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Effect of Water Content on Correlation of Biomechanical Properties and Grayscale of Articular Cartilage Using Low-Field MRI

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ABSTRACT

The early assessment of osteoarthritis is very crucial since articular cartilage has a very limited ability to regenerate and self-repair as the degeneration happened. Thus, MRI is the most important imaging modality for cartilage evaluation among all the other methods used to diagnose osteoarthritis. However, the cartilage image obtain from low-field MRI is still uncertain particularly in quantitative assessment. Hence this study aims to determine the effect of dehydration on the correlation between grayscale MRI image and biomechanical properties of articular cartilage. In this study, the cartilage specimens were obtained from bovine femoral head which were dehydrate in stages in terms of time expose to room temperature. The specimens were then scanned at every dehydration stage using 0.2 T MRI to obtain the cartilage image and characterized the image based on the grayscale's intensity. Subsequently, indentation test was conducted on specimens at every dehydration level to determine the cartilage biphasic properties of elastic modulus and permeability. The finding showed that the grayscale of cartilage had a moderate correlation with the cartilage biphasic elastic modulus and permeability. More importantly the low-field MRI was able to indicate the high rate of articular cartilage ability to loss its water content.

Keywords: Low-field MRI, articular cartilage, elastic modulus, permeability

1. INTRODUCTION

Articular cartilage is a tissue that plays an important role of bearing surface in synovial joint to allow painless and low-friction movement. The remarkable material properties of articular cartilage and its mechanism to distribute loads and dissipate energy, preserves the network structure from damage over a whole lifetime and under extreme condition [1]. Cartilage mainly consists of extracellular matrix (ECM) and low density of chondrocytes. The ECM is composed primarily 75% water of the cartilage weight, along with a cross-linked matrix with proteoglycans (PG) and type-II collagen fibers [2]. However, the cartilage has lacks of vasculature, lymphatics and nerves that limits the ability to self-repair once it is degenerate [3].

It is well established that the cartilage tissue is represented as biphasic material to describe the solid and fluid phases. The biomechanical properties of elastic modulus, E and permeability, k are found to be important variables in evaluating cartilage tissue as they define the functional biphasic behavior of articular cartilage [4,5]. Previous studies have shown that among the early

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signs of cartilage degeneration is the changes in biomechanical properties as a result of proteoglycan loss and water content modification [6–8]. Minor changes in the structure and composition could cause a significant alteration in the anisotropic mechanical characteristics of the complex cartilage [9,10]. Therefore, an early assessment of cartilage degeneration is crucial in enabling better interventions to prevent the progression of osteoarthritis [11].

Magnetic resonance imaging (MRI) is the main imaging modality in monitoring and evaluating the condition of articular cartilage due to its working principle. High-field MRI systems have been successfully used to assess thickness, proteoglycan and collagen content of cartilage [7,12]. This is possible via the interaction between interstitial water and the macromolecular constituents that affect the nuclear magnetic relaxation properties characterizing the spin energetics of the water proton system. Recently, imaging on low-field MRI has gained interest due to the practicality, and user friendly [13–16]. The low-field MRI has also shown the potential of producing similar cartilage image quality of high-field MRI [15,16]. However, the use of low-field MRI in detecting the condition of cartilage tissue seems to be challenging, as the reliability information obtained with low intensity magnetic fields is still uncertain [17].

Although the cartilage degeneration can be identified based on the quantitative assessment of cartilage thickness and volume using MRI scan image, the assessment was mostly conducted in the progressive state of osteoarthritis because at this stage the cartilage morphology are already changes and degenerates [18,19]. Moreover, neither cartilage volume nor thickness measurements can assess the condition of cartilage from those with mild osteoarthritis and without osteoarthritis. Studies have been reported that there are no significant differences in cartilage thickness in different grades of osteoarthritis [7,20]. Recent study has shown that the biomechanical properties began to decrease at the early stage of osteoarthritis which then leads to the alterations of cartilage morphology [21]. This issue has been raised as a significant concern in many studies, since theoretically, cartilage has been shown to be swelling in the early stages of osteoarthritis, prior to cartilage thinning and losing [7,20,21]. Therefore, biomechanical properties could indicate the actual condition of the cartilage in quantitative low-field MRI image in degeneration process. This study may lead to fundamental correlation between the biomechanical properties and image grayscale of low-field magnetic resonance imaging for progressive osteoarthritic articular cartilage.

Extensive studies in investigating the biomechanical behavior and MRI assessment of articular cartilage have been conducted by using a normal cartilage. However, most of the findings have showed that the effects of dehydration and water content of cartilage are yet to be explored [22–25]. Hence this study aims to determine the correlation between quantitative low-field MRI image greyscale and cartilage biomechanical properties of elastic modulus, E and permeability, k of articular cartilage at different concentration of water. The finding would clearly be helpful as partial dehydration of cartilage can occur during complex, long-lasting surgical procedures or develop during early arthritis and long-term loading [26].

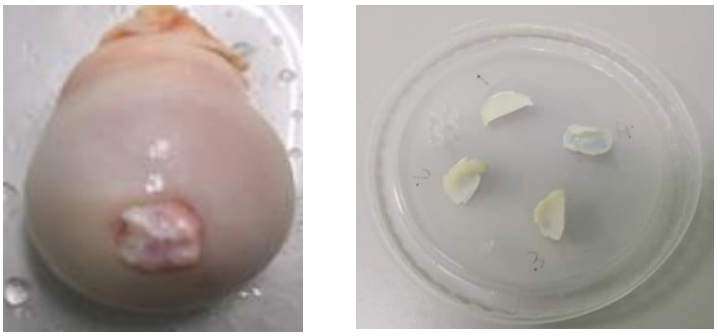
2. MATERIAL AND METHODS

2.1 Specimen Preparation

Cartilage samples were prepared using bovine hip joints which were obtained within 2 hours of slaughter from a local abattoir. The cartilage tissue extracted from humeral head that was separated from subchondral bone by using a scalpel as shown in Figure 1. The cartilage was cut into slices, where each of the sample was 10 mm diameter as according to the indenter diameter [27]. In order to maintain the hydration, the samples were immersed in phosphate buffered saline (PBS) [28]. The specimens (n=7) were then dehydrated by exposing the samples at the

room temperature of 25 °C [26]. The wet weight of the specimen was taken every 30 minutes using analytical balance and the percentage of water content was calculated as [29].

$$\text{Water \% by weight} = \frac{Wet\ weight - Dry\ weight}{Wet\ weight} \text{x}100\% \quad (1)$$



(a) (b)

Figure 1. (a) Bovine humeral head, (b) cartilage specimen.

2.2 Magnetic Resonance Imaging

The specimens were scanned using 0.18 T low-field MRI Esaote C-scan machine as shown in Figure 2. Standard gradient echo imaging sequence was applied as in previous cartilage imaging studies using low-field MRI [30,31]. The scanning was performed at different water content level, starting with the initial state up to 90 minutes after exposing the samples to dehydration effects.

(a) (b)

Figure 2. (a) Esoate C-scan MRI system (b) scan set up.

2.3 Greyscale Characterization of MRI Image

The MRI images were generated in a standard DICOM (Digital Imaging and Communication in Medicine) format and processed using Matlab software. A region of interest (ROI) was selected at the centre of the cartilage specimen which was the indentation test point to characterise the biomechanical properties. The ROI was consisted of 9 pixels (3×3 pixels) across the thickness of the cartilage specimen as shown in Figure 3.

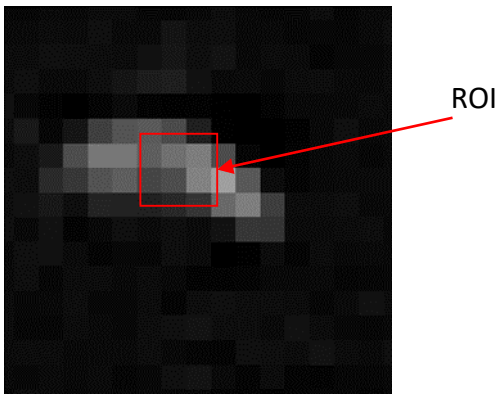


Figure 3. ROI of cartilage specimen in MRI image.

2.4 Characterization of Biomechanical Properties

The biphasic biomechanical properties of elastic modulus and permeability were characterized using a combination of creep indentation test and finite element (FE) analysis [32]. The cartilage specimen was indented at the ROI using 4 mm diameter spherical indenter using the indentation test set-up as shown in Figure 4. The test was subjected to 0.38 N compression load which resulted between 10% to 20% deformation of the cartilage thickness. Cartilage displacement was recorded using LabVIEW data acquisition software (National Instruments Corporation, Austin, TX, USA) every 0.01 seconds for at least 2000 seconds so that the cartilage deformation reached at equilibrium state. During the test, the cartilage specimen was submerged in PBS to avoid the tissue from dehydrated.

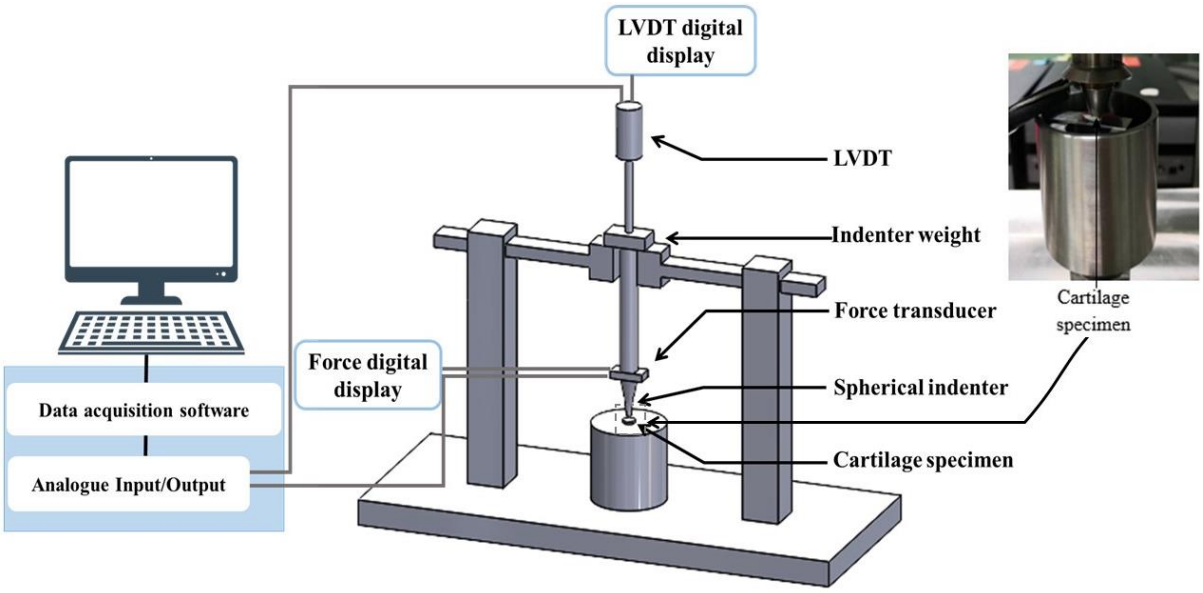


Figure 4. Schematic diagram of indentation test rig.

The articular cartilage was modelled as axisymmetric biphasic poroelastic element to represent the solid and fluid phases of the tissue using Abaqus 6.14 (DS Simulia Corp., Providence, RI, USA) software. The FE model of the cartilage was developed using the measured thickness with 5 mm width with 2 mm radius spherical indenter as shown in Figure 5. The indenter was modelled as analytical rigid surface while the cartilage was modelled using four-node bilinear displacement and pore pressure (CAX4P) elements [32].

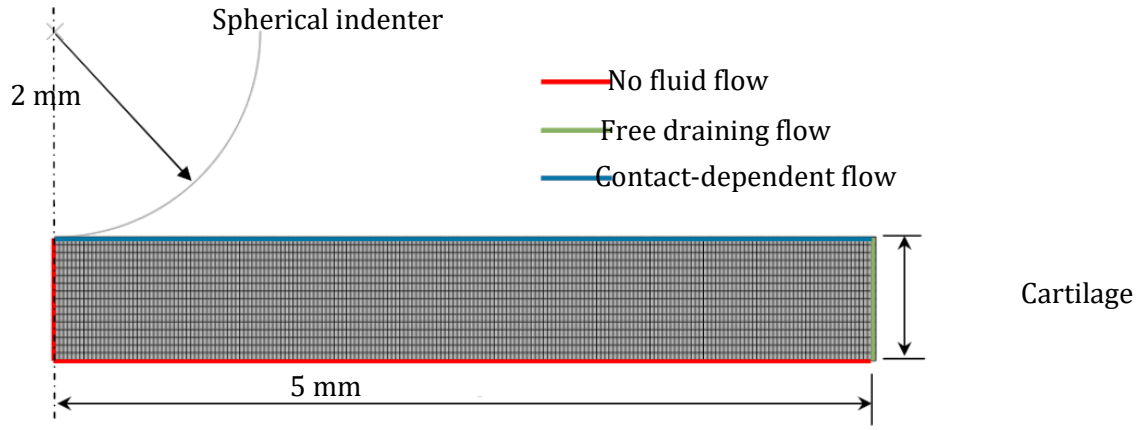


Figure 5. Axisymmetric FE model of cartilage specimen.

The boundary conditions were imposed such that the nodes along the axisymmetry axis were restricted in horizontal direction, while the movement in horizontal and vertical directions were restricted at the bottom nodes of the cartilage. The movement of spherical indenter was constrained to actuate in vertical direction. For fluid flow constraint, contact-dependent flow was applied at the top of the cartilage surface [32,33] . In addition, fluid flow was prevented at the bottom and the vertical symmetry axis of cartilage surface. For the outer edge of the cartilage, the nodes were maintained at zero pore pressure to allow the unrestricted fluid flow. These boundary and interface conditions were applied to simulate the experimental creep indentation test.

The FE model was consequently incorporated with the creep indentation test data to characterize the biomechanical properties of the cartilage. The values of the elastic modulus and permeability were iteratively changed in the FE model to match the experiment deformation-time curve using non-linear least-squares method in Matlab software (R2019, MathWorks Inc., MA, USA). The optimized properties were obtained when the function reached the minimum squared error between the curves [32].

3. RESULTS AND DISCUSSION

3.1 The Effect of Dehydration On Water Content and MRI Image Greyscale

The average percentage of cartilage specimens' water content for initial state, 30 minutes, 60 minutes, and 90 minutes were 76.8±4.5%, 72.9±6.1%, 66.1±9.8% and 57.9±12.6% respectively as shown in Figure 6. The initial percentage of water content was found to be between 70% and 80% which was in the range of previous studies [26,34,35]. Based on the results, the percentage loss of water content of the cartilage was 5.1% in 30 minutes and lead to 24.6% in 90 minutes.

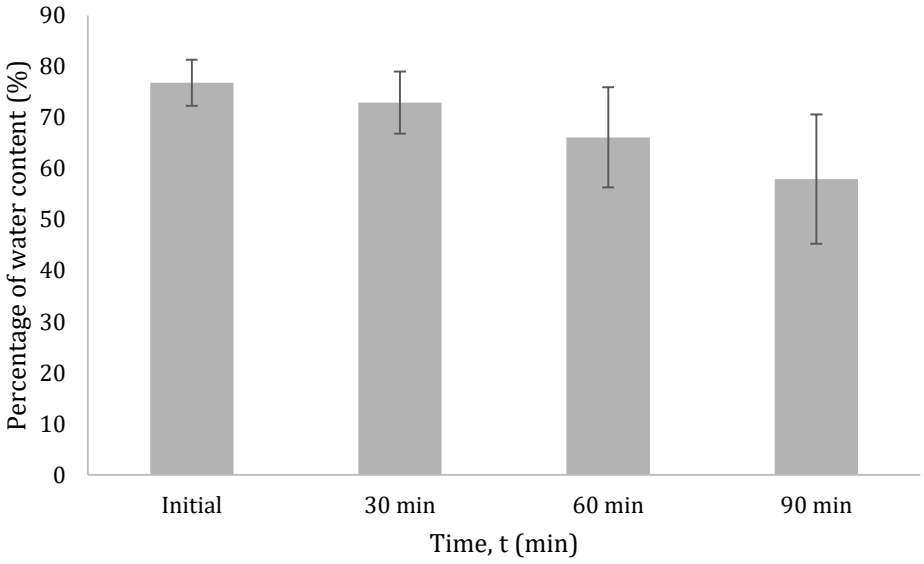


Figure 6. Percentage of water content of cartilage specimen.

Similar result was also observed in previous studies, where exposing the cartilage for a particular duration may lead to dehydration[26,36]. It took between 8 to 10 hours for a complete dehydration at room temperature (25°C) in 49% moisture environment. At this stage, the general structure of the cartilage was altered specifically the content of glycosaminoglycan (GAG) and thickness of the tissue [26].

3.2 The Effect of Dehydration on MRI Image Greyscale

Figure 7 shows the MRI image greyscale of the cartilage specimens based on the dehydration. In this study, the average image greyscale value of fresh cartilage was 2201.3 ± 241.3 which was similar range in previous study [15]. The greyscale value was then dropped to 1879.5 ± 387.7 after 30 minutes and further decreased to 1398.8 ± 407.2 at 36.5% after 90 minutes.

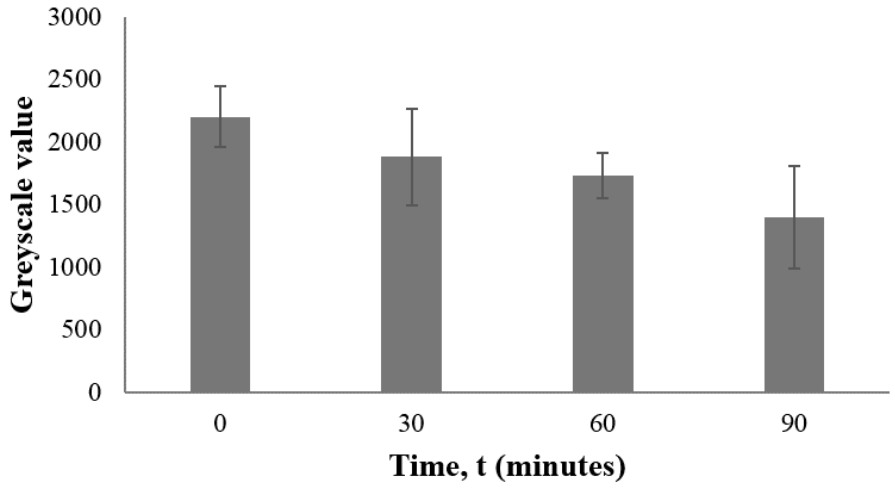


Figure 7. Greyscale of cartilage specimens against time.

This was obviously due to the decrement at the water content level at the final state, which was in agreement with previous study where higher water content led to the higher greyscale value of the MRI image [37,38]. Similar trend was also identified related to the study of the grayscale of superficial and deep zones of articular cartilage. The superficial zone image had

a higher grayscale value compared to the deep zone images [39], where a superficial zone had a higher water content. Therefore, the results showed that there was a great potential of using the low-field MRI at the early stage of detecting osteoarthritis. The indicator used was by examining the water content level of the articular cartilage[40].

3.3 The Effect of Dehydration on Biomechanical Properties

As to generate a deformation graph hence to characterize the biphasic properties of elastic modulus, E and permeability, k of the cartilage, the effect of hydration on biomechanical properties both experimentally and computationally data was combined using Matlab software [41]. An average value of elastic modulus for the fresh cartilage was 0.39±0.13 MPa which was within the range of previous studies [4,23,41]. It was expected that the highest elastic modulus of the cartilage was found at 90 minutes with the value of 2.51±0.51 MPa as shown in Figure 8. This is due to the dehydration of the tissue that only allow small deformation in indentation test [42]. The elastic modulus was increased significantly at 84 % from fresh condition only after 30 minutes. This increment was escalated at 60 minutes and 90 minutes with 148 % and 551 % respectively.

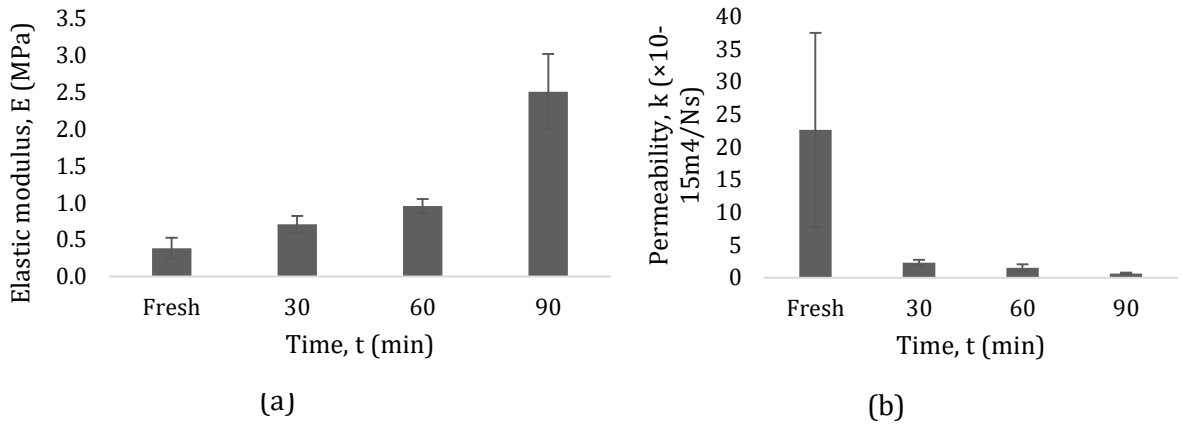
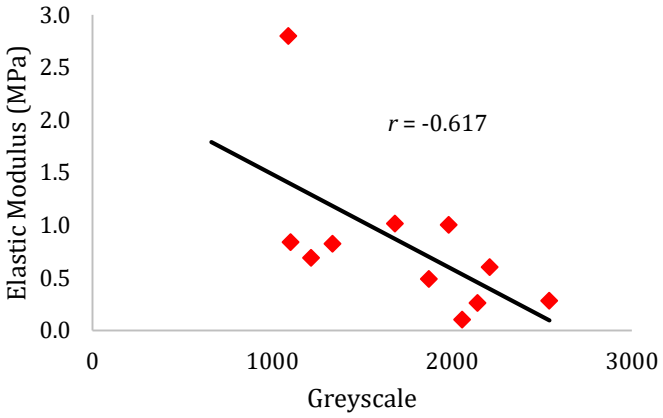


Figure 8. Cartilage biphasic biomechanical properties at different time interval, (a) elastic modulus, (b) permeability.

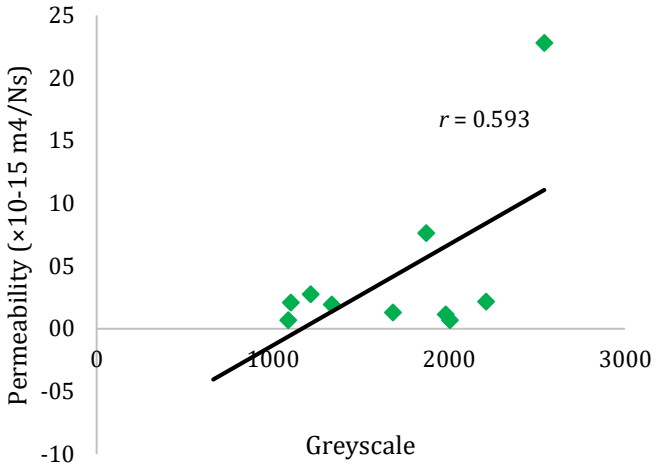
However, opposite trend of permeability was anticipated where the highest value of 22.59±14.85 $\times 10^{-15}$ m^4/Ns was found at the fresh cartilage as shown in Figure 8. The value decreased substantially to 89.8 % after 30 minutes. The permeability of the cartilage was then decreased to 93.3 % and 97.2 % at 60 minutes and 90 minutes respectively. This phenomenon was due to the resistance of fluid flow through the cartilage matrix and hence affected the rate of deformation [43,44].

3.4 Correlation of Biomechanical Properties and MRI Greyscale

A linear Pearson correlation analysis was performed to identify the effect of dehydration between biomechanical properties of the cartilage and MRI greyscale as shown in Figure 9. It was found that a decrease of the elastic modulus resulted in an increment in the greyscale value that created a moderate correlation (r = -0.617). On the other hand, there was an increase of the permeability which resulted in an increment in the greyscale value and also created a moderate correlation (r = -0.593). In a previous research, the correlation between biomechanical properties and MRI greyscale was performed on cartilage at the fresh stage MRI [45], or rather used a high-field with commensurate correlation between 0.5-0.8 [46]. The results showed the potential of using the low-field MRI in quantitative assessment of the health and condition of articular cartilage.



(a)



(b)

Figure 9. Linear Pearson correlation between MRI greyscale and biomechanical properties of the cartilage, (a) elastic modulus, (b) permeability.

4. CONCLUSION

Based on the present results, the application of using the low-filed MRI in assessing the health of articular cartilage has been represented. Although the MRI images obtained by using low intensity magnetic fields is still uncertain, yet in this study shown its ability and potential to observe the water content effect on the grayscale intensity. Furthermore, the result shows that the correlation between the grayscale and the biomechanical properties is between the ranges obtained in a high-field MRI. Therefore, the result shows a great potential of using the low-field MRI to assess the condition of articular cartilage. This study also presented the importance of the hydration of the articular cartilage during testing and medical procedures as it can lead to major changes on the structure integrity of the articular cartilage.

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