BIOMECHANICAL STUDY OF ARTICULAR CARTILAGE IN EARLY STAGE OF OSTEOARTHRITIS

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A report submitted
in fulfilment of the requirement for the degree of
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DECLARATION

I declare that this project report entitled "Biomechanical study of articular cartilage in early stage of osteoarthritis" is the result of my own work except as cited in the references.

Signature : ………………………

Name : Muhammad Khairani bin Ibrahim Hamdi

Date : ………………………

APPROVAL

I have checked this report and the report can now be submitted to JK-PSM to be delivered back to supervisor and to the second examiner. I declare that this report meets the scope and quality demanded for the degree of Bachelor of Mechanical Engineering award.

Signature : ………………………

Supervisor's Name : Prof Madya Dr. Mohd Juzaila bin Abd. Latif

Date : ………………………

DEDICATION

I wish to dedicate my report to both my beloved parents, family and fellow friends who have given me their unwavering support throughout this study. This report is also dedicated to my revered supervisor for his guidance and effort. And finally, I dedicate this project to the osteoarthritis community to help lessen their problem in encountering this disease.

ABSTRACT

With the newest advanced in technology, more progressive stages of OA can be detected and studied to provide precaution and prevent the osteoarthritis development. However, osteoarthritis development usually has less attention during the early stage due to its lack of symptom and severity indication. In previous studies, pathological changes of osteoarthritis joint always circling around one main contributor, which is cartilage degeneration. The cartilage degeneration is the cost of biomechanical properties alteration due to the changes in water content of the cartilage. A normal cartilage has a water content range of 77.5% ± 2.5%, hence, allowing the concept of water content cartilage to determine the biomechanical properties of cartilage during early-stage osteoarthritis. Therefore, this study aimed to investigate the possible correlation between water content and cartilage degeneration in order to determine the biomechanical properties of articular cartilage during early-stage osteoarthritis. Cartilage specimens obtained from the bovine femoral head of a cow were submerged in PBS solution for 576 hours. Each specimen's water content was calculated based on its dry weight and wet weight after dehydrated to get a range of 80% ± 5% water content for the characterization of early osteoarthritis properties. Each water content has its own Young's modulus and permeability inserted in the Finite Element Analysis to represent the biomechanical properties of the cartilage based on its water content. A similar pattern of graph defined by Finite Element Analysis for contact pressure and pore pressure was found. It illustrated the relationship between the permeability of cartilage and the fluid pressurization. Each pressure had a percentage difference range of 20% ± 5% between the water content of 75% and 80%, while a significant percentage difference of 42.5% ± 2.5% was found between the water content of 80% and 85% for both pressures. Correlation analyses was then performed to determine the relationship between the cartilage displacement and the increase of water content. The cartilage displacement was positively correlated with the increase of water content ($r = 0.967$). Meanwhile, correlation of contact force and water content shows an inverse correlation coefficient ($r = -0.975$) that represents the effect of high-water content to the lubrication of cartilage surface and its fluid pressurization. Hence, in this study, the results indicate that the increase of water content accelerates the cartilage deterioration as it provides low fluid pressurization to maintain the equilibrium form of cartilage during compression.

ABSTRAK

Dengan kemajuan teknologi yang terkini, tahap osteoartritis yang lebih progresif dapat dikesan dan dikaji untuk mencegah dan menyekat perkembangan osteoartritis. Walau bagaimanapun, perkembangan osteoartritis biasanya kurang mendapat perhatian pada tahap awal kerana kurangnya symptom dan kesan yang dirasai. Dalam kajian sebelumnya, perubahan patologi sendi osteoartritis selalu dikaitkan dengan satu punca utama, iaitu degenerasi tulang rawan. Degenerasi tulang rawan adalah disebabkan oleh perubahan sifat biomekanik akibat perubahan kandungan air dalam tulang rawan. Rawan normal mempunyai julat kandungan air 77.5% ± 2.5%, oleh itu, memungkinkan teori kandungan air dalam tulang rawan untuk menentukan sifat biomekanik tulang rawan tersebut semasa osteoartritis peringkat awal. Oleh itu, kajian ini bertujuan untuk mengkaji kemungkinan korelasi antara kandungan air dan degenerasi tulang rawan untuk menentukan sifat biomekanik tulang rawan artikular semasa osteoartritis peringkat awal. Spesimen tulang rawan yang diperoleh dari kepala femoral lembu direndam dalam larutan PBS selama 576 jam. Kemudian, kandungan air setiap spesimen dihitung berdasarkan berat kering dan berat basah setelah dihidrasi untuk mendapatkan julat 80% ± 5% kandungan air yang bercirikan sifat osteoarthritis di peringkat awal. Setiap kandungan air mempunyai modulus dan kebolehtelapan tersendiri yang dimasukkan dalam Analisis Unsur Terhingga untuk menyubstitusi sifat biomekanik tulang rawan berdasarkan kandungan airnya. Corak graf yang serupa bagi tekanan sentuhan dan tekanan liang telah diperoleh melalui Analisis Unsur Terhingga. Ini menggambarkan hubungan antara kebolehtelapan tulang rawan dan tekanan air dalam tulang rawan. Setiap tekanan mempunyai julat perbezaan peratusan sebanyak 20% ± 5% antara kandungan air 75% dan 80%, sementara perbezaan peratusan sebanyak 42.5% ± 2.5% telah didapati antara kandungan air 80% dan 85% untuk kedua-dua jenis tekanan. Selepas itu, analisis korelasi telah dilakukan untuk menentukan hubungan antara jarak penipisan tulang rawan dan peningkatan kandungan air. Tulang rawan mempunyai korelasi positif dengan peningkatan kandungan air ($r = 0.967$). Sementara itu, korelasi daya sentuhan dan kandungan air menunjukkan pekali korelasi terbalik ($r = -0.975$) yang mewakili pengaruh kandungan air tinggi terhadap pelinciran permukaan tulang rawan dan tekanan cecairnya. Oleh itu, dalam kajian ini, hasil kajian menunjukkan bahawa peningkatan kandungan air mempercepat kemerosotan tulang rawan melalui kemerosotan tekanan ccecair yang menjejaskan proses bentuk keseimbangan tulang rawan semasa mampatan.

ACKNOWLEDGEMENT

Giving my 100% effort during the past whole year for the sake of the study was very challenging. I personally think being in the field that is outside of my expertise had really put me in a position where I had to squeeze water out of stone. Nonetheless, I love the challenge and especially pleased, with the opportunity that I got to contribute for the society.

I am thankful to Prof Madya Dr. Mohd Juzaila Bin Abd Latif for offering me this final year project and put me under his guidance throughout the study. I would also like to give my highest appreciation to my beloved family, fellow classmates and every person who has been helping me to complete this project.

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LIST OF ABBREVIATIONS

AAOS	American Academy of Orthopaedic Surgeons
ACR	American College of Rheumatology
BMI	Body Mass Index
CAX4P	4-node bilinear displacement and pore pressure
CAX4RP	4-node bilinear displacement and pore pressure, reduced integration with hourglass control
CS	Chondroitin Sulfate
CT	Computed Tomography
CVD	Cardiovascular Disease
ECM	Extracellular matrix
FE	Finite Element
FEA	Finite Element Analysis
KS	Keratan Sulfate
MRI	Magnetic Resonance Imaging
NSAIDs	Non-steroidal Anti-Inflammatory Drugs
OARSI	Osteoarthritis Research Society International
PBS	Phosphate-Buffered Saline
PG	Proteoglycan

LIST OF SYMBOLS

G	=	Shear modulus
K	=	Permeability
E	=	Modulus of elasticity/Young's modulus
v	=	Poisson's ratio
e	=	Void Ratio
°C	=	Celsius
N	=	Force
mm	=	Length
mg	=	Weight
MPa	=	Pressure
r	=	Linear correlation coefficient
%	=	Percentage

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Osteoarthritis is a degenerative disorder that is mainly based on the weakening condition of the articular cartilage. The articular cartilage is degenerated by many unknown causes, thus, caused pain and stiffness in the joint (Haq et al., 2003). Common factors of articular cartilage deterioration are ageing and genetic relation. Though these factors can be categorised as unmodified factors (Fathollahi et al., 2019; van der Kraan & van den Berg, 2008)**.** Other factors like poor muscle support, obesity accident that caused a change in bone alignment, over excessive nutrient supplies, and monotonous mechanical stress are classified as modifiable factors. According to the Global Burden of Disease figures from (Cross et al., 2014), roughly, there are 251 million people worldwide suffer from symptomatic and activity limiting osteoarthritis of the knee. This frightening disease is prevalent among older people. It was estimated that there are 524 million people were aged 65 or above, and the number could be tripled by 2050 (Rosman Azmillah; et al., 2013). Same goes for the increase of BMI, which could be the robust risk factor of the knee osteoarthritis. Practically, every rise of 5kg/m2 in BMI will result in an increase of 35% in the knee osteoarthritis (Zheng & Chen, 2015).

It is compulsory to understand the structure of the articular cartilage and how osteoarthritis can happen in the joint area. Articular cartilage is highly functional in resisting force in the joint area for an average individual's lifetime. Yet, it is isolated from any blood artery, lymphatic vessels and nerves. The articular cartilage is composed of condensed extracellular matrix (ECM) and a sporadically distribution of cells called chondrocytes. The ECM primarily consists of water, collagen, and proteoglycans. All of these components are important in maintaining the water within ECM (Sophia Fox et al., 2009). In which, the water critically influenced the mechanical and physicochemical behaviours of the articular cartilage (Gu et al., 1998). The articular cartilage degeneration is due to its weakening structure which caused by bad mechanical behaviour of the tissue. Logically said, one of the leading causes for the degeneration of articular cartilage is the water content inside it.

The water content inside articular cartilage defines the condition of the tissue, in which, the high level of water content risk the articular cartilage to be deteriorated. Based on (McDevitt & Muir, 1976), the earliest observable change of articular cartilage tissue in osteoarthritic models is the increase of the water content level inside the tissue. It is correlated with the decrease in the compressive equilibrium modulus inside the ageing joints models of animal and human autopsy. Water takes up to approximately 80% of the articular cartilage wet weight, which helps to carry and spread the nutrients to chondrocytes across the articular surface (Sophia Fox et al., 2009)**.** Hence, the water content and the biomechanical properties of cartilage has a significant influence in determining the condition of the cartilage. To prevent further articular cartilage deterioration between the joint, an analysis of articular cartilage water content and its biomechanical conditions in the initial stage of osteoarthritis is needed.

1.2 Problem Statement

Water content in the early stage of osteoarthritis is a severe issue that needs to be studied and examined. Most cases of osteoarthritis appeared on the knee as it is gradually used throughout daily activities. Knee osteoarthritis has five different stages that represent symptoms of the osteoarthritis, severity and its treatment. The first stage recognised as stage 0, which means no symptom of osteoarthritis and no treatment needed. However, the next four stages starting to show the signs of the early stage of osteoarthritis until severe osteoarthritis. Starting with stage 1, where no obvious symptom of osteoarthritis could be seen, but some minor stiffness felt around the knee. Stage 2 shows the sign of the proteolytic breakdown of the cartilage matrix. On that occasion, stage 3 takes place, where erosion at the cartilage surface area between the bones and the fibrillation happens. This process narrows the gap between the bones and leads to stage 4. In stage 4, the breakdown of the cartilage stirs a chronic synovial inflammation of the cartilage. With the reduced of synovial fluid, the gap between the bones becomes narrower. It causes friction, thus, provokes a great deal of knee pain to the patient (Arthritis in Knee: 4 Stages of Osteoarthritis - IBJI, 2016). On that account, early detection of osteoarthritis could be the best way to prevent the growth of osteoarthritis on the patient.

Articular cartilage is consisting of two biphasic material, which is a solid matrix phase and interstitial fluid phase (Mow, 1980). It is that correlated with the water content of the cartilage. The Extracellular Matrix of cartilage is mainly composed of collagen type II and proteoglycans, where, together with water influence the mechanical behaviour of the cartilage. The ability of water, permeability to move through the matrix, is key to mechanical behaviour, and it is affected by proteoglycan content (Maroudas, 1968). While, as a response of shear stress, the shear modulus, G of cartilage is affected by the collagen content in which, it is independent of flow (Zhu et al., 1993). Therefore, both shear modulus parameters and permeability will be studied throughout this project as they are considered representing the condition of the cartilage during osteoarthritis. Be that as it may, other properties still need to be examined to fully understand the mechanical behaviour of articular cartilage during the early stage of osteoarthritis.

Early stage of osteoarthritis is heavily related to the water content of the cartilage. The root factor of the increase in the permeability depleted strength as well as decreased young modulus is due to the rise in water content in the cartilage. The early stage of osteoarthritis is yet a mystery to the society, and there has not been enough research regarding the mechanical behaviour and pattern of the articular cartilage during early osteoarthritis stage. On that occasion, this project aims to study the biomechanical of articular cartilage in the early stage of osteoarthritis by characterising the biomechanical properties of the cartilage and its water content.

1.3 Objective

1. To study the relationship between the water content of cartilage and osteoarthritis development.
2. To examine the biomechanical properties of articular cartilage during the early stage of osteoarthritis by using Finite Element Analysis

1.4 Scope of project

1. The specimen obtained from the bovine femoral head was used in this study.
2. Finite Element Analysis was used to imitate the biphasic properties of the cartilage during the early-stage osteoarthritis.
3. The results gained from Finite Element Analysis was used to define the correlation between the water content of articular cartilage and its biomechanical properties.

1.5 General Methodology

Several procedures need to be carried out based on the objective of the study. First, the literature review related to the study were analysed and reviewed before the actual experiment. Any research materials such as journals and articles were considered as references for the literature review.

Next, several steps of specimen preparation were carried out. Articular cartilage of cow's bovine femoral head was used as the specimen in this study. It was bought from a local butchery in Jasin. A scalpel was used to separate the flesh from the bone. Any excess tissues and damaged surface were removed. Then, the small pieces of bone that attached to the cartilage in the joint were drilled out by using an electric hand drill. Next, a scalpel was used to separate the bones from the cartilage. Proper plastic cases were used to store the specimens in a designated area in the room at room temperature (25℃). Next, the samples were submerged in a regular PBS solution at a temperature between 4 to 7℃ for 24 hours. After a day, the cartilage samples were weighed, and different levels of the water content of cartilage were obtained. The PBS was prepared by dissolving PBS tablet in distilled water. The ratio of PBS tablet to distilled water used during this preparation was one tablet for 100ml of distilled water. The dry weight and the wet weight of the samples were then calculated to obtain the water content of the samples.

Then, a Finite Element model of cartilage was used to simulate and analyse on ABAQUS software. The properties of the cartilage, modulus of elasticity, E and permeability, k were inserted to represents certain percentage of water content in the simulation. The correlation of water content and early-stage osteoarthritis were characterised based on the result computed from the analysis. The mechanical properties and the water content of the cartilage were plotted in the graph, and its correlation was discussed. A report regarding the biomechanical properties and water content of the cartilage in the early osteoarthritis was written at the end of the study. Its flow of the method is shown in Figure 1.1 below:

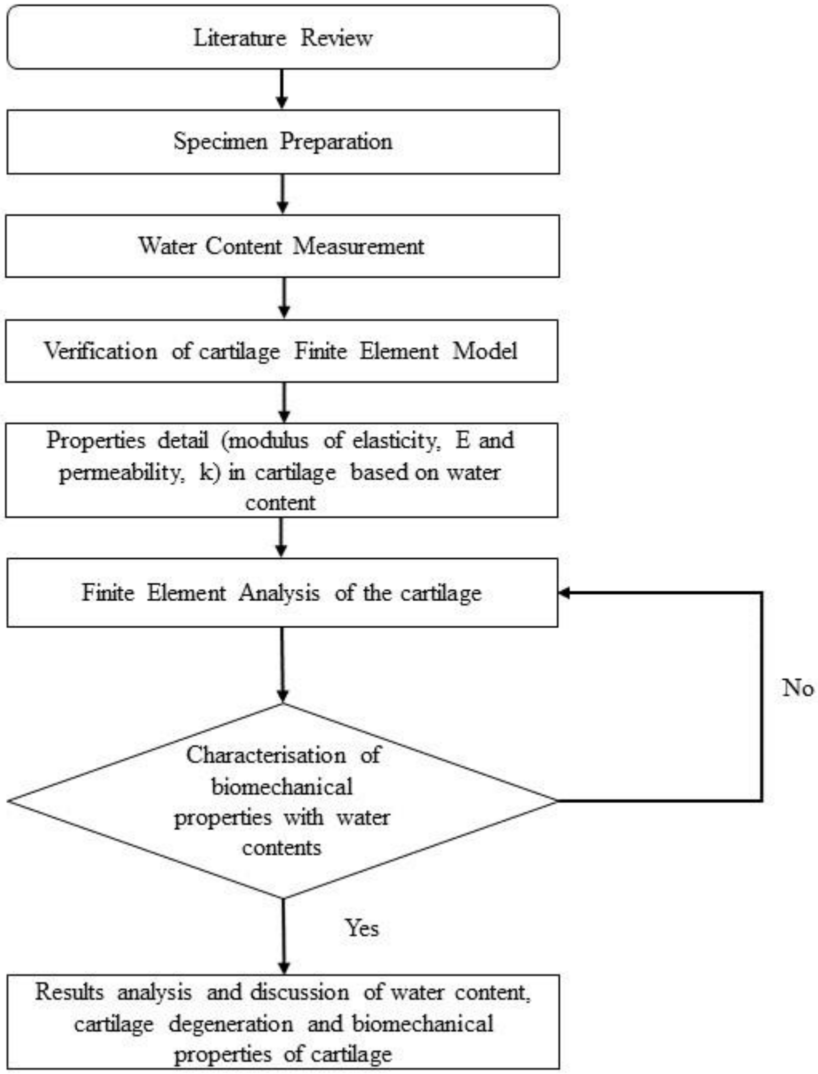

Figure 1.1: Flow chart of the general methodology.