
<td>76.37 (70.21-82.53)</td>
<td>71.74 (65.08-78.40)</td>
<td>72.10 (64.00-80.20)</td>
<td>78.20 (71.09-85.31)</td>
<td>0.175</td>
<td>0.583</td>
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<tr>
<td>Medial cartilage EI (0-255)</td>
<td></td>
<td>65.32 (58.64-71.99)</td>
<td>75.93 (67.93-83.92)</td>
<td>86.72 (80.23-93.21)</td>
<td>62.56 (54.33-70.80)</td>
<td>69.82 (63.87-75.77)</td>
<td>74.55 (68.68-80.41)</td>
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<tr>
<td>Central cartilage EI (0-255)</td>
<td></td>
<td>13.41 (10.39-16.42)</td>
<td>17.01 (14.50-19.52)</td>
<td>22.18 (19.47-24.89)</td>
<td>11.21 (8.72-13.70)</td>
<td>16.20 (14.22-18.17)</td>
<td>18.03 (15.47-20.59)</td>
<td>0.101</td>
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Figure 5: Ensemble average waveform and 95% confidence interval of the external absolute (A&B) and normalized (C&D) knee flexion moment and the external knee adduction moments for males (blue) and females (red).
Figure 6: Medial cartilage thickness at 90°, 115° and 140° for both males and females with 95% confidence intervals.

Figure 7: Central cartilage thickness at 90°, 115° and 140° for both males and females with 95% confidence intervals.
Figure 8: Lateral cartilage thickness at 90°, 115° and 140° for both males and females with 95% confidence intervals.

Figure 9: Medial cartilage echo-intensity at 90°, 115° and 140° for both males and females with 95% confidence intervals.
Figure 10: Central cartilage echo-intensity at 90°, 115° and 140° for both males and females with 95% confidence intervals.

Figure 11: Lateral cartilage echo-intensity at 90°, 115° and 140° for both males and females with 95% confidence intervals.
Chapter 5

5 Discussion

The purpose of this study was to compare femoral cartilage thickness and EI when measured using ultrasound imaging at 90°, 115°, and 140° of knee flexion between males and females, and to assess the association between gait biomechanics and cartilage outcomes.

Our primary findings indicate that cartilage is thicker in the medial, central, and lateral compartment at 90° than at 140°, thicker in the central compartment at 115° than at 140° and thicker in the lateral portion at 90° than at 115°. These effects were influenced by sex, and males had a larger difference between measurement positions in cartilage thickness in medial and central cartilage between positions than females. EchoIntensity values were lower in the central and lateral compartments at 90° compared to 115° and 140° and lower when measured at 115° compared to 140°. We also found consistent main effects of sex, indicating that femoral cartilage was thicker in males than females at all positions.

5.1 Cartilage Thickness Between Measurement Positions

Thicker femoral cartilage was found when measured at 90° of knee flexion than at 140° in all compartments of cartilage which agreed with our hypothesis. If probe placement is suprapatellar, then potions of the femur in view will change as the knee flexes due to inferior patella translation. Therefore, ultrasound imaging of the knee using maximal knee flexion likely provides a view of an inferior portion of the distal femur. Cartilage morphology is not uniform across the distal femur and thicker cartilage is found at the anterior intercondylar notch and posterior medial and lateral condyles of
the distal femur compared to the rest of the bone surface. These portions align with areas of the knee joint that experience the most contact force during gait. Peak patellofemoral and tibiofemoral contact force occur at 20% of stance phase when the knee is flexed between 10-20° in healthy individuals (Figure 12). When the knee is flexed to 90°, the patella translates inferiorly about the femur to such an extent that the portion of cartilage that is experiencing patellofemoral contact force at the peak KFM is in view of the ultrasound probe. The portion of the femur that experiences tibiofemoral contact force during 10-20° of flexion cannot be viewed with a suprapatellar ultrasound probe placement as anatomically the patella cannot translate inferiorly enough to show the posterior femur even in maximum knee flexion (Figure 12). Cartilage measured at 140° of knee flexion may not provide a view of cartilage that articulates with the patella or tibia during peak KFM. This may explain why cartilage viewed at 140° of knee flexion is thinner than at other measurement positions in control individuals.

5.2 Interaction Effect of Sex and Position on Cartilage Thickness

There was an interaction effect of sex and position. Cartilage was thinner when measured at 90° compared to 115° and 140° and at 115° compared to 140° but this effect was mainly found in males for both medial and central cartilage. Cartilage thickness distributions differ in males and females across the distal femur, which are partially attributable to differences in knee anatomy between sexes. Females have a shallower distal femur with 21% less total knee joint surface area at this portion of the bone. Most ultrasound probes measuring femoral cartilage range in length from 4-7cm with a width of 1cm. The distal femur has an approximate surface area of 5478mm² in females and
6554mm$^2$ in males. This would mean that the ultrasound probe can view approximately 3% more of the female femoral trochlea than the male in a single view. Therefore, the ultrasound probe may be viewing a portion of the femur that was visible at a previous measurement position in females, but not in males. This may explain why thickness differences between positions were found in males because a larger knee joint surface would make it easier to view unique areas of the joint by manipulating testing position. Therefore, sex is an important characteristic to consider for future research implementing ultrasound to view femoral cartilage. A smaller probe may be beneficial to use in females or in individuals with smaller knees to increase precision. Alternatively, if trying to comprehensively quantify cartilage thickness, then 2 positions of knee flexion (90°, 140°) may be suitable for females whereas males may require 3 (90°, 115° and 140°).

5.3 Echo-intensity Between Measurement Positions

Central and lateral EI was lower in males and females when femoral cartilage was measured at 90° of knee flexion compared to 115° and 140° and at 115° compared to 140°. Previous research using MRI has shown that T2 relaxation times were higher in the posterior central portion of the distal femur than in the anterior central and the posterior femoral trochlea. T2 relaxation time of cartilage provides a measure of cartilage structural integrity and water content, and longer times are inversely correlated with collagen network organization and structure. Ultrasound EI has also been used to measure cartilage composition. Individuals with no cartilage thinning but are at risk for OA, have higher EI scores than controls despite having no difference in cartilage thickness. Greater osteophyte formation and cartilage thinning in individuals with OA are seen in areas of the femur that experience low habitual mechanical stress with
sporadic amounts of elevated contact force. This area of femoral cartilage may be synonymous with the area viewed at 140° of knee flexion and may mean that this area is most susceptible to deformation. Therefore, results from this study indicate that femoral cartilage when measured in a more knee flexed position may be less resistant to deformation.

5.4 Cartilage Differences Between Males and Females
Anatomical differences may partially explain why males had thicker cartilage across all positions than females. Males have 23% thicker cartilage than females across the distal femur. This may be in part to males having a greater femoral aspect ratio (mediolateral distance versus anteroposterior distance) and larger distal femoral heads than females to adjust for larger compressive force. We also found that absolute KFM and KAM were greater in males compared with females in this study, which contribute to greater knee compressive forces that may explain the difference in cartilage thickness. Alternatively, when normalized there was no difference in knee moments between sexes. However, this study only normalized joint moments to body weight and height, and the knee joint does not scale proportionally to body size. Factors such as femoral shaft length and muscle mass percentage have been associated with cartilage thickness. Research indicates that males have a larger muscle mass percentage within the quadriceps relative to body size, which may provide a protective factor against cartilage thinning. Further evaluations of individuals’ musculoskeletal properties may be useful to explain differences in cartilage morphology between sexes.
5.5 Associations Between Gait Biomechanics and Cartilage Outcomes

No relationships were found between gait biomechanics and cartilage features despite numerous group differences among both outcomes. We hypothesized that a greater KFM would be associated with thicker cartilage. Previous research using ultrasound found that the KFM was associated with thicker medial femoral cartilage in control subjects. This differs from our findings but may be due to probe placement. Previous research placed the probe transversely over the medial femoral condyle at 90° of knee flexion. This position may be able to view cartilage that is affected differently by patellofemoral and tibiofemoral compressive force during gait than when the probe is placed transversely over the superior portion of the patella.

Peak KAM has also been associated with an increased medial to lateral thickness ratio in healthy populations, but associations between peak frontal and sagittal gait biomechanics and cartilage thickness are seldom explored outside of studies involving patients with OA or individuals with increased risk of OA (e.g., individuals with obesity or those with ACL injury). In control populations without cartilage impairments, the low physical demands of walking may mask the association between mechanical loading and cartilage features. Alternatively, other tasks such as running or landing that involve higher weight-bearing stress may provide greater variability in biomechanical outcomes. A large degree of variance is seen within patellofemoral contact force when gait is performed on a variety of gradients. For instance, in jumping tasks, the peak KFM is associated with smaller T2 relaxation times in femoral and tibial cartilage. Similarly, in recreational runners a higher peak KFM was associated with a lower cartilage EI within the medial compartment. Recreationally active individuals perform a variety of
movements throughout the day. We assessed biomechanical features from a single step, which may be insufficient to establish associations between habitual loading and femoral cartilage features. Future studies should consider the role of cumulative load on cartilage features that considers the interaction between gait biomechanics and activities of daily living.

5.6 Study Strengths

Males and females were closely matched by age (±1 year) and BMI (±1 BMI point). Age and BMI are strongly associated with cartilage characteristics and gait biomechanics. Therefore, matching participants provides control for these confounders and reduces the variance within our parameters of interest (cartilage characteristics and gait biomechanics), which improves statistical efficiency. Secondly, previous research assessed regional cartilage thickness at a single site in the joint. Conversely, we assessed cartilage thickness across the entire bone surface, with average thickness across each compartment used for thickness measurements. This provides a more robust representation of cartilage thickness compared to single measurements between the cartilage bone interface to the synovial space cartilage interface. Thirdly, a separate investigator conducted all image segmentation and was blinded to both sex and joint position to reduce rater bias. Finally, efforts were made to control variables that affect gait biomechanics when assessing walking patterns using motion capture. For instance, cluster markers were used to reduce the influence of motion artifact, laboratory standard footwear and form-fitting clothing were used for all participants, and gait speed was maintained within 5% of the individuals’ practice trials.
5.7 Study Limitations

There are limitations to consider when interpreting the results of this study. Firstly, the cross-sectional study design impairs the ability to ascertain if gait biomechanics or sex determine differences in cartilage characteristics. Secondly, we only assessed the distal femoral cartilage. Associations between cartilage thickness within the tibia and gait biomechanics have been seen in previous literature in controls.\textsuperscript{65,104}

Furthermore, assessments of cartilage were made using a suprapatellar probe placement, which does not evaluate the posterior area of the femur. A previous study found an association between the KFM and medial cartilage thickness when viewing cartilage at $90^\circ$ with the probe placed transversely over the medial femoral condyle.\textsuperscript{21} Therefore, a comprehensive assessment of knee cartilage using ultrasound should consider more than one position of probe placement. Furthermore, ultrasound assessments of cartilage are limited by probe size, and the medial and lateral convex surfaces of the femur are outside the view of the probe. However, these areas likely experience very little contact with the patella or tibia during gait and are not of interest in the context of knee loading and cartilage. Next, gait biomechanics were only assessed over a single step. Single-step biomechanics do not accurately approximate habitual loading from activities of daily living. Further studies assessing habitual loading in addition to gait biomechanics may give more insight into associations between cumulative loading and cartilage characteristics.

5.8 Conclusion

Findings indicate that knee position during ultrasound image acquisition influences femoral cartilage features and should be considered by clinicians and researchers for future study designs. Moreover, measurement position had a greater effect
on cartilage thickness measures in males compared with females. Males also had thicker cartilage than females across the distal femur. However, within this sample, the external KFM and KAM during walking were not associated with any cartilage outcome. Further studies may evaluate if biomechanics during more demanding tasks that elevate mechanical loading are associated with cartilage features.

Figure 12: Images showing the knee flexed at 20° (A), 90° (B) and 140° (C) of flexion. The blue box represents patellofemoral contact, and the red box represents peak tibiofemoral contact at the point of knee flexion where the peak knee flexion moment occurs (A). The blue and red box translate to show where these contact positions have shifted to when the knee is flexed to 90° (B) and 140° (C). The arrow indicates ultrasound probe placement and the portion of cartilage that is in view at both positions.
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Appendices

Appendix A: Data Collection Form

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**Data Collection Sheet**

Date: 
Database ID: 
Assessors Staff ID: 

<table>
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<tr>
<th>Age:</th>
<th>Sex:</th>
<th>Height:</th>
<th>Mass:</th>
<th>Dominant Limb: R/L</th>
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**Imaging (check completed) (12 MHz, Gain: 50, Depth 4cm)**

<table>
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<tr>
<th>Cartilage</th>
<th>90 degrees</th>
<th>115 degrees</th>
<th>140 degrees</th>
</tr>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td></td>
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R Max Knee Flexion: _______  L Max Knee Flexion: _______

**Biomechanics (check completed and enter walking speed)**

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<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
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<tbody>
<tr>
<td>Right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Left</td>
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</tbody>
</table>

Speed: ___________

**Notes:**
Appendix B: Letter of information and Consent form

University of Western Ontario School of Kinesiology

Informed Consent to Participate in the Research Study:

The influence of knee position and sex on ultrasound images of femoral cartilage and their relationship with gait

Principle Investigator:

Derek Pamukoff, Ph.D

Co-Investigator:

Harry Battersby, Graduate Student

Funding Source: This study will be funded through the NSERC 2022 Grant, Discovery and Research Tools and Instruments

Conflict of Interest: There are no conflicts of interest to declare related to this study

Introduction:

• You are being invited to participate in this research study about the influence of knee position and sex on knee cartilage characteristics.

• You were selected as a possible participant because you are between the ages of 18-30 years, have a body mass index between 18.5-30, participate in exercise at least three times a week and meet all the screening criteria regarding lower extremity injury history.

• We ask that you read this form and ask any questions that you may have before agreeing to participate in the study.
Purpose of Study:

- The purpose of this study is to investigate whether knee position influences cartilage characteristics in males and females when measured using ultrasound imaging. A secondary purpose is to examine relationships between cartilage characteristics and gait biomechanics.

- Participants in this study are from the University of Western Ontario, we anticipate up to 50 individuals will be enrolled in this study and the study should take 4-6 months to complete.

Description of the Study Procedures:

If you agree to participate in this study, we will ask you to visit the biomechanics testing laboratory, within Thames Hall at the University of Western Ontario, for 1 testing session. The session will last approximately 60 minutes. During the session, we will obtain measures of patellofemoral cartilage thickness and echo intensity via ultrasound imaging. We will also obtain gait characteristics such as knee flexion angles and knee flexion moments from participants gait trials. Each of these assessments is described below.

After reading this informed consent document, and asking any questions you have about the study, you will be asked to fill out a medical history form. The purpose of this form is to ensure it is safe for you to participate in the study and it will take approximately 5 minutes to complete. While we do not intend to use any medical information in this study, we may refer to the telephone screening and/or medical history form in the event that an unexpected trend emerges in the data (for example, a particular medication is impacting the results of the study).

The following experimental procedures will then be carried out.

*Ultrasound Imaging:* You will lay on your back for 30 minutes in non-weight bearing position prior to the imaging. You will then have your knee positioned at 90°, 115° and 140° by the investigator using a handheld goniometer. This will be done aligning the goniometer with the center of your knee and creating an angle between the ankle and hip joint. Ultrasound imaging will be used to measure cartilage thickness within your knee joint. Three measurements will be taken at the top of the kneecap (patella) in order to view cartilage on the end of the femur (thigh
bone). Ultrasound imaging will take approximately 5 minutes after the initial 30 minute unloading period.

Walking trials: 20 Retroreflective markers will be placed on your body at specific landmarks. These will be the front and back of your hip, the mid-point of your thigh, the medial and lateral side of your knee, the mid-point of your shin, your ankle and your toe. You will then perform five practice walking trials down a 10m runway. A force plate will be at the midpoint of your walk which you will make contact with during these trials. You will then perform 10 valid walking trials, 5 each for your right and left foot to contact the force plate. These will be filmed by motion capture cameras in order to measure lower limb kinetics.

Timeline for Testing Procedures and Protocol

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<th>Expected Time (minutes)</th>
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<td>Ultrasound imaging</td>
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<td>Gait Trials</td>
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<td>Total Time</td>
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</table>

Risks/Discomforts of Being in the Study:

- The study has the following risks. When maneuvering the knee to 140 degrees of flexion there may be some discomfort. This is unlikely however if discomfort is felt at any degree of knee flexion, you should let the investigator know and the action will be stopped. The risk here is minimal as you the investigator will be
with you the entire time monitoring your safety and making sure you are comfortable.

- Participation in the study is entirely voluntary and you may ask to stop any testing at any time.
- This study contains no known risks related to pregnancy.
- This study may include risks that are unknown at this time.

Benefits of Being in the Study:

- There are no direct benefits to you for participating in this study. You will, however, be contributing to our understanding of how knee position and sex effect cartilage characteristics within young, physically active individuals.

Voluntary Participation/Withdrawal:

- Your participation in this study is voluntary. You may decide not to be in this study, or to be in the study now and then change your mind later. You may leave the study at any time without affecting your current or future relations with study team personnel or the University.

- You may refuse to answer any questions you do not want to answer, or not answer an interview question by saying “pass”.

- If after fully participating in this research study you would like to be withdrawn from the study, please contact study personnel to permanently remove your data.

- There is no penalty or loss of benefits for not taking part or for stopping your participation in this study.

Dismissal From the Study:
• The investigator may withdraw you from the study at any time for the following reasons: (1) withdrawal is in your best interest (e.g. side effects or distress have resulted) or, (2) you have failed to comply with the study requirements.

Rights of Study Participants:

• If you are harmed as a direct result of your participation in this research study, the investigators of the study will do everything they can to assist you. However, cost of care due to any injury will be covered by the participant and/or his/her insurance company the taking part in this study.
• You do not waive any legal rights by signing the consent form.

Costs and Compensation to Participate:

• There is no cost to you to participate in this research study.
• You will be compensated $20 for your time

Confidentiality

• The records of this study will be kept private and will be maintained for 7 years after the completion of the study.
• Participants will not be named in any reports, publications or presentations that may come from this study.
• Paper records will be kept in a locked file in a locked laboratory.
• All electronic information will be coded and secured using a password protected computer.
• Access to paper and electronic records will be limited to authorized study personnel; however, please note that representatives of Western University’s
Health Sciences Research Ethics Board, that oversees the ethical conduct of this study, may look at your study records for quality assurance purposes.

- All identifiable information collected for the study will be kept confidential and will not be shared with anyone outside the study unless required by law.

Contacts and Questions:

- The primary investigator conducting this study is Derek Pamukoff and the coinvestigator is Harry Battersby. For questions or more information concerning this research you may contact Derek Pamukoff or Harry Battersby.

- If you believe you may have suffered a research related injury, contact Derek Pamukoff at who will give you further instructions.

- If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Human Research Ethics. The REB is a group of people who oversee the ethical conduct of research studies. The HSREB is not part of the study team. Everything that you discuss will be kept confidential.

Copy of Consent Form:

- You will be given a copy of this form to keep for your records and future reference.
Appendix C: Ethics Approval Letter

Date: 25 March 2022

To: Dr Derek Paunkoff

Project ID: 120659

Study Title: Walking patterns and regional knee cartilage mapping using ultrasound imaging

Application Type: HSREB Initial Application

Review Type: Delegated

Meeting Date / Full Board Reporting Date: 12/Apr/2022

Date Approval Issued: 25/Mar/2022

REB Approval Expiry Date: 25/Mar/2023

Dear Dr Derek Paunkoff,

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals and mandated training must also be obtained prior to the conduct of the study.

Documents Approved:

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No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB, except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonization Good Clinical Practice Consolidated Guideline (ICH-GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 000096X0.

Please do not hesitate to contact us if you have any questions. Sincerely,
Appendix D: Covariate Contributions

Table 4: Covariate contributions of BMI and Gait speed in association with cartilage thickness when measured at 90°.

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Table 5: Covariate contributions of BMI and Gait speed in association with cartilage thickness when measured at 115°.

<table>
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<th></th>
<th>Male</th>
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<td>β</td>
<td>t</td>
<td>p</td>
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<td>0.03</td>
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Table 6: Covariate contributions of BMI and Gait speed in association with cartilage thickness when measured at 140°.

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<tbody>
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Table 7: Covariate contributions of BMI and Gait speed in association with echointensity when measured at 90°.

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Table 8: Covariate contributions of BMI and Gait speed in association with echointensity when measured at 115°.

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Table 9: Covariate contributions of BMI and Gait speed in association with echointensity when measured at 140°.

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<th>Male</th>
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</table>
Curriculum Vitae

Harry Battersby

EDUCATION

Western University, London ON
Faculty of Health Science, School of Kinesiology, Department of Integrative Biosciences
Master of Science – Biomechanics focus (2021-2023)
Thesis – The influence of knee position and sex on ultrasound imaging of femoral cartilage characteristics

The University of Portsmouth, Portsmouth UK
Faculty of Health Science, Department of Health and Exercise Science
Bachelor of Science (First class standing, “Designation equivalent to Dean’s Honour Roll”) - Biomechanics focus (2016-2020)
Dissertation – Joint angle and balance asymmetry within the lower limbs of individuals two years post anterior cruciate ligament reconstruction compared to a control population

RESEARCH EXPERIENCE

Western University, London ON

Biomechanics Laboratory (2021 – current)

Wolf Orthopedic Biomechanics Laboratory (2021 – current)

Methodological skillset acquired

Cortex motion capture software

Logiq E – Ultrasound

Biodex Dynamometer

The University of Portsmouth, Portsmouth UK
Biomechanics Laboratory (2018 – 2020)

Methodological skillset acquired

- Qualisys motion capture software
- Helen Hayes marker set
- EMG application and data analysis

**PEER-REVIEWED PUBLICATIONS**


**PRESENTATIONS**


**FUNDING AND SUPPORT**
Canadian MSK Rehab Research Network, 2022 Trainee Travel Awards
Funding time – August 2022
Funding amount = $500
Reason – Travel for *North American Congress on Biomechanics*

**TEACHING EXPERIENCE**
Western University, London, ON

*Teaching Assistant –*

KIN 2241 Biomechanics (2021-present)

- Lead a class of approximately 200 second year university students one to two times a month in going over laboratory assessments and providing an introduction to biomechanics. Also assisted in grading and office hours to give feedback to students on a one-to-one basis.

**MEMBERSHIP IN PROFESSIONAL SOCIETIES**
Canadian Society of Biomechanics (2022 – present)
American Society of Biomechanics (2023 – present)