Computational Investigation of Early-stage Interventions of the Knee

MECH3890 Individual Engineering Project

Computational investigation of early stage interventions of the knee

Authors Name: Ronald Piku

SID: 201208729

Supervisors Name: Dr. Qingen Meng

Examiners Name: Dr. Junfeng Yang

Date of Submission: 29/04/2021

SCHOOL OF MECHANICAL ENGINEERING

UNIVERSITY OF LEEDS

MECH3890 – Individual Engineering Project

TITLE OF PROJECT: Computational investigation of early-stage interventions of the knee.

PRESENTED BY Ronald Piku

STUDENT DECLARATION (from the "LU Declaration of Academic Integrity")

I am aware that the University defines plagiarism as presenting someone else's work, in whole or in part, as your own. Work means any intellectual output, and typically includes text, data, images, sound or performance. I promise that in the attached submission I have not presented anyone else's work, in whole or in part, as my own and I have not colluded with others in the preparation of this work. Where I have taken advantage of the work of others, I have given full acknowledgement. I have not resubmitted my own work or part thereof without specific written permission to do so from the University staff concerned when any of this work has been or is being submitted for marks or credits even if in a different module or for a different qualification or completed prior to entry to the University. I have read and understood the University's published rules on plagiarism and also any more detailed rules specified at School or module level. I know that if I commit plagiarism I can be expelled from the University and that it is my responsibility to be aware of the University's regulations on plagiarism and their importance. I re-confirm my consent to the University copying and distributing any or all of my work in any form and using third parties (who may be based outside the EU/EEA) to monitor breaches of regulations, to verify whether my work contains plagiarised material, and for quality assurance purposes. I confirm that I have declared all mitigating circumstances that may be relevant to the assessment of this piece of work and that I wish to have taken into account. I am aware of the University's policy on mitigation and the School's procedures for the submission of statements and evidence of mitigation. I am aware of the penalties imposed for the late submission of coursework.

Signed: Ronald Piku

Date: 26/04/2021

Table of Contents

1. Chapter 1 – Introduction.....1

1.1 Introduction.....1

1.2 Aims.....2

1.3 Objectives.....2

1.4 Project Report Layout.....3

1.5 Changes to Scope of Project.....3

2. Chapter 2 – Literature Review.....4

2.1 Introduction.....4

2.2 The Anatomy of the Knee.....4

2.3 Osteoarthritis and the Knee.....7

2.4 Effects of Material Properties and Preservation Methods of the Meniscus on Articular Cartilage.....8

2.5 Using FEA Models to Analyze the Knee.....9

2.6 Application of Literature Review to Present Work.....11

2.7 Discussion of Literature Outcomes.....11

3. Chapter 3 – Methods.....13

3.1 Introduction to Models.....13

3.2 Geometry of Models.....13

3.3 Material Properties.....15

3.4 Load and Boundary Conditions.....15

3.5 Outputs of Interest.....16

3.6 Discussion of Methods.....16

4. Chapter 4 – Results.....19

4.1 Results.....19

4.2 Discussion of Results.....21

5. Chapter 5 – Conclusions.....25

5.1 Achievements.....25

5.2 Discussions.....25

5.3 Conclusions.....25

6. Chapter 6 – References.....27

7. Chapter 7 – Appendices.....30

A1 Mesh Convergence Study.....30

A2 Detailed Results.....32

Abstract

This report examined the performance of the knee joint pre and post meniscal replacement surgery and considered which current preservation method for artificial menisci reduces the chance of osteoarthritis the most. It is concluded by suggesting how artificial menisci in the future can be improved to reduce the chance of the patient developing osteoarthritis in later life. This was done by creating 2-D axis symmetric FEA models representing the knee joint for each different meniscus and analyzing the stress and contact pressures in the joint for each case.

From the results collected, it is clear to see that as the elastic modulus of the meniscus increases so does the maximum stress in the meniscus. However, an increase in elastic modulus also leads to a decrease in contact pressure at the joint and a reduction in the max stress in the articular cartilage. High stress and contact pressure are associated with osteoarthritis, therefore, the ideal meniscus should have as high of an elastic modulus as possible, which is currently achieved through cryopreservation preservation techniques. Unfortunately, these models cannot yet be used to influence surgical decisions since the geometry of the knee is much more complex than the model presented, and the material properties are best represented using transverse isentropic properties. However, they do provide a baseline for future projects and in-vivo studies.

Chapter 1 – Introduction

1.1 – Introduction

Osteoarthritis is one of the five leading causes of disability in the elderly population and is usually associated with mechanical insult to the knee joint.[1] The meniscus plays a key role in preventing injury to the knee by providing lubrication, 'shock absorption', load transfer and stabilization.[4] For this reason, many early-stage intervention methods for the meniscus exist to prevent further damage to the knee. This report specifically focused on meniscal replacement, which is predominantly reserved for unstable, vertical, peripheral tears in patients younger than 50 years old.[2] Unfortunately, the chance of osteoarthritis is further increased in patients following meniscal replacement due to the inferior mechanical properties of artificial replacement menisci.[1] This report will aim to identify the best preservation method for artificial menisci currently available. It will conclude by suggesting what elastic modulus an ideal replacement meniscus should have in order to reduce the chance of osteoarthritis. Consequently, the information provided from this study should help clinical professionals choose how to preserve the menisci they use in practice to reduce the chance of patients developing osteoarthritis in later life, and furthermore, should also suggest what improvements can be made to artificial menisci to improve their performance. These improvements will prove to be beneficial to clinicians since there is a large financial incentive to reduce the number of follow up interventions and frees up necessary resources for other treatments (such as surgeons). The patient will also see great benefit from the results presented considering that a better artificial replacement meniscus will lead to a decrease in pain and better performance of the knee joint.

Many Finite Element Analysis (FEA) studies have been used to analyze the meniscus, however, there has been little work done to test performance of different preservation methods. There is a general consensus across all other studies that suggest the healthy meniscus performs the best, so this hypothesis was also tested. Performance is an incredibly difficult factor to define due to the complexity of the knee joint and its applications. For this report, performance was defined as the response of stress and contact pressure distributions in the knee as a consequence of an external force applied to the joint. Better performance is indicated by lower stress and contact pressure in the joint.

To measure performance of the knee joint, a 2-d axis-symmetric FEA model was created using isotropic material properties, which analyzed the stress distributions and contact pressures for a variety of menisci with varying elastic moduli. FEA methods are preferred here since clinical trials are much more expensive, more time consuming and potentially even dangerous to patients due to the invasive nature of the treatment. Although, it is not suggested that any results presented are implemented without further clinical studies. Instead, these results should be used as a precursor to any further testing necessary.

The preservation methods tested in the study were: a healthy meniscus, a cryopreserved meniscus, and a deep-frozen meniscus. Further menisci were also tested to develop relationships between elastic modulus and stress & contact pressure. Stress distributions are important to consider since larger stresses in the joint leads to greater pressure which can cause pain in the patient or even mechanical insult. Furthermore, contact pressure is another important parameter to consider since this affects the tribology of the joint, where larger contact pressure leads to a reduction in tribology. The consequence of this is that fluids which are typically used to lubricate and assist the joint are less free to move, thus producing increased pressure and potential mechanical insult. Therefore, the best performing menisci would reduce both parameters as much as possible.

1.2 – Aims

The aim of the project is to provide an FEA model showing how menisci preservation methods and elastic modulus of the meniscus affects the chance of developing osteoarthritis post-surgery, and which preservation method/elastic modulus performs best.

1.3 – Objectives

- Provide a standard knee model with an organic, healthy meniscus to see how it responds to an external force, which will be used as a datum for other models.
- Develop a damaged knee model with no meniscus to discover the effects of a damaged meniscus on overall knee function when subject to an external force and compare with a standard model.

- Provide a post intervention knee model for each replacement meniscus to show how different preservation methods affect knee function when subject to an external force and define an ideal elastic modulus for a successful graft.
- Discuss limitation of model and how to improve the model to provide greater clinical relevance.

1.4 – Project Report Layout

The report starts with the introduction to the problem and lays out the aims, objectives, and any changes to the scope of the report in Chapter 1. Chapter 2 then presents a detailed literature report which provides a critical analysis of previous studies on early-stage intervention methods and describes how these studies influenced the project. Following this, the methods of the model created are presented in chapter 3 with the results of the model shown in chapter 4. Chapter 5 concludes the report by identifying the key conclusions and discussing the potential for future work in the area. Critical analysis and discussion have been presented throughout the report.

1.5 - Change to Scope of Project

There have been a few minor changes to the original scope of the report. For example, initially the performance of the knee in response to light sport was considered, but this was deemed too general of an area to cover. Instead, the response of the knee to gait was considered since it is something which everyone must be able to do to carry out everyday tasks. In further iterations, the response to light sports such as speed walking or hiking may be considered.

Furthermore, a model with transverse isentropic material properties was also included in the report to see how the current model could be improved in the future. This was not originally included in the scope of the project.

Chapter 2 – Literature Review

2.1 – Introduction

Over the years, there have been many studies surrounding the knee and how it is affected by mechanical insult and osteoarthritis. Using FEA to carry out these studies is a relatively new concept, with the first study of this kind being published in 1972.[2,3] FEA has been preferred in recent times due to its accuracy, cost efficiency and ability to test a variety of inputs with relative ease, making it a near perfect match for analyzing complex structures such as the knee. Moreover, the main benefit of using FEA to model the knee is that it offers a non-invasive method to obtain information which may otherwise be unobtainable.[5] This protects the patient from any harm and is usually used as a sensitivity test for experimental results in the future.

2.2 – The Anatomy of the Knee

The anatomy of the human knee is well known, and a detailed diagram of it can be seen in figure 2.1. As shown in figure 2.1, there are many components in the knee, each with different material properties and geometries. Analyzing such a complex structure in Abaqus would be too time consuming and beyond the scope of this report (since outputs of parts such as the medial collateral ligament are irrelevant when considering the meniscus), so a simplified model was created instead. The parts included in the Abaqus model are the femur; tibia; femoral and tibial articular cartilage and finally the meniscus.

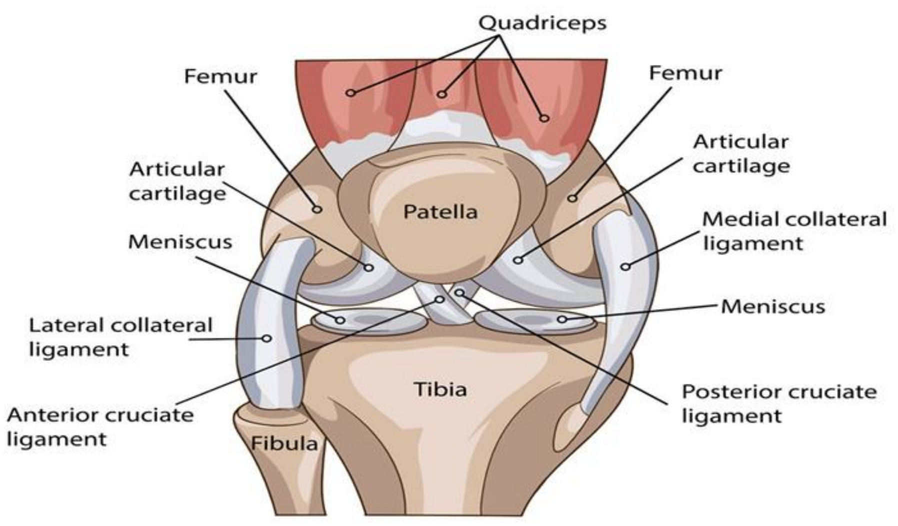


***Figure 2.1**: Anatomy of a human knee.[6]*

Anatomy of the Meniscus

The main function of the meniscus is to provide lubrication, 'shock absorption', load transfer and stabilization.[4] To fully understand how these functions are achieved, it is important to first consider the structure of the meniscus. A human knee typically has two roughly crescent shaped menisci, one on the lateral side of the joint and one on the medial. Both of which are attached to the tibial cartilage through the insertion of meniscal horns which are attached to the underside of the meniscus. Biochemically, the meniscus is an Extracellular Matrix (ECM) which is typically compromised of approximately 72% water and 22% collogen. The remaining 6% includes a mixture of DNA, glucosamino-glycans, adhesion glycoproteins, and elastin.[7, 9] Collogen is the main fibril network within the meniscus and is predominantly orientated in the circumferential direction, however, this changes towards the top layer of the meniscus where the collogen fibers are orientated in the radial direction. In-between these two layers, there is a section where the radial and circumferential collagen fibers 'tie' together. Here, vertical compression loads are transferred into hoop stresses (stress perpendicular to the axis and the radius of the object) making load transfer easier for the meniscus to deal with due to its greater strength in the circumferential direction.[7]

As a consequence of the high-water content in the meniscus, it acts as a biphasic material under compression. In the first phase, most of the water in the meniscus is compressed, acting as a protective layer for the fibril component of the meniscus, which provides great 'shock absorption'. However, if the force is applied long enough to the knee, the meniscus enters its second phase seeing as the water cannot be compressed further. At this stage, water may start to leak from the meniscus if the force is high enough, causing permanent damage to the meniscus and reducing its 'shock absorption' capabilities since the water may never be restored. Furthermore, damage may be caused to the fibril network due to the excessive stresses which can lead to mechanical insult and potentially osteoarthritis. Unfortunately, the meniscus does not naturally heal due to poor blood circulation and nutrition at the center of the meniscus, therefore early-stage intervention methods are usually required to prevent further damage.[7]

The meniscus achieves stability by limiting excess motion in the joint.[10] It can do so because of the meniscal horns which attach the meniscus to the tibial plateau. These horns reduce the movement of the meniscus thus improving the congruency between the two cartilage layers. Finally, lubrication is achieved through the use of synovial fluid. The synovial fluid decreases the coefficient of friction in the joint, thus reducing the forces and stress within the joint. Furthermore, synovial fluid acts as a source of nutrition for the meniscus through the process of synovial diffusion.[7]

Anatomy of Articular Cartilage

Similar to the meniscus, articular cartilage is composed of an ECM but with a slightly different composition. Depending on where you look, the water content of cartilage may be between 70-80% or 70-85%, with more reports leaning towards the previous range.[11-13] Since this value may depend on many factors such as age, weight etc., the pool of people tested can affect this value which may explain the discrepancy. The rest of the network is again compromised of collagen and proteoglycans.[11] Consequently, like the meniscus, articular cartilage is also considered a biphasic material which typically sees permanent damage occur once it reaches its second phase. This damage can decrease the congruency between the two cartilage surfaces which causes large stress, leading to osteoarthritis.

Considering that this report focuses on the meniscus, it is important to further delve into the relationship between the meniscus and the articular cartilage. Many studies show that patients are much more likely to develop osteoarthritis after meniscectomy surgeries due to the inferior material properties of artificial menisci.[1] One study even showed that the removal of the meniscus altogether further increased the stress in the cartilage, however this study was carried out on animal subjects so may not be entirely applicable to human meniscectomy. Moreover, the species of the subject was not specified so it is hard to compare the results, but all subjects showed increased stress in the articular cartilage with no meniscus present compared to some meniscus present.[14] These results confirm that the meniscus closely interacts with the articular cartilage offering it some form of protection, with the level of protection dependent on the material properties of the meniscus. Consequently, because of the relationship between the meniscus and the articular cartilage, it was deemed crucial to include both the femoral and tibial cartilage in the Abaqus model.

Anatomy of the Femur and Tibia

Primarily, the tibia and the femur provide structural rigidity to the joint keeping it stable. Beyond that, there is no clear information indicating that either bone affects the function of the articular cartilage or the menisci. For this reason, there is no need to further investigate the anatomy of the bones. However, it is important that both femur and tibia are included in any FEA model because of the structural rigidity they provide.

2.3 – Osteoarthritis and the Knee

As mentioned previously, osteoarthritis is a very prevalent condition in the population, with three specific groups at extreme risk: the elderly, people who are overweight and patients who have undergone total or partial meniscectomies.[14-16] It is even estimated that approximately 5% of the US population is affected by knee or hip osteoarthritis. [15] Although this may seem like a relatively low percentage, due to the pain it induces and the potential to cause disability, osteoarthritis is one of the leading causes of disability in the elderly population.[15] This section focuses mainly on how total meniscectomy affects the development of osteoarthritis in the knee, but first it is important to understand how osteoarthritis is classified and what it is.

Typically, osteoarthritis is diagnosed based on radiographic appearance. To diagnose osteoarthritis, one study suggests radiographers should look to identify heterogeneous groups of conditions that lead to joint symptoms and signs which are associated with defective integrity of articular cartilage.[17] However, this is a somewhat difficult statement to interpret because not all cases of defective integrity of cartilage leads to osteoarthritis. This is currently the definition used by the American Rheumatism Association and is quite dated (developed in 1981). Another, more recent study, shows that not only is some articular cartilage lost, but there is also some bone remodeling, capsular stretching and weakness of muscles surrounding the joint.[16] Since research regarding osteoarthritis has progressed significantly over time, an update to the classification may be necessary which includes these signs of osteoarthritis.

Now that the symptoms of osteoarthritis have been identified, we can consider how this might be prevented. Evidently, the degradation of the articular cartilage is of primary significance here so that is what has been analyzed for the rest of the report. In future projects, one may consider making more detailed models which represent bone, capsules, and muscles in the knee in order to analyze the effects these have on osteoarthritis. There are two clear ways in which osteoarthritis may develop, the first being hereditary and the second being through wear & tear. Wear & tear is usually caused by an application of a force through the joint which causes greater stresses. The larger the force, the greater the stress and degradation of the cartilage. This is the reason why people who play sports and people who are overweight are affected more by osteoarthritis. It is also important to mention that the degradation of cartilage is time dependent due to its biphasic properties. The longer the cartilage is subject to a force, the more the water content of the cartilage leaks out. Since this water content cannot be easily replaced, the cartilage is permanently degraded. Therefore, two ways in which the cartilage degrades through wear and tear have been identified, stress and time of force applied. Analyzing the time of force applied to the joint is beyond the scope of this project, so just the effect of stresses in the articular cartilage are considered.

2.4 – Effects of Material Properties and Preservation Methods of the Meniscus on Articular Cartilage

Seeing that large stresses in the articular cartilage are partially responsible for the development of osteoarthritis, it is time to look at how the meniscus affects these stresses. It is clear that the meniscus reduces stress in the articular cartilage since many studies and FEA models show that when a meniscus is removed, stress in the cartilage greatly increase.[14, 18]

One way that the meniscus reduces stress in the cartilage is by increasing congruency between the two articular cartilage layers. The synovial fluid which is produced in the meniscus acts as a form of lubrication, thus reducing frictional forces in between the cartilages. The results of this can be seen by analyzing the contact pressures in the joint. Another way in which the meniscus may reduce stresses is by acting as a ‘shock absorber’ in the knee. However, this property of the meniscus is openly disputed so the effect it has on the cartilage is also brought into question. Even though the majority of studies acknowledge this function, one study states that it is simply not true since previous studies considered energy storage instead of energy absorption.[19] The report also claims that energy is dissipated rather than stored, implying that any stress caused by this shock absorption will also dissipate once the load is removed. For this reason, ‘shock absorption’ is not be considered as affecting stresses in the articular cartilage. The final way in which the meniscus helps to reduces stresses is by improving the transfer of load through the joint. It does this by increasing the contact area between the two cartilages and thus reducing pressures and stresses in the joint.[14] Multiple studies suggest that both load bearing, and congruency are decreased following meniscectomy, the reasons why are detailed next.[1, 14, 20]

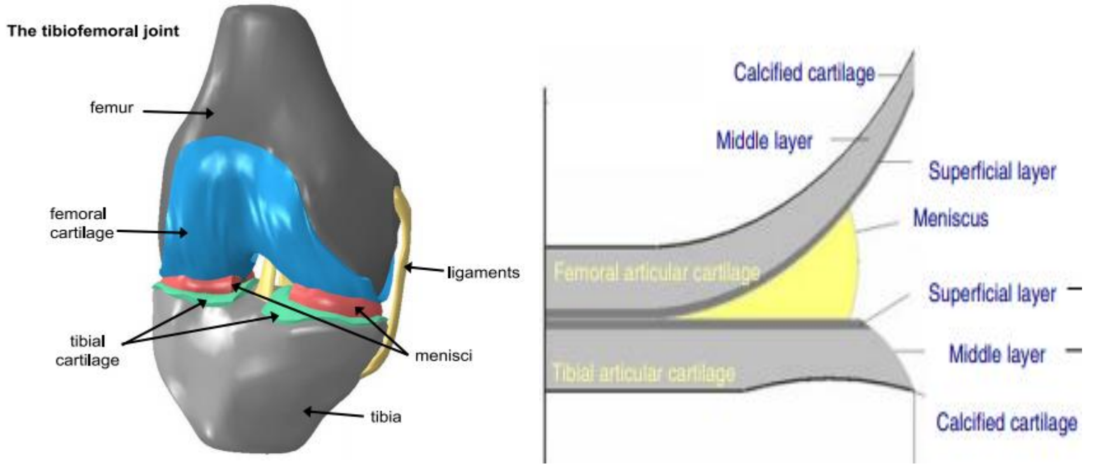
Due to the way in which artificial menisci are stored, the material properties of the meniscus are likely to change. Currently, there are 4 types of preservation methods: A fresh graft, cryopreservation, deep-frozen & lyophilized grafts.[18] Fresh grafts are considered to have the same material properties as normal menisci since they are harvested just 15 minutes before a surgery.[18] For this reason, and the fact that they rarely used in practice, these types of menisci have been ignored. Furthermore, lyophilized grafts tend to change the shape and size of the menisci which has a great effect on contact pressures across the joint, and they are also rarely used in practice.[18, 21] Consequently, these types of grafts have also been ignored, which leaves us with cryopreservation and deep-frozen grafts. Cryopreserved grafts typically have a Youngs modulus value of 88.72 MPa, which is significantly larger than a normal healthy meniscus (35 MPa) and deep-frozen grafts (69.17 MPa).[22, 23] There has been little research on how each preservation method affects stress in the articular cartilage, however, there have been multiple studies which test how elastic modulus affects stress. These studies all agree that the higher the elastic modulus of the meniscus, the lower the stress in the articular cartilage.[1, 4, 20] The congruency between these results suggest that it can be safely assumed that a cryopreserved meniscus will produce the smallest stress in the articular cartilage, therefore decreasing the chance of osteoarthritis in the knee. Consequently, one would assume that cryopreserved grafts are the best option currently available for artificial menisci. Additionally, preservation method also affects the cellular structure of the meniscus. Cryopreservation avoids complete destruction of cells in the meniscus, whereas deep-freezing completely destroys the cells in the meniscus.[24] The maintenance of viable cells in the meniscus has been shown to be a key factor in long term survival of the articular cartilage.[25-27] Therefore, from these FEA studies, it appears clear that cryopreservation will be the best technique for preservation. However, a conclusive statement cannot be made until in-vivo studies are carried out.

There are also other, more practical factors to consider when choosing which preservation method to use. For example, cryopreservation is an expensive and difficult method to use and may increase the transmission of infectious diseases (due to the remaining viable cells).[18] On the other hand, cryopreservation offers the ability to store the meniscus for long periods of time, meaning donor menisci can be saved until a suitable match is found.[18] The main benefit of the deep-frozen meniscus is that transmission of disease is much less likely, leading to more successful surgeries.[18]

2.5 – Using FEA Models to Analyze the Knee

<u>Different Types of FEA Models</u>

FEA models are a great way to analyze the knee due to its large complexity and ability to obtain key results without surgical intervention.[5] Typically, there are two types of models used, 2-D & 3-D. An example of both types of models are shown in figure 2.2 Both of these have their own advantages and disadvantages, and usually the model type is selected dependent on the scope of the project being carried out. For example, 3-D models allow for detailed representations of the joint and forces and are considered to provide more accurate outputs due to its more accurate representation of the joint. However, if constraints on time or cost are an issue, one may opt for the use of 2-D models instead. 2-D models use simplified geometries to represent the knee which sacrifice the accuracy of output results in favor of efficiency. 2-D models are much easier to modify and run for a much shorter time than 3-D models. For this project, a 2-D model was preferred since there was a restriction on time and multiple inputs were to be tested. This allowed for larger amounts of data to be collected which was useful in determining relationships between stresses and Youngs modulus.



(a) (b)

Figure 2.2 *– A 3-D model (a) and 2-D model (b) of the tibiofemoral joint.*[1, 5]

<u>Difficulties Surrounding FEA Modelling</u>

Although FEA modelling has its benefits, it also has its drawbacks. The first complication arises when constructing the models of the knee. Due to the knee's extreme complexity, obtaining accurate geometries of all the parts are difficult to obtain. These are usually obtained through CT or MRI imaging, meaning that capturing accurate geometries is dependent on the resolution of the machine, which can lead to small discrepancies.[5] To avoid this issue, one may choose to take multiple images of different patients and taking an average of the results collected. Alternatively, if accurate measurements cannot be taken, one may opt for the simplification of certain parts such as ligaments.[5] Further simplifications may be required if a 2-D model is created since it is difficult to represent 3-D geometries in a 2-D space.

The other complication associated with FEA modeling is that validation of the model is difficult to achieve. Validation has been described as the ability to provide evidence that model generated results correspond to the outcomes of the real-world scenario simulated.[5] Evidently, this may prove incredibly difficult to obtain since In-vivo studies would be required. The best way that results may be validated is by comparing them to previous literature, however, since the inputs of the models are likely to be different from the knee on which the studies have been carried out on, the validation is rather unreliable. An alternate way of confirming the accuracy of the outputs is through a mesh convergence study on the model. If the results converge to a finite value as the mesh of the model becomes coarser, it can be assumed that the model is working as expected. Although this does not validate the results, it does verify them.

2.6 – Applications of Literature Review to Present Work

From the literature presented, it is evident that development of osteoarthritis is closely related to the amount of stress in the articular cartilage. Therefore, in order to reduce the chance of osteoarthritis, the meniscus selected should be the one which reduces the stress in the articular cartilage the most. Consequently, the stress outputs are of primary concern. Secondarily, the contact pressure in the joint should also be measured since this is a good indicator of congruency of the joint. Since one of the functions of the meniscus is to increase congruency, it is important to maintain or improve this in order for the knee to function appropriately. To analyze this, a 2-D model was selected because a variety of Youngs moduli are tested. This was chosen because it allows for a variety of results to be collected and relationships to be developed. Furthermore, due to the issues surrounding FEA modelling stated above, some simplifications regarding the knee’s geometries had to be made. For example, all ligaments were excluded since there is no direct correlation between them and osteoarthritis.[5] Further implications are explored in greater detail in Chapter 3.

2.7 – Discussion of Literature Outcomes

From previous studies, it is expected that the cryopreserved artificial meniscus is the best choice for meniscectomy since it has the higher Youngs modulus. On the contrary, deep-frozen menisci have greater practical benefits such as its easier to store and is cheaper than cryopreservation. However, when one considers the effect that deep-freezing has on the ECM of the meniscus, it is apparent that the deep-frozen meniscus is the worse choice. Maintenance of the ECM has been proven to be beneficial in the long term of protecting the joint from osteoarthritis, which is the ultimate goal of early-stage intervention. In order to make a better decision on what preservation method works best, further investigation is required. Firstly, contact pressures should be considered since this is a good indicator of congruency between the cartilages.

Additionally, since the meniscus has multiple function, the ideal meniscus should also address issues such as stability in the knee. This has not been directly associated with osteoarthritis so was deemed to be beyond the scope of this report, but a conclusive study on the knee should include this.

Moreover, it could even be argued that none of the present studies are viable to predict which is the best preservation method because of the inability of FEA to accurately simulate long term performance and the inability to validate models. These are key factors to consider, but at the moment are only possible to do so through In-vivo studies. Therefore, all studies, including this one, should only be used as precursors for further In-vivo studies. FEA can provide a good indication of what factors are important and is helpful in developing relationships between inputs and outputs, but without validation, their accuracy is questioned.

Chapter 3 – Methodology

3.1 – Introduction to Models

A selection of FEA models were created to represent the knee on ABAQUS version 2019. Each model uses the same units of mm and MPa. All the models were very similar, except a different meniscus with different elastic moduli were tested in each one. The elastic moduli tested were: 10 MPa, 35 MPa (healthy meniscus), 50 MPa, 69.17 MPa (deep-frozen meniscus), 88.72 MPa (cryopreserved meniscus) & 120 MPa. Supplementary to these, two further models were created in order to develop a deeper understanding of the joint. The first of these was a knee model excluding a meniscus, which was developed to see the effect that the meniscus has on the articular cartilage. The second model created was a knee with a healthy meniscus which uses transverse isentropic materials. This was included to show how the results are affected by using more accurate inputs.

The models were created in 2-D space and assumes that the knee is axis-symmetric. All components of the model (bone, cartilage & meniscus) were modeled using quadrilateral elements and were meshed in a structured manner. However, the meniscus employs a biased mesh with a mesh biased ratio of 10 in order to increase computational efficiency. In order to determine the ideal number of elements to use in each model, a mesh convergence study was executed on the meniscus and cartilage. The results of this study can be found in appendix 1, along with the number of elements chosen for each model. The mesh convergence study also shows that all the results converge to a final value, which indicates that each model has been verified. Finally, the surfaces which are in contact with each other were defined as contact surfaces with no friction. This is because friction is hard to quantify in the knee, so was excluded.

3.2 – Geometry of Models

Each model created has the same geometries, excluding the model with no meniscus. Both of these can be seen in better detail in figure 3.1, which also includes dimensions in mm. For both the femur and tibia, a width of 22.40 mm was selected since this is an average width found from one MRI study.[28] Furthermore, an arbitrary height of 9.4 mm was selected for both bone sections. This can be extended or shortened further, but no clear benefit was identified. The articular cartilage surrounding the femur was assigned a constant thickness of 2 mm, whereas the articular cartilage on the tibial plateau has a constant thickness of 2.4 mm. These values have been applied in previous models and are also confirmed by the literature.[1, 28]

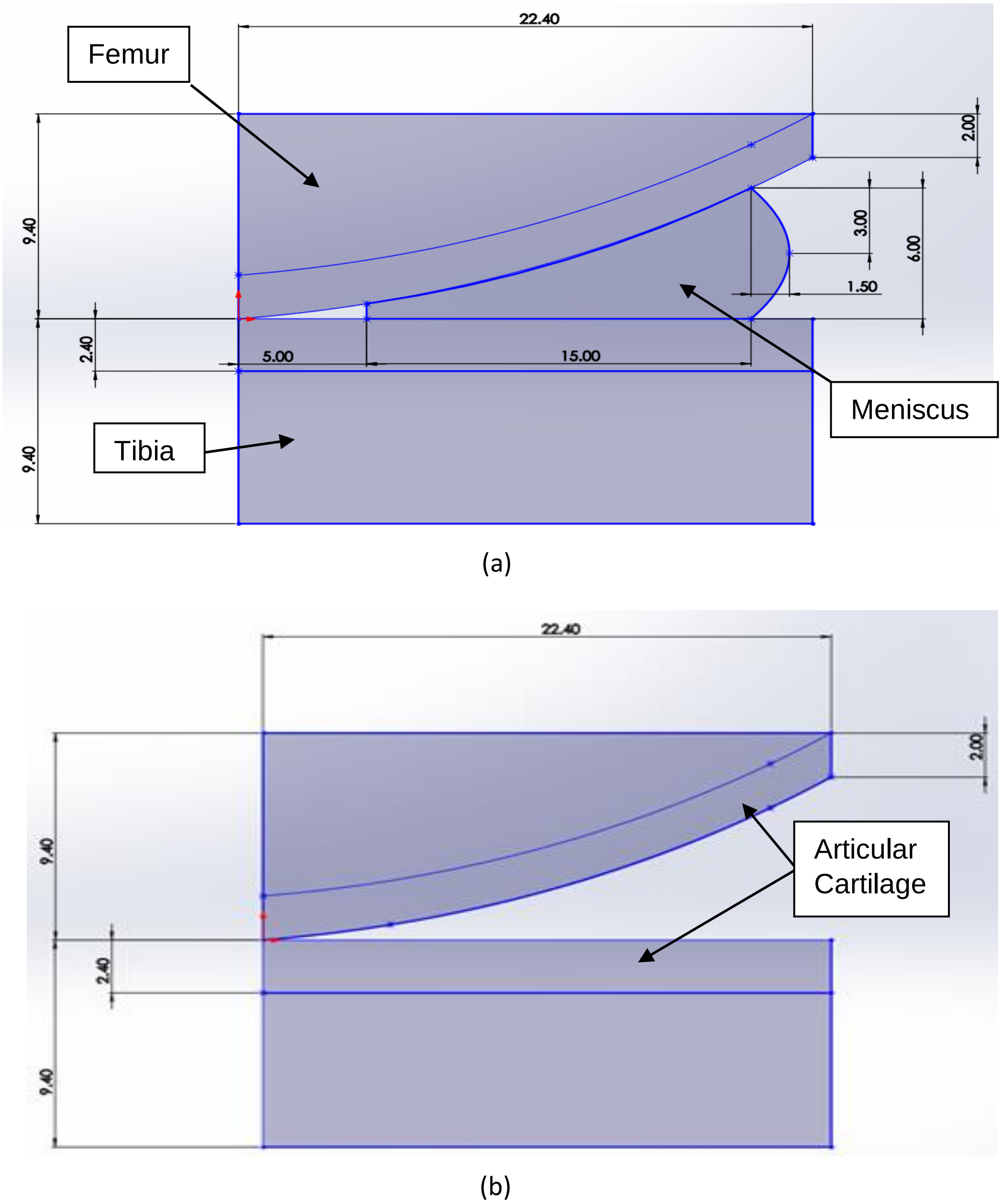


***Figure 3.1** – Geometries show for (a) models including a meniscus (b) model excluding meniscus.*

The geometry of the meniscus was much more difficult to represent. Although there is literature available on the shape and size of the meniscus, it was later found that applying these geometries to the model led to errors which became apparent when carrying out the mesh convergence study. This is because ABAQUS has issues when applying meshes to sharp edges since stress values tend to infinity as area tends to zero. Therefore, some simplifications had to be applied to the geometry of the meniscus in order to help with convergence, however the original shape was maintained as much as possible. The original shape represents a meniscus which was used in a previous study, where the height of the meniscus was 6 mm, the width of the meniscus was 15 mm and the bulge was given as 1.5 mm.[28, 29] These geometries were maintained, however, the top edge of the meniscus was modelled to fit flush to the bottom of the femoral articular cartilage. This was applied in order to eradicate sharp edges in the meniscus.

3.3 – Material Properties

The material properties used can be found in table 3.1 which shows the elastic modulus (E) and poisons ratio (v) for each part. Linear isotropic material properties were selected in order to improve efficiency and because certain properties were not available for each part. Additionally, a constant value of v was applied to every meniscus tested. This was chosen in order to determine a relationship between E and stress & contact pressures.

Part	***Material Properties***
Bone	E = 400 MPa, v = 0.3.[1]
Articular Cartilage	E = 637 MPa, v = 0.42.[23]
Healthy meniscus (linear isotropic)	E = 35 MPa, v = 0.3.[23]
Healthy meniscus (transversely isentropic)	$E_x = E_y = 20$ MPa, $E_z = 140$ MPa, $V_{xz} = 0.2$, $V_{xy} = 0.3$, $G_{xz} = 50$ MPa.[1]
Deep-frozen meniscus	E = 69.17 MPa, v = 0.3.[22]
Cryopreserved meniscus	E = 88.72 MPa, v = 0.3.[22]
10 MPa Meniscus	E = 10 MPa, v = 0.3.
50 MPa Meniscus	E = 50 MPa, v = 0.3.
120 MPa Meniscus	E = 120 MPa, v = 0.3.

Table 3.1 *– Material properties applied to models.*

3.4 – Load and Boundary Conditions

First of all, an initial displacement load of 0.01 mm was applied to the top edge of the femur in order to establish an initial contact between the two articular cartilages. This was solely applied in the first step of the test and was removed in the second step. The reason for doing this is to help the solution converge.[4] In the second step of the analysis, an axially compressive load is applied to the top surface of the femur. The magnitude of the load applied was equal to 0.7 x bodyweight (the average force through one knee in gait). Since body weight can vary by large amounts across the population, and average bodyweight of 62kg was selected.[30] Therefore the load applied was equal to 608.22N. This force was applied to the model in terms of a pressure with a value of 0.2459 MPa along the top edge of the femur. A pressure was preferred here since it represents an equally distributed force better than a concentrated load, which is what would be expected in normal gait.

Due to the structural rigidity of bone, the nodes at the bottom of the tibia were constrained in all directions in order to represent the stiff and fixed tibia.[4] The elements in the femur were constrained such that the bone can only be moved in the axial direction.[4] Finally, the nodes along the axis of symmetry were constrained so that they remain on this axis and are also constrained in the x-direction. This boundary condition was applied in order to represent the symmetry of the model.

3.5 – Outputs of Interests

Evidently, stress in the articular cartilage is of most importance when analyzing the potential for the development of osteoarthritis. It has also been suggested that excessive shear stress has been associated with articular cartilage damage.[31, 32] Therefore, max shear stress in the articular cartilage will be measured. Consequently, the meniscus which produces the lowest max sheer stress in the articular cartilages will be deemed to have the best performance since this indicates a lower chance of developing osteoarthritis. Furthermore, the max contact pressure across the joint has been measured. The ideal meniscus should reduce contact pressure as much as possible since this is a good indicator of congruency in the joint. Finally, the max of radial, axial, circumferential and sheer stress in the meniscus will be considered in an attempt to develop stress relationships. This will then be compared to max von misses stress to ensure that the meniscus does not yield.

3.6 – Discussion of Methods

Although an attempt was made to represent the knee as accurately as possible, some simplifications were necessary in order to help the mesh converge and also due to restrictions on time. The first of these is the simplifications applied to the geometries of the model. As mentioned previously, the shape of the meniscus had to be changed in order to help the model converge and avoid errors while running, although it is likely that this may affect the accuracy of the models. This can be confirmed by looking at previous studies which show that changes in meniscus geometry (especially thickness) have a large relative effect on stresses in the articular cartilage.[4] However, it is difficult to comment on how much accuracy may be affected unless an in-vivo study is carried out. This was not possible for this study due to restriction on time and cost but should be considered for future studies. Furthermore, the assumed axial symmetry of the model is another simplification which is likely to affect accuracy. This is because of the difference in shape and composition of the lateral and medial menisci. The lateral meniscus is considered to be smaller than the medial meniscus and said to occupy a larger surface of the articular cartilage.[7] Since contact area and contact pressure are inversely proportional, any change in contact area will affect the contact pressure in the joint indicating the lateral and medial sides of the knee experience different contact pressures. Even though the menisci are geometrically different in 3-D space, in 2-D space they appear to have the same geometry as they share roughly the same thickness and length. Consequently, it was deemed appropriate to make the model axis symmetric. One further benefit of using axial symmetry is that the majority of previous literature uses the same property, making it easier to directly compare results, which is one possible way of validating them.

Another simplification that was made is the use of linear isotropic material properties instead of transversely isentropic. Linear isotropic properties were selected for these models because transverse isentropic properties were unavailable for the artificial menisci. Also, since one of the aims of the report is to develop relationships between Elastic modulus and stress, using transverse isentropic properties would have made this more complicated due to the consideration of radial, axial, and circumferential elastic modulus. In addition to this, the poisons ratio of all the models was assumed to be constant since changing this would likely have an effect on stresses therefore also affecting the relationships established between elastic modulus and stress. Both of these simplifications are likely to decrease the accuracy of the model since they do not accurately represent a real knee. However, they were deemed as reasonable because previous reports make similar assumptions allowing for better comparison and verification of results, and also because removing these simplifications would be beyond the scope of this report.

In the interest of increasing accuracy of the models, it is suggested that future projects aim to increase the complexity of the knee so as to provide a better representation of the joint. One way in which this can be done is by constructing the model in 3-D space rater than 2-D space. This will allow for greater accuracy in the geometry of both the medial and lateral menisci which is known to have a large effect on stresses within the joint.[4] Additionally this will also allow for more components to be inserted into the model, such as ligaments, meniscal horns etc., which will again produce a better representation of the knee. Another way in which complexity of the model can be increased is by applying transverse isentropic material properties to the meniscus and cartilage. Doing so will help to encapsulate the higher elastic modulus in the circumferential direction for both the meniscus and articular cartilage which will have a large effect on stress distribution. Future projects should also look to carry out sensitivity tests on the poison’s ratio of the meniscus as this can vary depending on the preservation method. By doing this, a better estimate of the ideal material properties for an artificial meniscus may be presented.

Chapter 4 – Results

4.1 – Results

Table 4.1 shows the max sheer stress in the articular cartilage (**τ_{max}**), max stress in the meniscus (S_{max}) and also the max contact pressure in the joint ($Cpress_{max}$). For more detailed results regarding the model, see appendix 2.

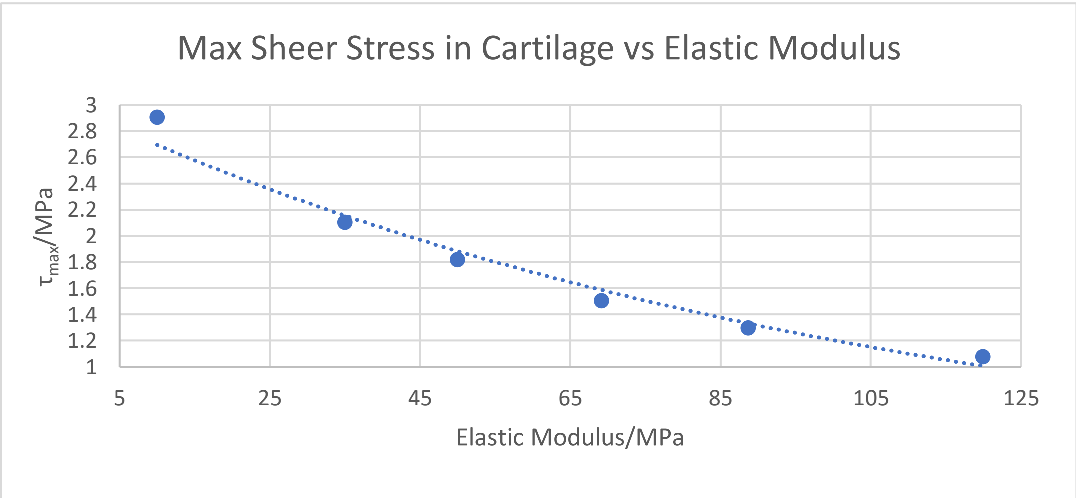
Model type	S_{max} (meniscus)/ MPa	Max Von misses (meniscus)/ MPa	τ_{max} (cartilage)/ MPa	$Cpress_{max}$/ MPa
10MPa meniscus	1.027	1.64	2.902	16.05
Healthy meniscus (35MPa)	1.085	2.619	2.102	10.35
50MPa meniscus	1.26	2.536	1.816	8.627
Deep-frozen meniscus (69.17MPa)	1.424	2.707	1.504	6.918
Cryopreserved meniscus (88.72Mpa)	1.568	2.775	1.294	5.822
120MPa meniscus	1.811	2.923	1.077	4.637
Damaged model	N/A	N/A	4.08	20.21
Transverse isentropic model	0.5874	2.48	2.343	12.24

Table 4.1 **–** Results showing max stress' and contact pressures in the meniscus and articular cartilage.

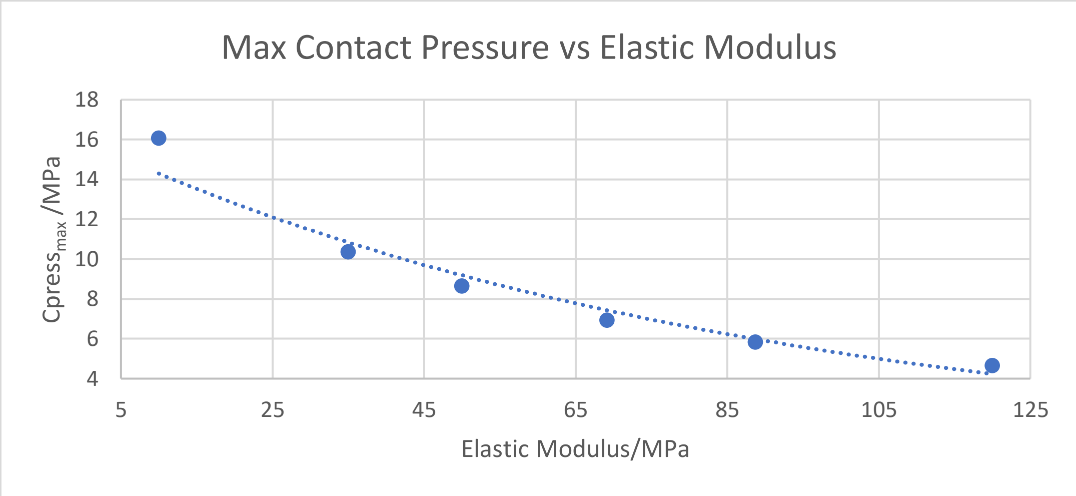
The results presented in table 4.1 show that the 10 MPa meniscus produces the largest shear stress in the articular cartilage, implying that it is has the worst performance of all the menisci tested. Additionally, it also produces the largest contact stresses in the joint which confirms this. It can also be seen that the 120 MPa meniscus produces the lowest shear stress and also lowest contact pressure suggesting that this is the best performing menisci. A clear relationship between E and sheer stress and contact pressure is also apparent and can be seen better in figure 4.1. The graphs shown in figure 4.1 show a near logarithmic relationship between E and sheer stress and contact pressure. Therefore, it is suggested that a meniscus with an elastic modulus as high as possible should be selected in order to reduce the chances of developing osteoarthritis.

It is also important to mention the transverse isentropic and damaged models as well since they are not included in figure 4.1. As expected, removal of the meniscus leads to much larger sheer stresses and contact pressures in the joint which is confirmed by the results in table 4.1. Similarly, comparing the transverse isentropic model to the healthy meniscus model shows that there is a slight increase in both contact pressures and sheer stresses in the articular cartilage. However, a large decrease in the max stress in the meniscus can be observed.

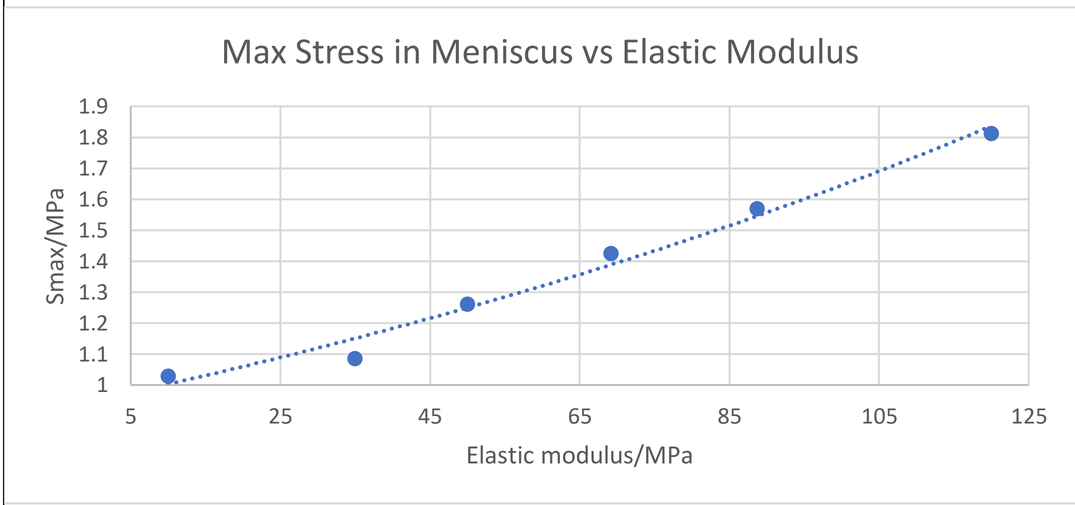
Finally, the max stress and von misses stress in the meniscus was measured and the results are shown in table 4.1. This was primarily done to ensure that the meniscus does not yield under a compressive force, since this could quickly lead to injury in the knee. As shown in table 4.1, none of the menisci tested produced max stresses higher than the max von misses stress. Therefore, it can be safely assumed that all menisci tested are suitable for use. Furthermore, figure 4.1 shows that there is a positive correlation between max stress in the meniscus and E. Although there is no indication that this may affect osteoarthritis, it is important to consider since high stresses in the meniscus are usually associated with larger chances of mechanical insult and pain in the joint.



(a)



(b)



(c)

Figure 4.1 – Graphs showing relationships between (a) elastic modulus and max sheer stress in articular cartilage (b) elastic modulus and max contact pressure & (c) elastic modulus and max stress in meniscus

4.2 – Discussion of Results

<u>What is the Best Current Preservation Method?</u>

When analyzing the best preservation method to use for an artificial meniscus there are many factors to consider. The key factors in regard to reducing the chance of developing osteoarthritis have been identified as the stress in the articular cartilage and the contact pressure across the joint. From the results in the previous section, it is evident that menisci with higher elastic moduli perform better across both of these fronts. This would indicate that the cryopreserved meniscus is the better option considering that it has a higher elastic modulus than the deep-frozen meniscus. However, there are other factors which need to be considered before a final decision can be made and one of these is the stress in the meniscus. The results in figure 4.1 (c) show that the stress in the meniscus greatly increases as the elastic modulus of the meniscus increases. An increase of stress in the meniscus typically leads to greater pain for the patient which should be avoided since this could affect their ability to carry out everyday tasks. Since the deep-frozen meniscus has a lower elastic modulus, this would produce less pain in the patient but at the consequence of having a higher risk of developing osteoarthritis due to the larger stresses in the articular cartilage.

To better aid our decision, lets look at some more practical factors of selecting a preservation method. The first of theses is the effect of the preservation method on the collagen fibril network. As mentioned previously, the cryopreservation technique maintains some of the meniscus' original fibril network whereas the deep-frozen meniscus has none of its original network. The benefit with maintaining some of the original network is that it has been proven to reduce the chance of developing osteoarthritis in the long term. This is because the ECM can help provide support of heathy knee function by still being able to maintain the lubrication and 'shock absorption' aspects which would typically be associated with a healthy meniscus. Since the deep-frozen meniscus has no ECM, it can no longer provide these benefits which can increase the chance of developing osteoarthritis. On the other hand, the disadvantage of maintaining the ECM is that it can reduce the chance of rejection of the artificial implant. This is an important factor to consider due to the lack of menisci available and also because of the increased costs associated with storing and developing new artificial menisci. Not only is the chance of rejection lowered, the cost of storage and development is also lower for the deep-frozen meniscus making it a much more cost-effective option. However, since this report is solely interested in reducing the chance of developing osteoarthritis, practical factors such as cost have little weight. Therefore, since the cryopreservation method produces lower sheer stresses in the articular cartilage, lower contact pressures in the joint and maintains the original ECM of the meniscus to some degree, it was determined that this is the best current preservation method to be used for artificial menisci in order to reduce the chance of developing osteoarthritis.

<u>What Elastic Modulus Should an Artificial Meniscus Have?</u>

Now that the best current preservation method has been identified, the next step is to suggest what material properties artificial menisci should aim to have in the future.

When looking at figure 4.1 (a) and (b), a near exponential relationship can be seen between elastic modulus and sheer stress & contact pressure. As the elastic modulus increases, a plateau can be seen towards the end of both graphs, suggesting that there is a point where the is no benefit in further increasing the elastic modulus. Doing so would only further increase stress in the meniscus which is an undesired outcome. One report suggests that the ideal range before this happens is between 100-120 MPa.[1] This appears to roughly agree with the results in figure 4.1 but cannot be confirmed since elastic moduli higher than 120MPa were not tested due to time restrictions. However, since there is some congruency between the results of both models, it is reasonable to assume that artificial menisci should aim for an elastic modulus within this range in order to reduce osteoarthritis. Before proceeding with this conclusion, further tests would need to be done. For example, the ECM of a meniscus with these material properties needs to be analyzed since this is an important factor in reducing osteoarthritis. Since this is entirely dependent on the method of preservation, this is not something that can be commented on now, but artificial menisci should aim to preserve as much as the ECM as possible. For this reason, there is a general consensus that a healthy meniscus will always be the best performing meniscus possible. This is because it allows the meniscus to maintain all of its functions which ultimately aid in protecting the joint from osteoarthritis. However, there are many complications associated with attempting to mimic such a structure. The most important is the high risk of rejection, making it incredibly difficult to secure a successful transplant, hence why fresh grafts are rarely used in practice although they are available. If at all possible, further work should be done to reduce the chance of rejection before attempting to develop a meniscus which mimics a healthy one. Until such a breakthrough is made, artificial menisci should aim to have an elastic modulus between the range of 100-120 MPa. However, it is suggested that in-vivo studies are first carried out since such high elastic moduli produce large stresses in the meniscus which can cause pain in the patient. The extent to which this pain is manageable should be analyzed.

<u>Accuracy of Results & Future Work</u>

Since traditional methods of validation do not exist, the only way to confirm the accuracy of the results presented is to compare them to previous literature. One study confirms that stress in the meniscus increases as the elastic modulus of the meniscus increases which agrees with the results in figure 4.1 (c).[4] The study also shows that the max stress in the meniscus occurs in the circumferential direction which is also observed in this model (see appendix 2). However, although there is an agreement in relationship, there is slight discrepancy between measured values. Since the study uses transverse isentropic material properties for its model, it must be compared to the transverse isentropic model rather than the linearly isotropic model. In their model, a max circumferential stress of 0.8165 MPa was reported, which is slightly higher than the 0.5874 MPa stress shown in table 4.1.[4] One explanation for this increase is that their model uses a higher circumferential elastic modulus, which as seen in figure 4.1 (c) leads to larger stresses in the meniscus. Another explanation could also be that the geometries used in the model are slightly different, which as mentioned previously has large effects on the results. Therefore, since both models report the same relationships for the meniscus and any discrepancy for results can be accounted for, it is assumed that the results of the meniscus are accurate. The issue with this however is that it is assumed the model which is being used for comparison is also accurate, which is a long reach since there is no real way to validate results. Consequently, in order to improve confidence in the accuracy of the results in table 4.1, they should be compared with results from another model. This was done earlier in the chapter when considering the max elastic modulus that a meniscus can have before it reaches its point of diminishing returns. Since both models suggest an elastic modulus in the range of 100-120 MPa, this indicates congruency between the results thus increasing the confidence in the accuracy of those presented in table 4.1. Greater confidence regarding the accuracy of the results may be hard to achieve since there is little literature available surrounding the topic, so the next step would be to proceed to in-vivo studies.

For future work, it is recommended that the simplifications made to the model are tackled first. Firstly, models should be developed using transverse isentropic material properties since this is a more accurate representation of the components of the knee. Next, a 3-D model should be developed which captures the geometry of the knee more accurately and also allows for the inclusion of other parts such as ligaments and muscle. Making such changes should increase the accuracy of the model. In order to get more applicable results, further tests should be carried out on factors such as poisons ratio, loading time etc. Doing so will provide a better guide for the ideal material properties of artificial menisci. The results from such a study should then be used to aid in-vivo studies in the future. To obtain a truly optimal meniscus, such a study should be combined with studies surrounding the shape and size of the meniscus since it is reported that this has larger effects on stress than material properties.[4]

Chapter 5 – Conclusion

5.1 – Achievements

- Identified key factors leading to osteoarthritis in the knee and its effects.
- Menisci with varying elastic moduli were tested and a relationship between this and stress & contact pressures were developed.
- A model with no meniscus was created to confirm the importance of the meniscus in the joint.
- A model using transverse isentropic material properties was developed to see the effect this would have on stresses in the joint.
- The best current preservation method in order to reduce osteoarthritis was identified.
- The ideal elastic modulus range for an artificial meniscus was identified and also the point of diminishing returns.
- Improvements for future models were identified.

5.2 – Discussions

The models presented have been verified and reasonably validated which shows that they may be used to aid clinical decisions. Key relationships were established for the meniscus and its effects on the joint which can be used to help further understanding. However, due to the many simplification applied to the model, it is far from reasonable to assume that they can provide the most accurate representation of the joint possible. To do so, future work should be aimed at targeting these simplifications in order to produce a more complex and accurate model. Once such models have been created, they should be used alongside in-vivo studies of the knee. Doing so can greatly reduce the costs and danger associated with in-vivo studies and can also make them more reliable.

5.3 – Conclusions

Currently, the best preservation method available for menisci is cryopreservation. It produces the lowest stresses and contact pressures in the articular cartilage indicating that it has the lowest possibility of leading to osteoarthritis. Additionally, it maintains more of the meniscus' ECM which aids in lubrication and 'shock absorption'. However, this comes at the cost of increased stresses in the meniscus which could cause pain and is more likely to lead to failure of the meniscus. It is also more costly than the deep-frozen technique. Ideally, artificial menisci should mimic an organic, healthy meniscus but the risk of rejection is too high. Therefore, artificial menisci should aim for an elastic modulus of between 100-120 MPa in order to reduce the chance of developing osteoarthritis in later life. A further objective for developing future menisci is to maintain as much of the ECM as possible, however, this is entirely dependent on the method of preservation rather than elastic modulus.

Chapter 6 – References

[1] Vaziri, A. et al. 2008. Influence of Meniscectomy and Meniscus Replacement on the Stress Distribution in Human Knee Joint [online]. Place of publication: Springer Link. [Accessed on: 08/11/2020]. Available from: https://link.springer.com/article/10.1007/s10439-008-9515-y

[2] Brekelmans, W. et al. 2009. A New Method to Analyse the Mechanical Behaviour of Skeletal Parts [online]. Place of publication: Acta Orthopaedica Scandinavica. [Accessed on: 08/11/2020]. Available from: https://www.tandfonline.com/doi/abs/10.3109/17453677208998949

[3] Kazemi, M. et al. 2012. Recent Advances in Computational Mechanics of the Human Knee Joint [online]. Place of publication: Hindawi Publishing Corporation. [Accessed on: 16/04/2021]. Available from: https://www.hindawi.com/journals/cmmm/2013/718423/

[4] Meakin, J. et al. 2002. Finite element analysis of the meniscus: the influence of geometry and material properties on its behaviour [online]. Place of publication: Elsevier. [Accessed on: 15/04/2021]. Available from: https://www.sciencedirect.com/science/article/pii/S0968016002001060

[5] Cooper, R. et al. 2019. Finite element models of the tibiofemoral joint: A review of validation approaches and modelling challenges [online]. Place of publication: Elsevier. [Accessed on: 13/04/2021]. Available from: https://www.sciencedirect.com/science/article/pii/S1350453319301572

[6] Wilson, A. 2017. Anatomy of the human knee. [online]. [Accessed on: 11/04/2021]. Available from: https://profadrianwilson.co.uk/knee-treatments/knee-anatomy/

[7] Fox, A. et al. 2014. The Human Meniscus: A Review of Anatomy, Function, Injury, and Advances in Treatment [online]. Place of publication: Wiley online library. [Accessed on: 08/11/2020]. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/ca.22456

[8] Brophy, R. 2012. Surgical Options for Meniscal Replacement [online]. Place of publication: American academy of orthopaedic surgeons. [Accessed on: 08/11/2020]. Available from: https://journals.lww.com/jaaos/FullText/2012/05000/Surgical_Options_for_Meniscal_Replacement.2.aspx

[9] Makris, E. et al. 2011. The knee meniscus: Structure–function, pathophysiology, current repair techniques, and prospects for regeneration. [online]. Place of publication: Biomaterials. [Accessed on: 11/04/2021]. Available from: https://www.sciencedirect.com/science/article/pii/S0142961211007022

[10] Arnoczky, S. 1992. Gross and vascular anatomy of the meniscus and its role in meniscal healing, regeneration and remodeling. Place of publication: Knee Meniscus: Basic and Clinical Foundations. New York: Raven Press. p 1–14.

[11] Mansour, J. 2003. Biomechanics of Cartilage. [online] Place of publication: Lippincott Williams and Wilkins. p 68–77. p. CH 5. [Accessed on: 16/04/2021]. Available from: https://www.mbz-herrsching.de/media/files/biomechanics-of-cartilage.pdf

[12] Athanasiou, K. et al. 2009. Articular Cartilage Tissue Engineering. [online]. Place of publication: Morgan & Claypool publishers. [Accessed on: 11/04/2021]. Available from: https://www.morganclaypool.com/doi/pdf/10.2200/S00212ED1V01Y200910TIS003

[13] Eschweiler, J. et al. 2021. The Biomechanics of Cartilage—An Overview. [online]. Place of publication: Life, Volume 11, Issue 4. [Accessed on: 11/04/2021]. Available from: https://www.mdpi.com/2075-1729/11/4/302/htm

[14] McCann, L. et al. 2009. Influence of the meniscus on friction and degradation of cartilage in the natural knee joint. [online]. Place of publication: Elsevier. [Accessed on: 11/04/2021]. Available from: https://www.sciencedirect.com/science/article/pii/S1063458409000429

[15] Felson, D. 1996. Weight and osteoarthritis. [online]. Place of publication: The American Journal of Clinical Nutrition, Volume 63, Issue 3, Pages 430–432. [Accessed on: 26/04/2021] Available from: https://academic.oup.com/ajcn/article/63/3/430S/4651478?login=true

[16] Felson, D. 2006. Osteoarthritis of the Knee. [online]. Place of publication: The New England Journal of Medicine. [Accessed on: 15/04/2021]. Available from: https://www.nejm.org/doi/full/10.1056/nejmcp051726

[17] Altman, R. et al. Development of Criteria for the Classification and Reporting of Osteoarthritis. [online]. Place of publication: Arthritis and Rheumatism. [Accessed on: 15/04/2021]. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/art.1780290816

[18] Mickiewicz, P. et al. 2014. Preservation and sterilization methods of the meniscal allografts: literature review. Place of publication: Cell and tissue banking. [Accessed on 15/04/2021]. Available from: https://doi.org/10.1007/s10561-013-9396-7

[19] Andrews, S. et al. 2011. The shocking truth about meniscus. [online]. Place of publication: Elsevier. [Accessed on: 15/04/2021]. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0021929011005860?via%3Dihub

[20] Shriram, D. et al. 2017. Evaluating the effects of material properties of artificial meniscal implant in the human knee joint using finite element analysis. [online]. Place of publication: Scientific Reports. [Accessed on: 15/04/2021]. Available from: https://www.nature.com/articles/s41598-017-06271-3

[21] Vadher, P. et al. 2006. Finite element modeling following partial meniscectomy: Effect of various size of resection. [online]. Place of publication: IEEE. [Accessed on: 15/04/2021]. Available from: https://ieeexplore.ieee.org/abstract/document/4462201

[22] Ahmad, S. 2017. Cryopreservation versus fresh frozen meniscal allograft: A biomechanical comparative analysis. [online]. Place of publication: Journal of orthopedic surgery. [Accessed on: 16/04/2021]. Available from: https://journals.sagepub.com/doi/full/10.1177/2309499017727946

[23] Venäläinen, M. S. et al. 2014. Importance of Material Properties and Porosity of Bone on Mechanical Response of Articular Cartilage in Human Knee Joint—A Two-Dimensional Finite Element Study. [online]. Place of publication: ASME. [Accessed on: 26/04/2021]. Available from: https://asmedigitalcollection-asme-org.eu1.proxy.openathens.net/biomechanical/article/136/12/121005/371072/Importance-of-Material-Properties-and-Porosity-of

[24] Fabbriciani, C. et al. 1997. Meniscal allografts: cryopreservation vs deep-frozen technique. [online]. Place of publication: Springer. [Accessed on: 16/04/2021]. Available from: https://link.springer.com/content/pdf/10.1007/s001670050038.pdf

[25] Brown, K L. Cruess, R L. 1982. Bone and cartilage transplantation in orthopaedic surgery. A review. [online]. Place of publication: The Journal of Bone & Joint Surgery. [Accessed on: 16/04/2021]. Available from: https://journals.lww.com/jbjsjournal/Citation/1982/64020/Bone_and_cartilage_transplantation_in_orthopaedic.20.aspx

[26] Friedlaender, G. et al. 1976. Studies on the antigenicity of bone. I. Freeze-dried and deep-frozen bone allografts in rabbits. [online]. Place of publication: The Journal of Bone and Joint surgery. [Accessed on: 16/04/2021]. Available from: https://europepmc.org/article/med/783164

[27] Shino, K. et al. 1984. Replacement of the anterior cruciate ligament by an allogeneic tendon graft. An experimental study in the dog. [online]. Place of publication: The Bone & Joint Journal. [Accessed on: 16/04/2021]. Available from: https://online.boneandjoint.org.uk/doi/abs/10.1302/0301-620X.66B5.6501359

[28] Guo, H. et al. 2013. Biphasic finite element contact analysis of the knee joint using an augmented Lagrangian method. [online]. Place of publication: Elsevier. [Accessed on:

19/04/2021]. Available from:
https://www.sciencedirect.com/science/article/pii/S1350453313000398

[29] Spiker, R. et al. 1992. A transversely isotropic biphasic finite element model of the meniscus. [online]. Place of publication: Elsevier. [Accessed on: 19/04/2021]. Available from: https://www.sciencedirect.com/science/article/pii/0021929092900383

[30] Walpole, S. et al. 2012. The weight of nations: an estimation of adult human biomass. [online]. Place of publication: BMC Public Health. [Accessed on: 19/04/2021]. Available from: https://bmcpublichealth.biomedcentral.com/articles/10.1186/1471-2458-12-439

[31] Eberhardt, A. W. et al. 1991. Contact of layered elastic spheres as a model of joint contact: effect of tangential load and friction. [online]. Place of publication: Journal of Biomechanical engineering. [Accessed on: 21/04/2021]. Available from: https://asmedigitalcollection.asme.org/biomechanical/article-abstract/113/1/107/399247/Contact-of-Layered-Elastic-Spheres-as-a-Model-of?redirectedFrom=fulltext

[32] Kelly, P. A. et al. 1996. Transmission of rapidly applied loads through articular cartilage Part 1: uncracked cartilage. [online]. Place of publication: Proceedings of the Institute of Mechanical Engineers. [Accessed on: 21/04/2021]. Available from: https://journals.sagepub.com/doi/10.1243/PIME_PROC_1996_210_388_02

Chapter 7 – Appendices

Appendix 1 – Mesh Convergence Study

Healthy Model			
No. of elements	Smax	ΔSmax	%Δ
10	2.641	-	-
20	2.627	-0.014	-0.53293
30	2.621	-0.006	-0.22892
40	2.619	-0.002	-0.07637
50	2.617	-0.002	-0.07642
60	2.616	-0.001	-0.03823

Cryopreserved model			
No. of elements	Smax	ΔSmax	%Δ
10	3.069	-	-
20	3.414	0.345	10.10545
30	3.336	-0.078	-2.33813
40	3.33	-0.006	-0.18018
50	3.327	-0.003	-0.09017
60	3.324	-0.003	-0.09025

Deep Frozen Model			
No. of elements	Smax	ΔSmax	%Δ
10	2.74	-	-
20	2.718	-0.022	-0.80942
30	2.71	-0.008	-0.2952
40	2.707	-0.003	-0.11082
50	2.704	-0.003	-0.11095
60	2.703	-0.001	-0.037

Transvers isentropic			
No. of elements	Smax	ΔSmax	%Δ
10	2.489	-	-
20	2.482	-0.007	-0.28203
30	2.48	-0.002	-0.08065
40	2.479	-0.001	-0.04034
50	2.479	0	0

Damaged Model			
Approx. Global size	Cpressmax	ΔCpressmax	%Δ
0.2	20.04	-	-
0.175	20.13	0.09	0.447094
0.15	20.17	0.04	0.198314
0.125	20.21	0.04	0.197922
0.1	20.21	0	0
0.075	20.22	0.01	0.049456
0.05	20.23	0.01	0.049432

Figure 5 – Mesh convergence studies for each model

Figure 5 shows the results of the mesh convergence studies carried out on each model. A mesh convergence was not done on the articular cartilage explicitly since it was done as part of the damaged model mesh convergence study. The results show that each model converges to a final value as can be seen by looking at the percentage change. Figure 5 also shows the number of elements used in each model (highlighted in green). For example, the healthy model uses 40 elements for the meniscus. Finally, from the mesh convergence of the damaged model, it is seen that the ideal approximate global size was 0.125. This is the approximate global size that was used for the articular cartilage in all of the models.

Appendix 2 – Detailed Results

E/MPa	S11/Mpa	S22/Mpa	S33/Mpa	S12/Mpa	Smax (meniscus)/Mpa	Smax (cartilage)/Mpa	Cpress max/Mpa	Max Von misses (meniscus)/Mpa
10	1.027	0.02216	0.9273	-0.3673	1.027	2.902	16.05	1.64
35	0.2648	0.0132	1.085	0.5324	1.085	2.102	10.35	2.619
50	0.5307	0.01976	1.26	0.5034	1.26	1.816	8.627	2.536
69.17	0.06541	0.0278	1.424	0.4442	1.424	1.504	6.918	2.707
88.72	0.2546	0.03465	1.568	0.3884	1.568	1.294	5.822	2.775
120	0.4548	0.04313	1.811	0.3359	1.811	1.077	4.637	2.923
Damaged	-	-	-	-	-	4.08	20.21	-
Transverse isentropic	0.1575	0.01942	0.5874	0.4636	0.5874	2.343	12.24	2.48

Figure 6 – Detailed results of each model

Figure 6 shows more detailed results for the models tested. Included are the radial, axial and circumferential and sheer stresses, as well as the results shown in table 4.1.