High-Resolution Ultrasound Elastography of Articular Cartilage *in Vitro*

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Abstract – Articular cartilage is comprised of three histologic zones that exhibit different Young's moduli. In addition, with age and disease the moduli can be altered. Therefore, diagnosis of joint diseases can be accomplished by detecting biomechanical properties of articular cartilage. In this report we investigate the feasibility of ultrasound elastography of bovine articular cartilage (n=5) employing instantaneous static compression using high-resolution (55MHz) ultrasound elastography *in vitro* as a potential arthroscopic technique. Elastograms were computed using cross-correlation technique and a gradient operator. The elastograms revealed near-zero strains within the samples, except at the articular surface and the interface between zones 1 and 2. The boundary conditions associated with the loading technique implemented herein that have to allow for a large acoustic window during imaging represent a fundamental challenge toward imparting local strains to the articular cartilage. Despite the complex boundary conditions, the feasibility of imaging strain within the cartilage during a sustained compression using elastographic techniques was demonstrated.

Keywords— **Articular cartilage;Arthroscopy; Elastography; Strain; Ultrasound.**

I. INTRODUCTION

Articular cartilage is poroelastic and serves to bear load in the articular joints. Biomechanical investigations have shown that the biomechanical properties of articular cartilage can be affected by disease processes, such as osteoarthritis [1,2]. Consequently, there have been attempts to develop arthroscopic indentation devices that enable measurement of the biomechanical properties of degenerate cartilage, with the aim of early diagnosis [3-13]. In particular, some groups have combined arthroscopic indenters with ultrasound probes, mainly to obtain more accurate estimates of cartilage thickness.

In order for arthroscopy to become the gold standard for diagnosing cartilage pathology [14], the associated data acquisition and presentation must be optimized. Consequently, we propose the use of ultrasound elastography to determine its feasibility for its eventual integration in arthroscopic indentation systems. Elastography is a technique that enables quantitative imaging of strains induced in soft tissues under load [15] that has been shown feasible in the case of poroelastic tissues [16]. With the advent of high frequency transducers, detailed strains mapping of small sections of tissue can be achieved.

In this report, we evaluate the potential feasibility of high frequency, ultrasound elastography as a rapid, noninvasive, nondestructive imaging modality for the early diagnosis and monitoring of treatment for articular cartilage pathologies.

II. METHODOLOGY

Full-thickness, 1-cm diameter cylindrical samples of articular cartilage (n=3) were obtained from bovine, femoral condyles with an average thickness of 4.71 ± 0.47 mm and the femoral head with an

average thickness of 3.39 ± 0.86mm in immature, healthy bovine. The samples were immersed in PBS within a custom-made loading device mounted onto an Instron 5848 MicroTester (Norwood, MA) equipped with a 100 N load cell (accuracy+/- 0.5N, with a 1-micron displacement resolution of the actuator; Fig. 1). The specimens were oriented such that the deep portion of the cartilage contacted an aluminum loading plate and the articular surface rested upon another rigid, impermeable surface containing a 3 mm opening to serve as the acoustic window for the high-resolution ultrasound transducer (f/2, 8mm focus, 55 MHz, 46 Hz frame rate, Vevo 770, Visualsonics, Toronto, Canada). The ultrasound probe was separated by 3-mm from the surface of the articular cartilage. A tare strain of 0.1% based on the measurement of the undeformed cartilage plugs was sustained for 30 seconds, followed by a ramp to strains ranging from 0.5 to 4.0% strain at 0.1 mm/sec for two femoral condyle samples and one femoral head sample (Fig. 2). For these samples, B-mode ultrasound scans were acquired immediately after the tare strain and immediately after ramped compression of the cartilage. Subsequently, a pre-strain of 10% based on the measurement of the undeformed cartilage plugs was applied for 30 seconds, followed by a ramp to strains ranging from 2% at 0.1 mm/sec for two femoral head samples. Radiofrequency (RF) ultrasound signals of these samples were acquired once equilibrium was attained. Displacement images and elastograms were generated using 1D crosscorrelation techniques and gradient operators on the RF signals (window size 0.3 mm, 85% overlap), respectively. Median filtering of the displacement data was also implemented. The setup used simulates a potential design for an ultrasound transducer incorporated into an arthroscopic indentation device.

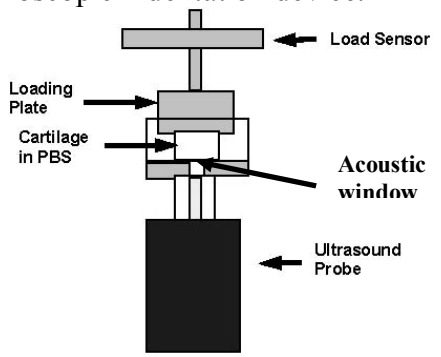

Figure 1. Compression apparatus and image acquisition arrangement.

III. RESULTS

Ramp compressions with high resolution displacement were applied and rapid stress relaxation of the articular cartilage samples recorded (Fig. 2).

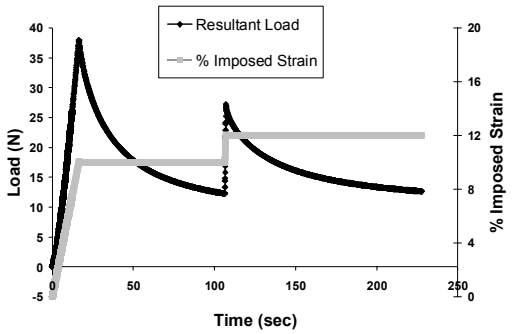

Figure 2. Load versus time for an imposed pre-strain of 10% followed by an additional 2% strain 90 seconds later demonstrating stress-relaxation of articular cartilage Load axis is on the left and the strain axis is on the right.

High quality RF signals and B-mode images were obtained of the cartilage plugs using the high resolution ultrasound with a 1/16" (Fig. 3A) and 1/32" diameter opening in the loading platen, (Fig. 3B). The full thickness of the cartilage sample can be observed and the articular layer can be discerned from zone 2. Abundant speckle is also visible within the cartilage, thus facilitating displacement and strain imaging.

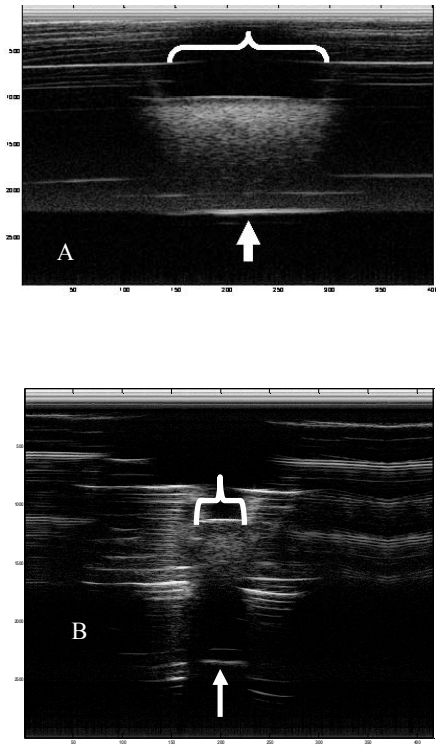

Figure 3. Grey-scale RF signal of cartilage sample within the compression apparatus with a 1/8" opening (A) and 1/32" opening (B). The bracket represents the opening in the lower loading platen, while the arrow shows the highly reflective metal loading platen.

Displacement images for all the samples imaged using the 1/8" opening in the loading plate revealed that while displacement of the region of interest did occur, a gradient of the displacements did not result (Fig. 4A). Rather, it appears that the entire region of the sample underwent rigid motion, displacing upwards through the opening as evidenced by circular indentations which were observed on the cartilage surfaces following the loading protocol. The corresponding elastogram therefore displayed zero strain within most of the sample (Fig. 4B). Only the articular surface and the interface exhibited local strain. Similar maps were obtained regardless of the extent of post-compression strain.

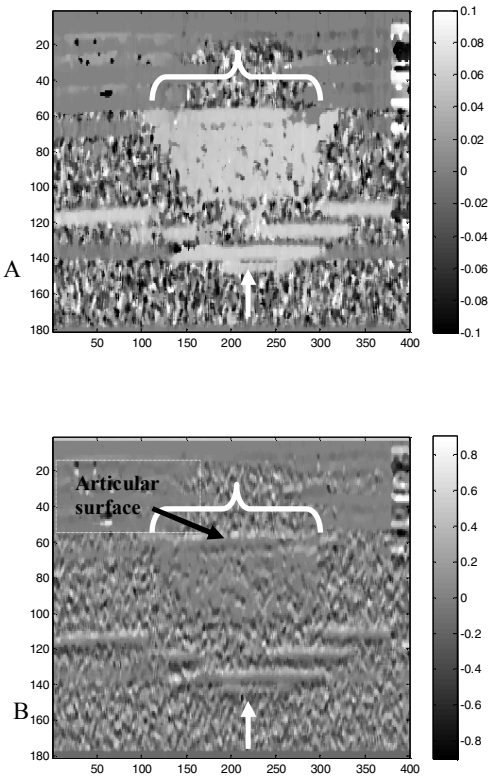

Figure 4. A) Displacement image of a femoral condyle cartilage sample showing uniform displacement in the region of interest, using a 1/8" opening. The scale ranges from -0.1mm to 0.1mm. B) Elastogram of the same sample showing essentially zero local strain except at the surface and interface of zone 1 and 2. The scale ranges from -0.9% to 0.9%.

The majority of displacement images for all the samples imaged using the 1/32" opening in the loading plate revealed that while displacement of the region of interest did occur, local displacements did not result (Fig. 5A). The corresponding elastogram displayed about 0.5% strain within a portion of zone 2, while the articular surface and the interface exhibited strains on the order of 0.2% (Fig. 5B). Thus, it appears that only a small portion of the applied load is transmitted to the region of interest due to the imposed boundary conditions.

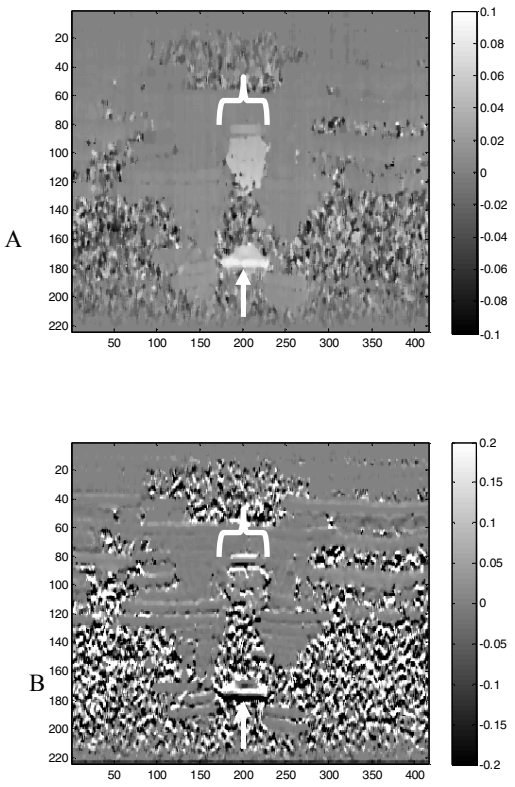

Figure 5. A) Displacement image of a femoral condyle cartilage sample showing a slight displacement gradient in the region of interest, using a 1/32" opening. The loading plate can also be perceived (arrow). The scale ranges from -0.1mm to 0.1mm. B) Elastogram of the same sample showing essentially zero local strain except at the surface and interface of zone 1 and 2. The scale ranges from -0.2% to 0.2%.

Whether the RF signals were captured immediately after the compressions or once equilibrium was achieved did not significantly impact the appearance of the cartilage on the elastograms. The elastograms were also similar between femoral condyle specimens and femoral head samples.

IV. CONCLUSION

The feasibility of high-resolution, ultrasound elastographic imaging of in vitro cartilage under compression was demonstrated for the first time to our knowledge. However, strain mapping of joint surfaces via ultrasound elastography is challenging using a static compression method. The boundary conditions that are required to simultaneously deform the cartilage and maintain an acoustic window between the transducer and the specimen render it difficult, but not impossible, to impart sufficient strains to the region of interest. An optimization of the technique is under investigation in order to overcome these important challenges.

REFERENCES

1. Kleemann RU, Krocker D, Cedraro A, Tuischer J, Duda GN. Osteoarthritis Cartilage. 2005 Nov;13(11):958-63.
2. Setton LA, Elliott DM, Mow VC. Osteoarthritis Cartilage. 1999 Jan;7(1):2-14.
3. Lyyra T, Jurvelin J, Pitkanen P, Vaatainen U, Kiviranta I. Med Eng Phys. 1995 Jul;17(5):395-9.
4. Laasanen MS, Saarakkala S, Toyras J, Hirvonen J, Rieppo J, Korhonen RK, Jurvelin JS. J Biomech. 2003 Sep;36(9):1259-67.
5. Toyras J, Lyyra-Laitinen T, Niinimaki M, Lindgren R, Nieminen MT, Kiviranta I, Jurvelin JS. J Biomech. 2001 Feb;34(2):251-6.
6. Laasanen MS, Toyras J, Vasara AI, Hyttinen MM, Saarakkala S, Hirvonen J, Jurvelin JS, Kiviranta I. 7. Saarakkala S, Korhonen RK, Laasanen MS, Toyras J, Rieppo J, Jurvelin JS. Biorheology. 2004;41(3-4):167-79.
8. Saarakkala S, Laasanen MS, Jurvelin JS, Torronen K, Lammi MJ, Lappalainen R, Toyras J. Osteoarthritis Cartilage. 2003 Sep;11(9):697-705.
9. Korhonen RK, Saarakkala S, Toyras J, Laasanen MS, Kiviranta I, Jurvelin JS. Phys Med Biol. 2003 Jun 7;48(11):1565-76.
10. Laasanen MS, Toyras J, Hirvonen J, Saarakkala S, Korhonen RK, Nieminen MT, Kiviranta I, Jurvelin JS. Physiol Meas. 2002 Aug;23(3):491-503.
11. Zheng YP, Mak AF. IEEE Trans Biomed Eng. 1996 Sep;43(9):912-8.
12. Korhonen RK, Saarakkala S, Toyras J, Laasanen MS, Kiviranta I, Jurvelin JS. Phys Med Biol. 2003 Jun 7;48(11):1565-76.
13. Vasara AI , Jurvelin JS , Peterson L , Kiviranta I . Am J Sports Med. 2005 Mar;33(3):408-14.
14. Oakley SP, Portek I, Szomor Z, Appleyard RC, Ghosh P, Kirkham BW, Murrell GA, Lassere MN. Osteoarthritis Cartilage. 2005 May;13(5):368-78.
15. Ophir, J., Céspedes, I., Ponnekanti, H., Yazdi, Y. and Li, X: Vol 13 (2), pp. 111-134, 1991.
16. Konofagou E.E., Harrigan T., Ophir J. and Krouskop T., *Ultras Med and Biol* 27(10): 1387-1397, 2001.