Faculty of Mechanical Engineering

STUDY OF BIOMECHANICAL PROPERTIES OF ARTICULAR CARTILAGE USING LOW-FIELD MAGNETIC RESONANCE IMAGING

Yew Wansin

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YEW WANSIN

A thesis submitted
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DECLARATION

I declare that this thesis entitled “Study of Biomechanical Properties of Articular Cartilage using Low-Field Magnetic Resonance Imaging” 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 : Yew Wansin

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 : Associate Prof. Dr. Mohd Juzaila Bin Abd Latif

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, causing pain in the human joints. It is well recognised that the OA is mainly caused by the 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 earliest stage is crucial for early intervention of the disease. MRI technique is widely used to assess the condition of the articular cartilage by examining the geometrical data. However, most of the diagnoses were performed at the progressive stage of osteoarthritis. Furthermore, most of the previous works and current clinical procedures were performed using high-field MRI which require significant purchase and maintenance costs. 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 humeral head of bovine were scanned using 0.18 T MRI. It was found that the gradient echo sequence of the low-field MRI was the most suitable sequence to image the cartilage. The images of cartilage were characterised based on the intensity of the greyscale. Creep indentation test was then conducted on the cartilage specimens and subsequently the indentation test was simulated using finite element method. The biomechanical properties of cartilage elastic modulus and permeability were characterised by integrating the experimental indentation test data and computational finite element model. The average elastic modulus was found to be 0.93 ± 0.72 MPa while the permeability was 0.58 ± 0.31 $\times 10^{-15} m^4/Ns$. Correlation analyses were performed to examine the relationship between the 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. 513) and higher correlation was observed with the permeability (r= 0.613). 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 intervention of OA disease.

ABSTRAK

Osteoartritis dikenalpasti sebagai salah satu isu kesihatan yang menyebabkan kesakitan pada sendi manusia. Degenerasi tulang rawan artikular dikenalpasti sebagai punca utama osteoartritis. Pada peringkat awal osteoarthritis, ciri-ciri biomekanikal elastik dan 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 melalui pemeriksaan data geometri. Walau bagaimanapun, 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 0.93 ± 0.72 MPa manakala purata untuk kebolehterapan adalah 0.58 ± 0.31 $\times 10^{-15} m^4/Ns$. 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=0.513) dan hubungan yang lebih tinggi diperhatikan pada kebolehtelapan (r=0.613). 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 osteoarthritis.

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LIST OF ABBREVIATIONS

CAX4	–	Four-node bilinear element
CAX4P	–	Four-node bilinear displacement and pore pressure
CAX4RP	–	Four-node bilinear displacement and pore pressure element, reduce integration
CT	–	Computed tomography
DAQ	–	Data acquisition
DICOM	–	Digital imaging and communications in medicine
ECM	–	Extracellular matrix
FE	–	Finite element
GRE	–	Gradient echo
LL	–	Lateral left
LR	–	Lateral right
LVDT	–	Linear variable differential transformer
ML	–	Medial left
MR	–	Medial right
MRI	–	Magnetic resonance imaging
OA	–	Osteoarthritis
PBS	–	Phosphate buffered saline
ROI	–	Region of interest
SE	–	Spin echo
T3D	–	Turbo 3D

US	–	Ultrasound
WHO	–	World Health Organisation
1D	–	One-dimensional
2D	–	Two-dimensional
3D	–	Three-dimensional

LIST OF SYMBOLS

E	–	Elastic modulus
k	–	Permeability
υ	–	Poisson's ratio
e	–	Void ratio
T	–	Tesla
r	–	Correlation coefficient
°C	–	Celsius

LIST OF PUBLICATION

1) Yew, W.S., Latif, M.J.A., Saad, N.H M., 2016. Characterization of Grayscale of MRI Images for Articular Cartilage, *Proceedings of Mechanical Engineering Research Day 201*6, pp. 143-144.

2) Yew, W.S., Latif, M.J.A., Saad, N.H M., Alhabshi, S.M.I., Mahmud, J., Kadir, M.R.A., 2017. Characterization of Articular Cartilage using Low-Field Magnetic Resonance Imaging Image, *Journal of Medical Imaging and Health Informatics,* volume 7, pp. 1-4. (ISI Journal Accepted).

CHAPTER 1

INTRODUCTION

1.1 Project Background

Osteoarthritis (OA) is one of the degenerative arthritis joint disorder that is most prevalent in knee, hips, and spine and it is one of the major health issue. It causes joint pain and stiffness. OA patients will have limitations in movement, cannot perform their major daily activities, and require help with care. It is estimated that 5.93% of the total population in Malaysia will develop osteoarthritis (Raj et al., 2016, 2014). The World Health Organisation (WHO) estimates that 9.6% of men and 18 % of women aged above 60 years old have affected by symptomatic OA (United Nations, 2015; Thysen et al., 2015; Leung et al., 2013). As the ageing population of the developed country increases, the prevalence of OA is expected to accelerate from 2015 to 2050 due to the proportion of the world's populations over 60 years has increased substantially.

OA is mainly caused by the deterioration of articular cartilage and affected the biomechanical properties of the articular cartilage at the early stage (Hani et al., 2015; Szarko et al., 2010; Knecht et al., 2006). Deterioration of cartilage is caused by wear or tear in the joint. It is most likely associated with ageing where it reduces the hydration of cartilage and affected the articular cartilage that have been continually stressed throughout the years to become thin and thus lead to the disease. Damaged cartilage become porous and high in permeability and leads to the decreased of modulud of elasticity and reduction in load bearing capacity (Grenier et al., 2014; Bhosale and Richardson, 2008). Due to the limited regenerative capacity of the articular cartilage, cartilage tissues repair remains a challenging task. Conseqeuntly, preventive strategies are yet to be identified to treat the

disease since the current prescriptions to modify or decelerate the disease are limited. In addition, non-surgical treatments for OA have limited efficacy partly due to the late detection of the structural deterioration of the disease (Favero et al., 2015). Therefore, in the final stage of the disease, most of the severe patient will undergo joint replacement surgery (Wang et al., 2012). Thus, the ability to diagnose the disease at its earliest stage is crucial because the treatment often depends on the early detection in the symptomatic OA disease.

Therefore, early detection of OA had caused great interest to researchers, radiologists, and orthopaedists. Nowadays, more than one measurement element of articular cartilage changes is needed to enhance the ability of the early symptoms of osteoarthritis. These include the alteration of cartilage composition components such as water content and proteoglycan content in cartilage and further examination on cartilage morphological components such as thickness and volume using imaging modalities (Hani et al., 2015; Liess et al., 2002).

Articular cartilage is only a few millimetres thick and possesses an irregular shape that make the detection of the minor changes in the early degeneration of the disease more challenging (Hani et al., 2015). Due to this, articular cartilage does not heal by itself under biological situation (Bergmann et al., 2013). The current gold standard for the early identification to assess the articular cartilage and diagnose the evolution of OA is based on medical imaging modalities such as computed tomography (CT) scan, X-ray, arthoscopy, ultrasound (US) and magnetic resonance imaging (MRI).

In recent decades, MRI has become the significant non-invasive imaging modality to examine the joint as a measure of the OA disease and assess the pathologic changes in bone and tissues especially articular cartilage (Fornari et al., 2015; Nissi et al., 2004). MRI is widely used to detect the osteoarthritis feature because it produces a high sensitivity of

contrast image in detecting intra-articular structures compare to others imaging modalities (Fornari et al., 2015; Kumar et al., 2011; Blumenkrantz and Majumdar, 2007; Liess et al., 2002). Research results had indicated that MRI is the most promising imaging modality because MRI enables quantitative assessment to measure volume and thickness of cartilage and semiquantitative assessment to examine the composition of (Hani et al., 2015; Wang et al., 2012). High-field MRI was normally used in previous studies to detemine the cartilage biomechanical properties based on the quantitative information from MRI images (Nissi et al., 2007; Nieminen et al., 2004; Wayne et al., 2003; Liess et al., 2002). Previous studies have reported that the diagnostic performance between high-field (1.5 T) and low-field (0.2 T) MRI showed equally well on the knee joint (Cotten et al., 2000). Figure 1.1 shows the images on the knee meniscal injuries appearance obtained from both high and low-field MRI. Therefore, in the present work, the aim is to investigate the potential application of low-field MRI image in examining the condition of cartilage as early intervention of OA disease.

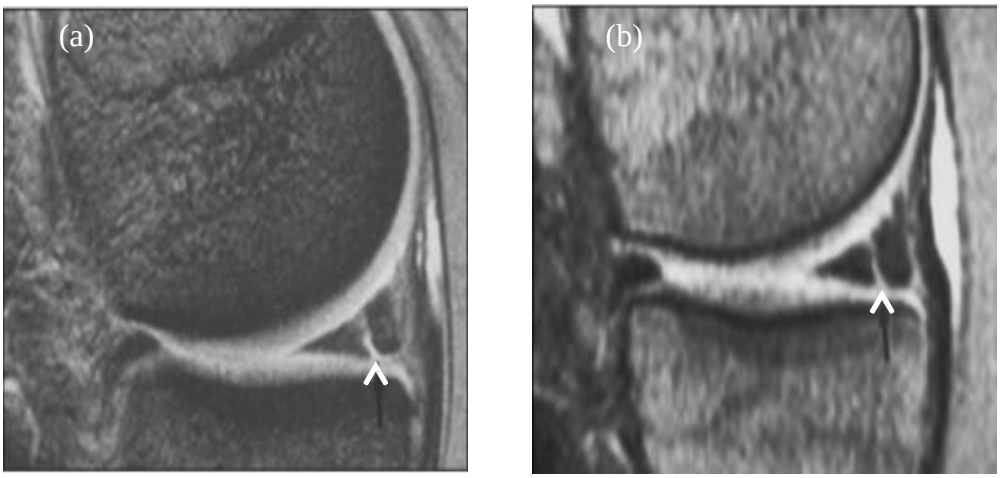

Figure 1. 1 MRI images (a) 1.5 T MRI and (b) 0.2 T MRI show equally diagnostic performance on the meniscal injuries (arrow). Adapted from Cotten et al., 2010