THE EFFECTS OF WATER CONTENT OF ARTICULAR CARTILAGE ON BIOMECHANICAL BEHAVIOUR

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DECLARATION

I declared that this project report entitled "The Effects of Water Content of Articular Cartilage on Biomechanical Behaviour" is the result of my own work except as cited in the references.

Signature : ....

Name : ....

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APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

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ABSTRACT

Osteoarthritis (OA) is a joint disease affects most of the patient around the world. The main cause of OA is the degeneration of articular cartilage. The primary stage of OA results in the change of biomechanical properties which include cartilage biphasic elastic modulus and permeability. The values of the mechanical compressive parameters and dynamic compressive moduli of articular cartilage in the early pre-osteoarthritic stage is decreased between 20 % and 80 % compared to healthy tissue as shown in a number of studies before. Hence, the aim of this study was to examine the effect of water content of the cartilage on biomechanical behaviour using combination of experimental method and computational method. The cartilage specimens were weighed for every 30 minutes to determine the changes of water content in cartilage specimens. Then, creep indentation test was carried out on the cartilage specimens in each time interval to obtain the time-dependent and the deformation response of the cartilage, hence to characterise the biomechanical properties of the articular cartilage. Correlation analyses were performed to examine the relationship between the percentage of water content and biomechanical properties of cartilage biphasic elastic modulus and permeability. It was found that the percentage of water content was highly correlated with elastic modulus (r=−0.7501), whereas a moderate correlation with permeability (r=0.5192). These findings show the significant effect of the water content in the cartilage specimens towards the biomechanical behaviour of articular cartilage.

ABSTRAK

Osteoartritis adalah penyakit sendi yang menjejaskan kebanyakan pesakit di seluruh dunia. Punca utama OA adalah degenerasi rawan artikular. Tahap primer OA menghasilkan perubahan ciri-ciri biomekanikal termasuk modulus elastik dan kebolehtelapan tulang rawan. Nilai parameter mampatan mampatan mekanikal dan modul mampatan dinamik rawan articular pada peringkat pra-osteoartritis awal menurun antara 20 % and 80 % berbanding tisu sihat seperti yang ditunjukkan dalam beberapa kajian sebelum ini. Oleh itu, tujuan kajian ini adalah untuk mengkaji kesan kandungan air tulang rawan terhadap sifat-sifat biomekanik tulang rawan menggunakan gabungan kaedah eksperimen dan kaedah pengkomputeran. Spesimen tulang rawan ditimbang untuk setiap 30 minit untuk menentukan perubahan kandungan air dalam spesimen rawan. Kemudian, ujian pelekukan dibuat pada spesimen rawan pada setiap selang masa untuk mendapatkan sambutan masa dan tindak balas ubah bentuk tulang rawan, untuk mencirikan sifat biomekanik rawan artikular. Analisis korelasi dilakukan untuk meneliti hubungan antara peratusan kandungan air dan sifat biomekanik modulus elastik dan kebolehtelapan tulang rawan. Berdasarkan hasil kajian, peratusan kandungan air menunjukkan hubungan tinggi dengan modulus elastik tulang rawan (r=-0.7501), dan hubungan sederhana dengan kebolehtelapan tulang rawan (r=0.5192). Penemuan ini menunjukkan pentingnya kandungan air dalam spesimen tulang rawan untuk mengkaji sifar-sifat biomekanik rawan artikular.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBEREVATIONS

CAX4P	Four-node bilinear displacement and pore pressure
DAQ	Data acquisition
ECM	Extracellular matrix
FE	Finite element
LVDT	Linear variable differential transformer
NICE	National Institute for Health and Care Excellence
OA	Osteoarthritis
PBS	Phosphate buffered saline

LIST OF SYMBOLS

E	=	Elastic modulus
k	=	Permeability
v	=	Poisson's ratio
e	=	Void ratio
°C	=	Degree celcius
r	=	Correlation coefficient

CHAPTER 1

INTRODUCTION

1.1 Background

Osteoarthritis (OA) is a joint disease affects most of the patient around the world. It is a combination of clinical and pathological disease that is a consequence of different kinds of pathogens in various patients (Vincent and Watt, 2018). The syndrome of OA such as arthralgia and functionally limited of the affected joint that often impair the quality of life (Michael et al., 2010; Vincent and Watt, 2018). OA most frequently affects the knees, hips, hands, feet and spine, however, the most common OA is knee OA (Franz et al., 2001; Roos, 2005; Sadeghi et al., 2018). Although there is only 8.9 % of the adult population found clinically significant OA in the knee, hand or hip, there is about one-third of the adult population found radiologically signs of OA (Michael et al., 2010).

The main risk factors for the development of OA are age, genetic predisposition, obesity, and also female sex (Chiu, 2010; Lambova and Muller-Ladner, 2018; Taruc-Uy and Lynch, 2013). Aging is probably lead to risk of disease by leading an abnormal repair mechanism, as it increases malalignment and joint relaxation, reduces muscle strength, and loses proprioception and balance (Roos, 2005; Taruc-Uy and Lynch, 2013; Vincent and Watt, 2018). There was approximately 5 % of the knee OA was found radiographically signs from the population age from 35 to 54 years (Roos, 2005). Of these, most of them have suffered previous knee injury. Besides that, there was approximately 60 % of genetic inheritance in OA found from twin studies, although the relative risk of each gene is small, the polymorphisms in various types of genes can still increase the possibility of OA (Vincent and Watt, 2018). Obesity may contribute to increase the joint mechanical load, as the poor muscle tone causes the joint loses its protection, leading the physiologic axis of the knee joint is altered (Roos, 2005; Vincent and Watt, 2018). OA is caused by a steady-state imbalance of tissue, which pushes the scales towards matrix degradation instead of synthesis (Vincent and Watt, 2018). This theory was proved and supported by the identification of fragments of proteoglycan in the patient's joint fluid that suffered OA. However, the main cause of OA is the degeneration of articular cartilage as shown in Figure 1.1 (Berberat et al., 2009; Cooke et al., 2018; Knecht et al., 2006; Rautiainen et al., 2015).

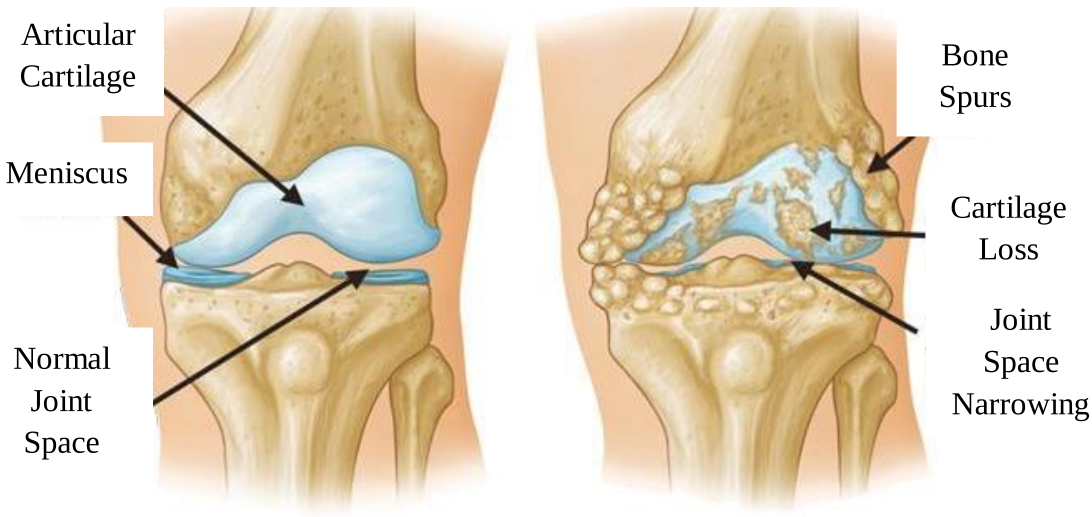

Figure 1.1 (a) Healthy joint structure and (b) OA joint structure. (orthoinfo.aaos.org)

Articular cartilage is one of the type of hyaline cartilage which is important for supporting the joint motion. It is a layer of smooth and glistening bluish-white tissue that encloses the articulating bone ends in synovial joint (Lu and Mow, 2008; Hashim et al., 2015). There are two distinct phases in articular cartilage: fluid phase and solid phase. The whole phase in articular cartilage is mainly composed of 60-85 % of water, 15-22 % of solid phase and 4-7 % proteoglycans by wet weight (Hashim et al., 2015). Articular cartilage consists of a dense extracellular matrix (ECM), which highly specialized cells are sparsely distributed, called chondrocytes (Fox et al., 2009). The ECM is principally composed of water, collagen, and proteoglycans, with other non-collagenous proteins and glycoproteins in a smaller amount (Fermor et al., 2015; Lüsse et al., 2000; Mow et al., 1980; Fox et al., 2009). A healthy cartilage consists of different amounts of water content between joint surfaces that reduce from the surface to the depth of cartilage (Berberat et al., 2009).

There is a number of experimental methods that are used in previous studies to characterise the biomechanical properties of articular cartilage, includes unconfined compression, confined compression and indentation test (Hashim et al., 2015; Knecht et al., 2006; Lu and Mow, 2008). Indentation test is used extensively due to the ease of sample preparation that the indentation test set-up enables cartilage to immerse in fluid throughout the test. There are two crucial biomechanical properties of cartilage in biphasic theory, which are elastic modulus, E and permeability, k. Permeability is inconstant throughout the tissue, and it specifies the fluid flow rate of the tissue, while elastic modulus is the stiffness measurement of cartilage tissue. They are characterised by integrating the FE model and creep indentation test due to each different thickness of the articular cartilage (Fermor et al., 2015; Hashim et al., 2017). The thickness of articular cartilage of synovial joint is important in characterising the biomechanical properties of elastic modulus and permeability.

1.2 Problem Statement

There are three broad stages of the progression of OA: the proteolytic decomposition of cartilage matrix, the fibrillation and erosion of the cartilage surface, and the beginning of the synovial inflammation (Knecht et al., 2006). The progression of degeneration of cartilage must be detected earlier, because the structural damage of the surface of the cartilage is mostly irreversible, it has a limited capacity for self-repair as the degeneration of cartilage occurs (Knech et al., 2006; Cooke et al., 2018; Sadeghi et al., 2018). Early diagnosis of OA will allow early treatment to minimize the pain and disability, and thus improve the patient's functional capacity and life quality (Knecht et al., 2006; Lambova and Muller-Ladner, 2018).

Compared with healthy tissues, the mechanical compressive parameters, include static (E, H_A) and dynamic compressive moduli of articular cartilage in the early pre-osteoarthritic stage are reduced by 20 % to 80 % as shown in a number of studies before (Knecht et al., 2006). In the previous study, the experimental method was investigated by using fresh and healthy cartilage that consists of 70 % to 80 % of water content. However, the early changes might remain undetected due to the thickness of cartilage is not significant, although the biomechanical properties of cartilage are decreased obviously. The Young's modulus in early OA samples is decreased 20 % lower compared to the healthy samples from numerous studies. Therefore, the cartilage static moduli can be detected in the moderate OA stages, while the dynamic compressive modulus can be detected in the early OA stage. It concludes that the material parameter could detect the mild pre-osteoarthritic cartilage changes.

Extensive studies of cartilage have been conducted to investigate the biomechanical behaviour using fresh cartilage (Armstrong & Mow, 1982; Démarteau, Pillet, Inaebnit, Borens, & Quinn, 2006; Guilak, Ratcliffe, Lane, Rosenwasser, & Mow, 1994; Hosoda, Sakai, Sawae, & Murakami, 2009; Knecht et al., 2006; Treppo et al., 2000). However, the effects of dehydration and water content of cartilage on its biomechanical behaviour are yet to be explored. Hence, this study aims to examine the effects of water content on the biomechanical behaviour of articular cartilage using experiment and computational method.

1.3 Objective

The objectives of this study are:

1. To investigate the dehydration of water content in articular cartilage.
2. To examine the effect of water content of articular cartilage on the biomechanical properties.

1.4 Scope of Project

In this study, the cartilage specimens from the bovine femoral head were prepared at different water content. The result of the cartilage specimens from the indentation test was then used to observe the deformation of the cartilage. Then, the finite element model of the cartilage specimens was developed using ABAQUS software. The characterisation properties of elastic modulus, E and permeability, k were determined.

1.5 General Methodology

To fulfil the objectives in this study, there are overall six procedures that required to be carried out. Firstly, the journals, articles, and any other reading materials related to the project were reviewed and revised in order to complete the Literature Review in Chapter 2. Then, the cartilage samples were harvested from the femoral bone of the bovine hip joint from the local abattoir in Jasin within 24 hours. Excessive tissues or any damaged surfaces were removed from the samples by using scalpel. Electric saw and electric drill were used to remove the cartilage from the bone with each 4 mm diameter. Throughout the preparation process, the cartilage was washed with phosphate buffered saline (PBS) solution to keep the cartilage hydrated. The cartilage was then immersed in regular PBS solution between 4 and 7 °C until ready for testing within 24 hours.

After preparing the cartilage specimens, the indentation test was conducted on the cartilage specimens to study the time-dependent and the deformation response of the cartilage, hence to obtain the characterisation of the biomechanical properties of the articular cartilage. Computational method by using ABAQUS software to run Finite Element Analysis (FEA) was be incorporated with indentation test results to characterise the biomechanical properties of articular cartilage.

The cartilage biphasic properties of elastic modulus, E and permeability, k were characterised using an ideal axisymmetric biphasic poroelastic finite element model. All the finite element models were established using ABAQUS 6.9 software. Finally, the effects of water content on biomechanical behaviour of articular cartilage were analysed. There is a flow chart as shown in Figure 1.2 to conclude the methodology of this study.

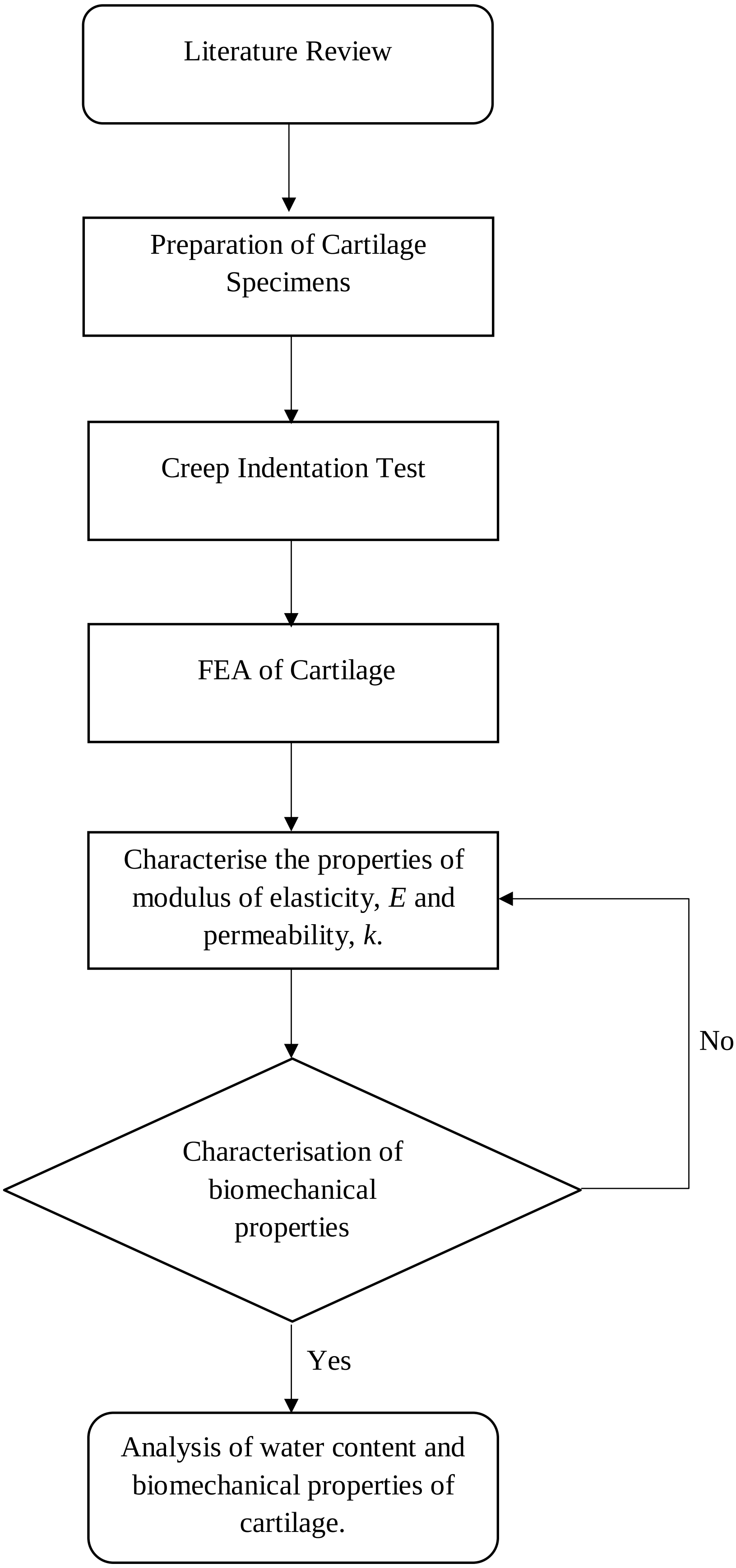

Figure 1.2 Flowchart of general methodology.

CHAPTER 2

LITERATURE REVIEW

2.1 Synovial Joint

Synovial joint, and also named as diarthrosis joint is a freely moveable joint with a large degree of motion compared to other types of joints (Huber et al., 2000; Sheet, 2005). It is categorized as an organ with the objective of skeletal articulation to help the people to move their knees, shoulders, hips, elbow and hands (Khurana, 2009; Mow and Lai, 1980; Sheet, 2005). It is remarkable pieces of nature's engineering that helps people to transfer heavy loads from a bone to another bone with nearly frictionless ease at low operating speeds for a lifetime (College, 2010; Mow and Lai, 1980; Sheet, 2005). The range of joint motion varies greatly and depends on the risk factors include ligamentous and muscular tensions encircle the joint and the apposition of soft connective tissues within it (Mow and Lai, 1980).

2.1.1 Types of Synovial Joint

Synovial joints are also commonly sub-classified into six different groups. These joints can be categorized as plane, hinge, condylar, ball and socket, ellipsoidal, pivot, and saddle joint (College, 2010; Rye et al., 2018). The reason for the classification of the types of synovial joint is due to the shape of the bone's articular surface and the way of joint's movement. Although they all have similar structural characteristics, each type of the synovial joint is individually customized to hold various types of body motion. The motion includes gliding, angular rotational, or special movement is involved in synovial joints. The types of synovial joints are shown in Figure 2.1.

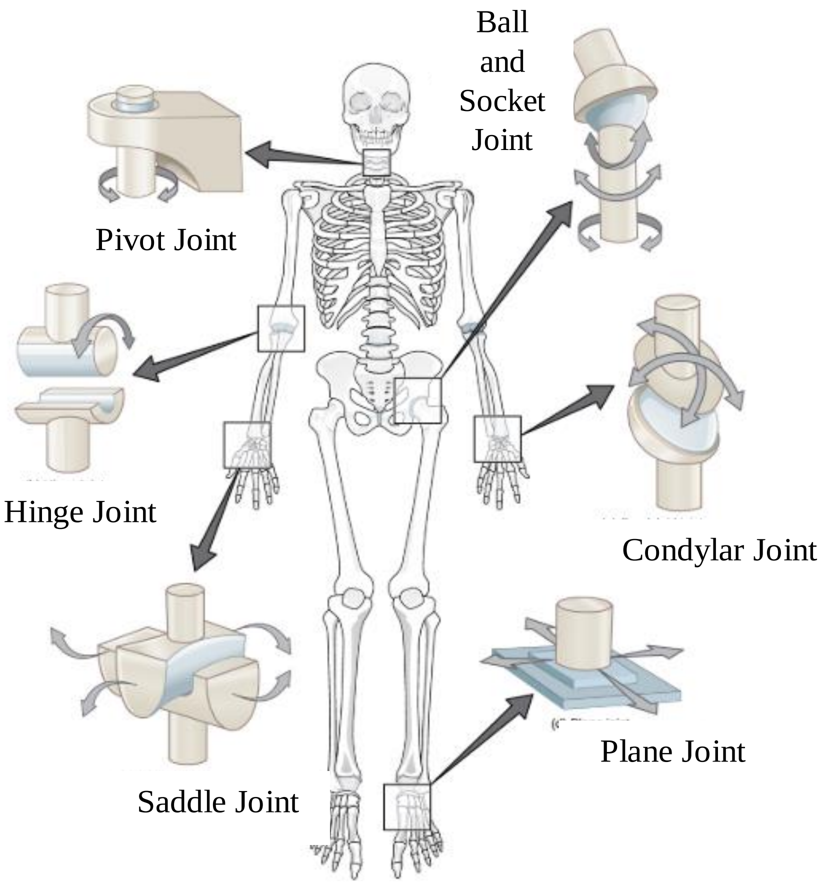

Figure 2.1 Types of synovial joint. Adapted from Rye et al., (2018).

Plane joint has flat or slightly curved surfaces of bone to support gliding movement. However, this kind of joint does not allow to twist or rotate a bone in relation to another due to its long shape of articular surface to limit the range of motion. It can be found in the carpal joints in the wrists and the tarsal bones of the feet. Hinge joint is the joint that consists of the slightly rounded end of one bone fits into the slightly hollow end of the other bone (College, 2010; Rye, et al., 2018; Sheet, 2005). This joint allows one direction of movement, one bone