UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

CHARACTERIZATION OF BIOMECHANICAL PROPERTIES OF ARTICULAR CARTILAGE ACROSS SYNOVIAL JOINT

Yusra Liyana Binti Jaafar

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CHARACTERIZATION OF BIOMECHANICAL PROPERTIES OF ARTICULAR CARTILAGE ACROSS SYNOVIAL JOINT

YUSRA LIYANA BINTI JAAFAR

**A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled "Characterization of Biomechanical Properties of Articular Cartilage across Synovial Joint" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	……………………………..
Name	:	Yusra Liyana Binti Jaafar
Date	:	……………………………..

APPROVAL

I hereby declare that I have read this thesis and in my opinion, this thesis is sufficient in terms of scope and quality for the award of the Master of Science in Mechanical Engineering.

Signature : ……………………………………….

Supervisor Name : Dr. Mohd Juzaila Bin Abd Latif

Date : ………………………………………..

DEDICATION

A million praise towards my family, my respectful supervisor, examiner and lecturers and to all my friends for their support and cooperation in helping me to complete this thesis.

Thanks to the Ministry of Higher Education (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM) for the financial support for my study.

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ABSTRACT

Degradation and loss of articular cartilage in synovial joint has long been recognized as the main source of osteoarthritis (OA). It is generally accepted that the biomechanical properties of articular cartilage seem to be more sensitive to pathological changes of the tissue. Extensive studies of cartilage have been carried out to characterize the biomechanical properties using both experimental and analytical approaches. These properties were then applied in computational models to investigate the biomechanical behavior of the cartilage. However, analytical analysis was developed based on the theory which idealized the geometrical and physical conditions of the cartilage and subchondral bone. Furthermore, previous experimental studies require the cartilage to be isolated which could possibly damage the cartilage. These could be the main reason as the behavior of the cartilage across the synovial joint is yet to be fully understood because it appears that only part of the cartilage in synovial joint were previously being investigated. Therefore, the study aims to develop new approach to integrate the experimental and computational methods which could enable to characterize the elastic modulus and permeability of the cartilage across the synovial joint. Articular cartilage of bovine humeral head was used to perform the indentation test in order to obtain experimental data. The cartilage was measured using profile projector for development of finite element (FE) model. New approach to integrate the experiment data and FE model were developed to examine the cartilage biphasic elastic modulus and permeability. Based on the result, the elastic modulus increased by 150.6% when cartilage thickness was increase more than twice. Meanwhile, opposite trend was seen for permeability, where the permeability decrease as the cartilage became thicker with 118.9% percentage difference. This could indicate that the actual geometry of cartilage includes of cartilage thickness and curvature does effect the biomechanical properties of articular cartilage across synovial joint. These findings will be serving as a guide in enhancing tissue engineering developments for cartilage repair and as an input for computational studies.

ABSTRAK

Kemerosotan dan kecederaan tulang rawan artikular pada sendi sinovia telah dikenalpasti sebagai punca utama osteoartritis. Ia telah diterima secara umum bahawa ciri-ciri biomekanik tulang rawan artikular adalah lebih sensitif kepada perubahan patologi pada tisu rawan. Kajian mendalam mengenai tulang rawan telah dijalankan untuk mengkaji ciri-ciri biomekanikal mengunakan kedua-dua teknik eksperimen dan analisis. Ciri-ciri biomekanik ini kemudiannya digunakan untuk model pengkomputeran untuk mengenalpasti sifat biomekanik tulang rawan artikular. Walaubagaimanapun, analisis yang telah dikembangkan berdasarkan teori yang berdasarkan geometri dan keadaan fizikal tulang rawan dan tulang subchondral yang ideal. Selain itu, dalam kajian terdahulu memerlukan tulang rawan artikular diasingkan dari keadaan asal yang mungkin menyebabkan kerosakan pada tisu tulang rawan. Ini merupakan penyebab utama kepada ketidakfahaman mengenai sifat tulang rawan pada sendi sinovia di sebabkan oleh hanya sebahagian dari tulang rawan pada sendi sinovia yang digunakan dalam kajian sebelum ini. Oleh itu, kajian ini bertujuan untuk membangunkan pendekatan baru untuk mengintegrasikan kaedah eksperimen dan pengkomputeran yang berupaya untuk mengenalpasti modulus elastik dan ketelapan tulang rawan artikular yang merangkumi seluruh sendi sinovia. Tulang rawan daripada humerus dari sendi bahu lembu telah digunakan untuk menjalankan ujian lekukan untuk mendapatkan data daripada eksperimen. Geometri tulang rawan telah diperolehi menggunakan profil projektor untuk membina model unsur tak terhingga. Pendekatan baru untuk mengintegrasikan eksperimen data dan model dari unsur tak terhingga telah dibangunkan untuk mengkaji dwifasa modulus elastik meningkat sebanyak 150.6% apabila ketebalan rawan meningkat melebihi dua kali ganda. Sementara itu, trend yang sebaliknya dilihat pada ketelapan, di mana nilai ketelapan menurun apabila rawan menjadi tebal. Ini adalah menandakan, nilai geometri sebenar rawan yang terdiri daripada ketebalan dan lengkungan rawan boleh mempengaruhi ciri-ciri biomekanikal tulang rawan artikular pada seluruh sendi sinovia. dan kebolehtelapan tisu tulang rawan artikular. Hasil daripada kajian ini mampu memberi panduan kepada perkembangan kejuruteraan tisu untuk pemulihan tulang rawan dan sebagai input kepada kajian pengkomputeran.

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LIST OF ABBREVIATIONS

OA	–	Osteoarthritis
FE	–	Finite Element
PGs	–	Proteoglycans
LVDT	–	Linear Variable Differential Transformer
DAQ	–	Data Acquisition
2D	–	Two Dimensional
3D	–	Three Dimensional
CT	–	Computed Tomography
MRI	–	Magnetic Resonance Imaging
CAX4RP	–	Four-node bilinear displacement and pore pressure, reduce integration
CAX4P	–	Four-node bilinear displacement and pore pressure
CAX4	–	Four-node bilinear
ECM	–	Extracellular Matrix
PFA	–	Paraformaldehyde
PBS	–	Phosphate Buffered Saline
LL	–	Lateral Left
LR	–	Lateral Right
ML	–	Medial Left
MR	–	Medial Right

LIST OF SYMBOLS

E	–	Elastic Modulus
ν	–	Poisson‟s Ratio
κ	–	Permeability

LIST OF PUBLICATIONS

A. Journal

1) Jaafar, Y.L., Latif, M. J. A., Hashim, N. H. A., and Kadir, M. R. A., 2016. The Effects of Thickness on Biomechanical Behavior of Articular Cartilage : A Finite Element Analysis. 11(8), *ARPN Journal of Engineering and Applied Sciences,* pp. 5331–5335.

2) Hashim, N. H., Latif, M. J. A., and Jaafar, Y. L., 2015. The Effects of Contact Area and Surface Curvature on Biomechanical Behavior of Articular Cartilage, *Biomedical Engineering (ICoBE), 2015 2nd International Conference*, pp. 1-4.

CHAPTER 1

INTRODUCTION

1.1 Background

Osteoarthritis (OA) is the most common joint disease and symptomatic health problem which lead to disability to middle age and older people (Egloff et al., 2012; Buckwalter and Martin, 2006). OA usually occurs at knee, hips, hand and spine. OA is caused by joint injury and degeneration of cartilage, which leads to the limitation in active joint movement. Joint injury is caused by exposing subchondral bone by accidents, poor training practices and improper gear. Pre-mature of OA may be occurs if the injury left untreated at early stage. Meanwhile, the degeneration of cartilage is caused by wear and tear in joint. Wear and tear of cartilage normally is caused by factor of aging where it reduces the cartilage hydration. The hydrated cartilage become thin and lost, thus lead to painful joint. Usually, the damage of cartilage tissue initiates at the surface of cartilage, where it become porous and high in permeability (Grenier et al., 2014). This leads to the decreased of modulus of elasticity and reduction in load bearing capacity of the articular cartilage (Bhosale and Richardson, 2008).

Articular cartilage is a smooth and glistening bluish-white tissue which covers the end surface of bones. The main function of articular cartilage is to transmit load between opposing joint surface, provides a low-friction gliding surface and shock absorber to minimize peak pressure on the subchondral bone. These functions are achieved from the unique material properties possesed by the cartilage. The cartilage tissue composes of fluid and solid phase. About 80% of the weight is fluid where water is the main content in this phase. The solid phase composes of proteoglycans and collagen. The cartilage tissue consist of four different zone with respect to depth, which from the surface to the subchondral bone are the superficial, middle, deep and calcified zones. This composition makes the articular cartilage structure inhomogeneous and possessed anistropic and nonlinear properties both in compression and tension.

Various constitutive material models have been used to describe cartilage from single-phase to multiphase models. However, the biphasic theory developed by Mow and co-workers has been widely accepted to represent the solid and fluid phases of the cartilage nature (Mow et al., 1980). In biphasic theory, there are two important biomechanical properties considered which are elastic modulus and permeability. The elastic modulus represents the stiffness of the tissue, while the permeability indicates the resistance to fluid through the cartilage matrix. Both of these properties are commonly characterized using a combination of experimental and analytical method (Toyras et al., 2001; Colombo et al., 2013). Although there are various experimental methods used in previous studies, creep test using indenter was the most preferable. This is due to the specimen preparation where the intact cartilage tissue on the bone could be tested whithout separating cartilage and bone.

Thus, the aim of this study is to investigate the effect of the actual geometry of articular cartilage across synovial joint on elastic modulus and permeability using combination of creep indentation test and simulation of axisymmetric finite element (FE) model. In experimental method, the deformation of cartilage tissue obtained from the creep indentation test. Meanwhile, axisymmetric FE model is developed in accordance to the measured thickness and curvature using Abaqus 6.9-1 (DS Simulia Corp., Providence, RI, USA) software.

1.2 Problem Statement

- The investigaton of cartilage behaviour by using computational method assumed that the cartilage to be flat with uniform thickness. However, this assumption may not appropriate, as the joint is varies in thickness (Li et al., 2013; Toyras et al., 2001; Shepherd and Seedhom, 1999).
- In previous studies, the cartilage biomechanical properties was characterized based on idealized geometrical and physical condition (Latif et al., 2013; Choi and Zheng, 2005) This may contribute to inacuracy of the characterized properties because the geometrical and physical conditions of cartilage in nature are inhomogeneous across the synovial joint.

1.3 Objective

The study embarks on the following objectives:

- To establish an experimental method to perform indentation test across the articular cartilage.
- To integrate the new approach of experimental and computational methods to characterize the elastic modulus and permeability of the cartilage.
- To determine the elastic modulus and permeability of articular cartilage across the synovial joint using the new integration of experimental and computational approaches.

1.4 Scope of Study

The design of indentation test apparatus is developed and fabricated to perform creep and thickness testing. Computational method using axisymmetric FE model is developed according to the measured thickness and curvature of articular cartilage using Abaqus 6.9-

1 (DS Simulia Corp., Providence, RI, USA). The data from both experimental and computational method are used to characterize the biphasic properties of articular cartilage which are elastic modulus and permeability. The parameter that is investigated in this study is the effect of cartilage thickness to characterized the biomechanical properties across synovial joint.

1.5 Significance of Study

The developed method of the present study could potentially be used to characterize the elastic modulus and permeability of cartilage for other synovial joints. The accuracy of characterized properties could be as input for computational studies which could generate better results. These finding will be serving as guide in enhancing tissue engineering developments for cartilage repair and as an input for computational studies.

1.6 Outline of Thesis

This thesis consists of six chapters as per the following sequence:

Chapter 1: Introduction

This chapter introduces the general information about OA disease, causes of OA and articular cartilage. This chapter also states the problem statement, objective, scope and significance of this study.

Chapter 2: Literature Review

This chapter consists of eigtht sections, which each section explains more about the topic. Topics contained in this chapter described the types of human joint and focused on the synovial joint and its anatomy, OA, articular cartilage and its composition, structure and function, biphasic theory of articular cartilage, characterization of the biomechanical properties of articular cartilage, computational modeling in development of finite element model of articular cartilage and bone, and lastly, animal model.

Chapter 3: Methodology

This chapter is divided into two major sections which are experimental and computational methods. The earlier section focused on the preparation of the experimental method which includes the development of indentation apparatus and material and specimen preparations. The later section describes how the indentation test was conducted to obtain the data of deformation of cartilage tissue. Followed by the procudure of cartilage thickness measurement and cartilage curve measurement to provide the actual geometry of the cartilage tissue that will be used on the computational method. For the computational technique, the data obtained from the experimental technique are used to develop the FE model that will be used to merge to provide a new value of biomechanical properties of articular cartilage.

Chapter 4: Results

This chapter presents the result obtained from the experimental, computational and both methods. The creep deformation of articular cartilage was shown for experimental results. The results of the computational simulation presents the effect of thickness of articular cartilage on contact pressure and pore pressure. The last two section show the biomechanical properties across synovial joint and the effect of cartilage thickness on characterized biomechanical properties. This result was obtained by the combination of experimental and computational techniques.