THE EFFECTS OF WATER CONTENT OF ARTICULAR CARTILAGE ON BIOMECHANICAL PROPERTIES AND MRI IMAGE

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DECLARATION

I declare that this project report entitled "The effects of water content of articular cartilage on biomechanical properties and MRI image" is the result of my own work except as cited in the references

Signature	:	....
Name	:	....
Date	:	....

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.

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

With my deepest gratitude that I dedicate this thesis to my beloved parents and family for their endless love and support. This is also dedicated to my respectful supervisor for his mentorship throughout this study, examiners, lecturers and all my friends for their unwavering support over the years.

ABSTRACT

Osteoarthritis (OA) is a major health issues among the population. It causes pain in human joint when moving. The main cause of OA is degeneration of articular cartilage. The earliest stage of OA resulted in the alteration of the biomechanical properties of cartilage elastic modulus and permeability. Hence, the ability to detect the disease at its earlier stage is crucial for early detection of the disease. MRI technique is common used to evaluate the articular cartilage and reflects its biomechanical and histological complexity. However, most of the diagnoses were performed at the progressive stage of OA. Besides that, high field MRI was used in most of the previous works and current clinical procedures. High field MRI required significant purchase and high maintenance cost. Therefore, this study aimed to investigate the potential application of low field MRI image in order to examine the condition of articular cartilage. Cartilage specimens obtained from the bovine femoral head were scanned using 0.18 T MRI. Gradient echo sequence of the low field MRI was found as the most suitable sequence to image the cartilage. The images of cartilage were characterized based on the intensity of the greyscale. Creep indentation test was then conducted on the cartilage specimens and follow by the indentation test was simulated using finite element method. The biomechanical properties of cartilage elastic modulus and permeability were characterized by integrating the experimental indentation test data and computational finite element model. The average elastic modulus was found to be 0.39 ± 0.14 MPa while the permeability was $22.59 \pm 14.85\text{x}\ 10^{-15}\ \text{m}^4/\text{Ns}$. Correlation analyses were performed to examine the relationship between greyscale of MRI image and biomechanical properties of elastic modulus and permeability of the cartilage. It was found that the cartilage greyscale was moderately correlated with cartilage biphasic elastic modulus (r= 0.617) and lower correlation was observed with the permeability (r= 0.593). Thus, present results indicate that the low field MRI have the potential and provide promising insight to determine the condition of articular cartilage. It could be further develop to serve as an early detection of OA disease.

ABSTRAK

Osteoartritis ialah salah satu isu kesihatan yang menyebabkan kesakitan pada sendi manusia. Punca utama osteoartritis merupakan degenrasi tulang rawan artikular. Pada peringkat awal osteoartritis, ciri-ciri biomekanikal elastik and kebolehtelapan tulang rawan akan mengalami perubahan. Kajian mendalam mengenai tulang rawan telah banyak dijalankan semasa perubahan patologi pada tisu rawan. Oleh itu, keupayaan untuk mengesan osteoartritis pada peringkat awal adalah penting untuk intervensi awal bagi rawatan penyakit ini. Kaedah pengimbas pengimejan resonans magnetik digunakan secara meluas untuk mengkaji keadaan tulang rawan artikular. Walau bagaimanpun, diagnosis ini biasa dijalankan pada peringkat perkembangan osteoartritis. Kebanyakan kajian lanjutan terdahulu dan prosedur klinikal semasa telah dijalankan dengan mengaplikasikan medan pengimejan resonans magnetik berkekuatan tinggi yang memerlukan kos pembelian dan penyelenggaraan yang tinggi. Oleh itu, kajian ini bertujuan untuk mengkaji potensi pengimejan resonans magnetik berkekuatan rendah dalam pemeriksaan keadaan tulang rawan. Tulang rawan daripada humerus sendi bahu lembu telah digunakan untuk pengimejan dengan mengaplikasikan medan pengimejan resonans magnetik yang berkekuatan serendah 0.18 T. Di dalam kajian ini, didapati urutan gema kecerunan adalah urutan yang paling sesuai dalam pengimejan resonans magnetik berkekuatan rendah untuk mengkaji tulang rawan. Imej tulang rawan ini kemudian dicirikan mengikut keamatan skala kelabu. Ujian lekukan dijalankan untuk mendapatkan data daripada eksperimen dan model unsur tak terhingga telah dibangunkan daripada pengukuran geometri tulang rawan. Kajian mengkaji ciri-ciri biomekanikal tulang rawan dilakukan dengan mengintegrasi data eksperimen ujian lekukan dan pengkomputeran unsur tak terhingga. Nilai purata elastik modulus tulang rawan adalah 0.39 $\pm$ *0.14 MPa manakala purata untuk kebolehterapan adalah 22.59* $\pm$ *14.85* $\times 10^{-15}\ m^4/Ns$*. Analisis korelasi telah dikaji untuk mengenalpasti hubungan antara skala kelabu dan sifat biomekanikal modulus elastik dan kebolehtelapan tulang rawan. Berdasarkan hasil kajian, skala kelabu tulang rawan menunjukkan hubungan sederhana dengan modulus elastik (r=0.617) dan hubungan yang lebih rendah diperhatikan pada kebolehtelapan (r=0.593). Hasil dari kajian ini menunjukkan pengimejan resonans magnetik yang berkekuatan rendah berpontensi untuk menentukan keadaan tulang rawan artikular. Pendekatan ini boleh dikaji secara mendalam bagi memberi panduan kepada intervensi rawatan yang awal dalam bidang penyelidikan penyakit osteoartritis.*

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LIST OF ABBEREVATIONS

CAX4RP	Four-node bilinear displacement and pore pressure element, reduce integration
DICOM	Digital imaging and communications in medicine
ECM	Extracellular matrix
FE	Finite element
GRE	Gradient echo
MRI	Magnetic resonance imaging
OA	Osteoarthritis
PBS	Phosphate buffer saline
SE	Spin echo

LIST OF SYMBOL

k	=	Permeability
E	=	Modulus of elasticity
v	=	Poisson’s ratio
e	=	Void ratio
T	=	Tesla
°C	=	Celsius

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Osteoarthritis (OA) is a human joint disease worldwide. OA commonly happens in the part of body that has weight-bearing joints, for example, hips, knees and spine (Taruc-Uy and Lynch, 2013). Fingers, neck, wrist and large toe also affected. The OA patient will feel joint aching while moving and pain after overuse. In United States, more than 40 million of population affected by OA and bring disability nationwide (Hansen et al., 2012). Approximately 10% of the persons over 65 years old or 2% of the adult population are suffer with the OA (Felson et al., 2016).

There are several factors cause the OA such as ageing, previous joint injury and obesity. Ageing plays a fundamental role in the idiopathic OA. Therefore, OA is the highly prevalent chronic disease among the senior citizen (Liess et al., 2002). While moving, the patient will feel pain and feel relieve by rest. Because of this, the movement of the patient is restricted and reduce in functional capacity. After some time, the joint will worn and the pain will more significant. In fact, the main cause of OA is degeneration of articular cartilage. Figure 1.1 shown the normal knee joint and OA knee joint.

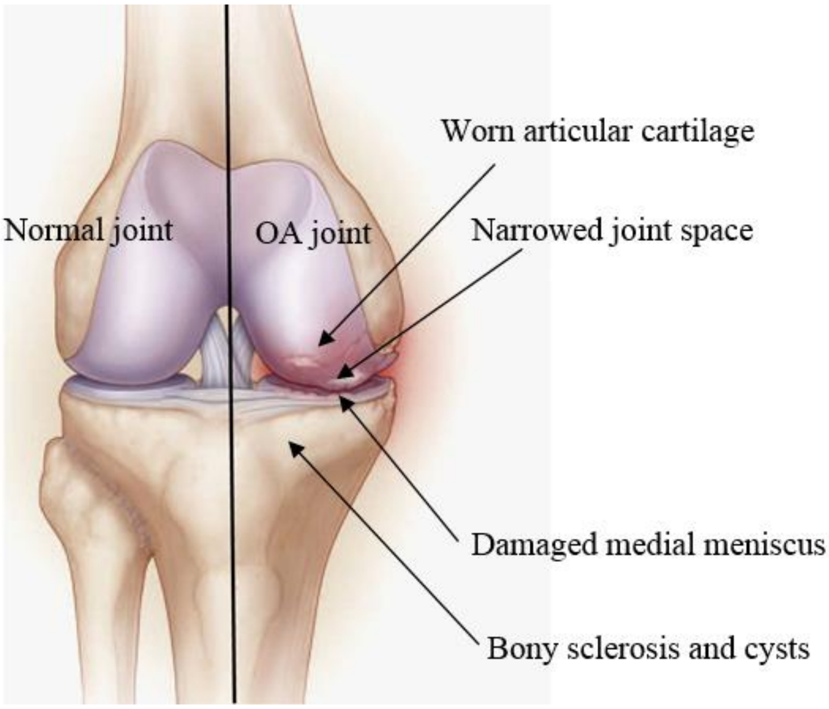

Figure 1.1: Normal knee joint and osteoarthritis knee joint (Uth and Trifonov, 2014).

Articular cartilage is the layer that covered the extremity bone in joint. It is a biphasic medium consists of fluid phase and solid phase. Water is the main component in the fluid phase and it fills the gap between solid matrix. It contributes about four fifths of the wet weight of the articular cartilage (Armstrong and Mow, 1982). The mechanical properties of articular cartilage strongly correlated with the water content of the tissue. An elevated water content in the cartilage tissue characterized the early form of OA. Water content in the cartilage decrease with ageing. This causes the permeability, k will decreased and the Modulus of elasticity, E will increased (Armstrong and Mow, 1982).

Magnetic resonance imaging (MRI) is a non-invasive imaging method to diagnose OA and visualize articular cartilage (Eckstein et al., 2006). The magnetic field strength of MRI can be categorised into low field MRI (<1.5 T), high field MRI (1.5 T- 7.0T) and ultra-high field MRI (>7 T). From the previous study, the results shown similar diagnostic accuracy, specificity and sensitivity when do the comparison between the high field MRI machine, low field and intermediate while imaging the extremity (Roemer et al., 2010).

1.2 PROBLEM STATEMENT

In the early stage of osteoarthritis, decreasing of the thickness of the articular cartilage is not significant but the decreasing of the biomechanical properties are significant. Proteolytic breakdown of the cartilage matrix, the fibrillation and erosion of the cartilage surface, and the beginning of the synovial inflammation are the three broad stages of progression of OA. The articular cartilages have limited regenerative capability. Therefore, early detection of OA could provide better early prevention of OA. This can reduce the disability and pain of the patient.

In the previous studies, the mechanical compressive parameters of the articular cartilage decreases between 20% to 80% in the early OA stage (Nieminen et al., 2004, Kumar et al., 2018). The early changes of the articular cartilage might undetectable using common clinical methods because the cartilage loss and marginal superficial changes are not significant. The evaluation of the interstitial water content of articular cartilage were carried out. T_1 relaxation time of MRI is strongly correlate to the water content of articular cartilage (Berberat et al., 2009). This method can examine degeneration of cartilage by approximating the changes in actual water content.

However, the low field MRI is not popular being use in examination of cartilage. In addition, most of the studies were investigated using the fresh and healthy cartilage where the water content was in the range of 70% to 80% (Berberat et al., 2009, Shiguetomi-Medina et al., 2017). The effects of water content on biomechanical behaviour of articular cartilage are yet to be explored. Therefore, this study aims to examine the effects of water content on characterised biomechanical properties and MRI image of articular cartilage.

1.3 OBJECTIVE

1. To examine the effect of water content on biomechanical properties of articular cartilage.
2. To examine the effect of water content on MRI image of articular cartilage.

1.4 SCOPE OF PROJECT

1. The cartilage specimen used in this study was obtained from bovine femoral head.
2. Characterization of modulus of elasticity, E and permeability, k of the cartilage were carried out using a combination of indentation test and finite element analysis (FEA).
3. The cartilage specimen was scanned using low field 0.18 T MRI system.
4. Characterization the greyscale of MRI image of articular cartilage was performed using MATLAB software.

1.5 GENERAL METHODOLOGY

In order to achieve the objective, there are procedures need to be carried out. Before starting the experiment, the literature review related to the study were reviewed. The journals, articles or any materials related to the research were reviewed.

The specimen and materials needed were prepared. The specimen used in this research was articular cartilage of bovine femoral head. The bovine hip joint bought from the local abattoir in Jasin. The flesh was removed by using scalpel. Then, the joint was cut out by using electric handsaw. The excess tissues and damaged surfaces were removed. After that, the joint was cut into slices and drilled out the small piece of bone that attached the cartilage by using electric hand drill. The bone was removed by using scalpel. The specimens were put in the room to dehydrate and get the different water content. During preparation process, the specimen need to soak in the phosphate buffered saline (PBS) to prevent dehydration. PBS is a solution that contains sodium chloride, sodium phosphate, potassium chloride and potassium phosphate. It was prepared by dissolved the PBS tablet in the distilled water with the ratio of 1 tablet in 100 ml of distilled water.

The specimens with different water content were scanned with the 0.18 T low field MRI Esaote C-scan MRI machine. The images generated from the MRI are processed using Matlab software. Based on the image grayscale, the details of the cartilage were characterize. After that, the cartilage specimens were used to do the indentation test. The indentation test is to study the time dependent and the deformation of the articular cartilage. Then, the model of articular cartilage was analysed by using ABAQUS software. The biomechanical properties, permeability, k and modulus of elasticity, E were characterized from the result. Finally, the correlation between the grayscale, permeability, k and modulus of elasticity, E were plotted in the graph.

The experimental and computational result were compared and discussed. A report for this research was written at the end of the research. The methodology of this research was summarized in the flow chart as shown in Figure 1.2.

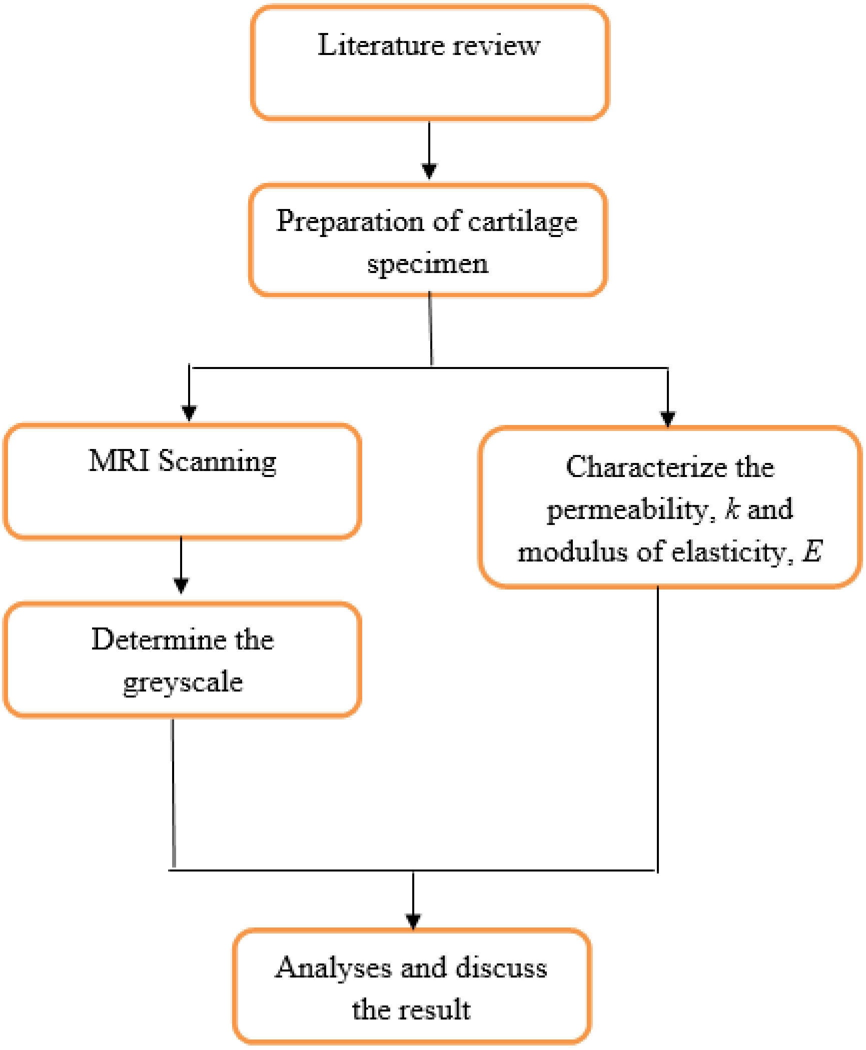

Figure 1.2 Flow chart of the general methodology.

CHAPTER 2

LITERATURE REVIEW

2.1 Synovial Joint

Synovial joint plays an important role in musculoskeletal system. The synovial joints characterized by articular cartilage and bathed in synovial fluid (Raleigh et al., 2017). It provides the body stability, movement and manipulate objects within the immediate environment (Eckstein et al., 2006). The key function of the synovial joint is to ease the implementation of the basic mechanical task of motion (Mow and Lai, 1980). Synovial joint consents the movement between the long bones. Knees, hips, shoulders, elbows, and phalangeal are the parts consist of synovial joints.

2.1.1 Types of Synovial Joint

Human synovial joints can be categorized into six types which are condyloid joint, ball and socket joint, pivot joint, hinge joint, plane joint and saddle joint. Figure 2.1 shown the types of synovial joint in human body.

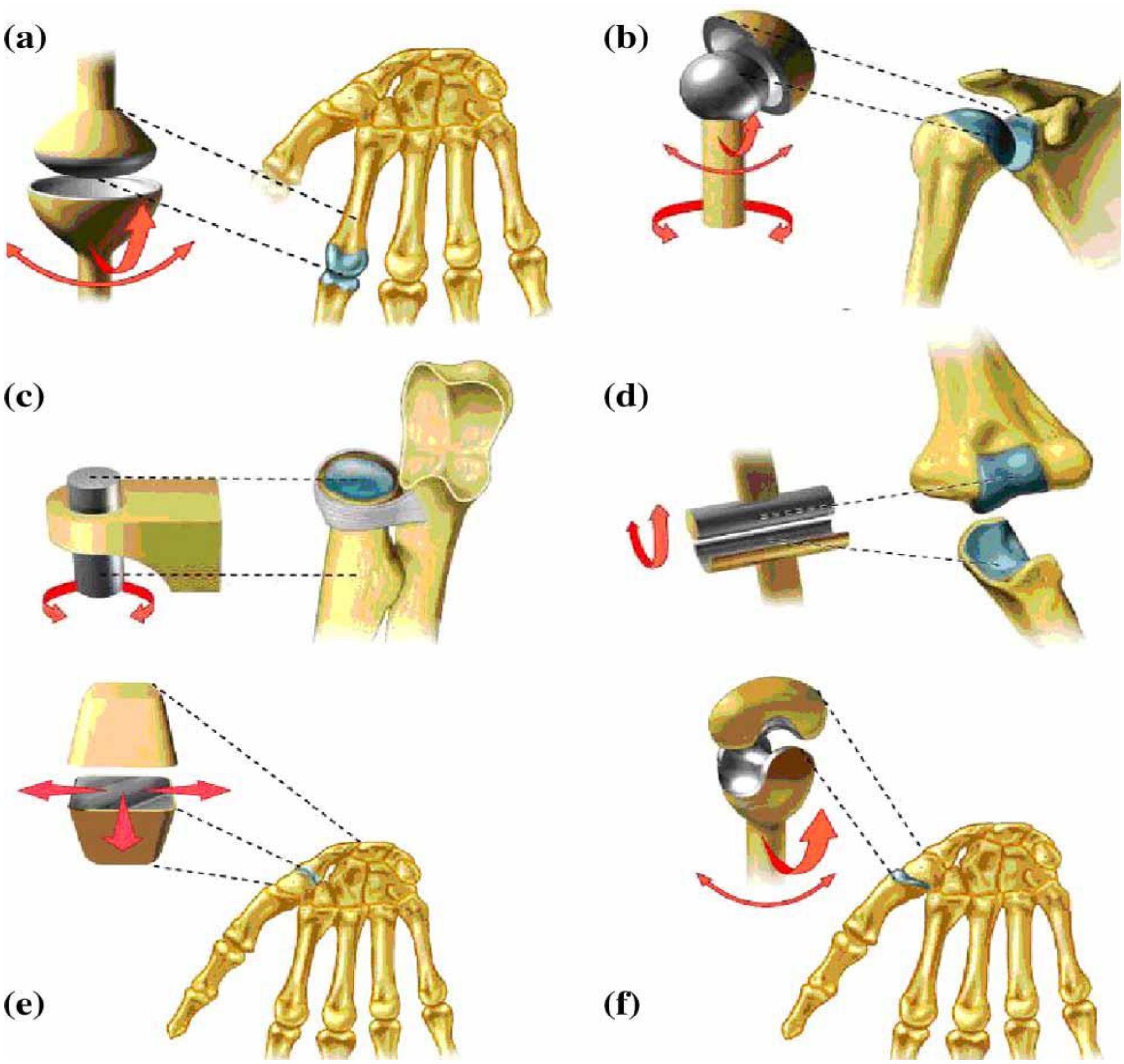

Figure 2.1: Types of synovial joints. (a) condyloid joint (b) ball-and-socket joint (c) pivot joint (d) hinge joint (e) planar joint (f) saddle joint (Yang et al., 2008).

Pivot joint is the joint that allow rotational movement. It consists of a rounded end bone that can fit into a ring formed by the other bone. Joint of neck vertebrae and wrist are the example of the pivot joint which allow the head to turn left and right and palm turn up and down. Hinge joints like the hinge of door. It enables swinging motion and bending motion. Hinge joints usually found at knees, elbows, ankles, toes and fingers. For saddle