Elastographic Imaging of the Strain Distribution
at the Anterior Cruciate Ligament and ACL-Bone Insertions

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Abstract—The anterior cruciate ligament (ACL) functions as a mechanical stabilizer in the tibiofemoral joint. Over 250,000 Americans each year suffer ACL ruptures and tears, making the ACL the most commonly injured knee ligament. Methods which permit the in situ monitoring of changes in ACL graft mechanical properties during healing are needed. A long term goal in ACL reconstruction is to regenerate the ACL-bone interface. To this end, an understanding of mechanical properties of the ligament-bone interface is needed. However, experimental determination has been difficult due the small length scale (<1 mm) involved and limited resolution of standard techniques. The current study uses elastography to characterize the functional properties of the ACL and the ACL-bone interface under applied load. In a first experiment, bovine joints were excised, cast in an agar gel matrix and externally compressed. In a second experiment, tibiofemoral joints were mounted on a MTS 858 Bionix Testing System. The ACL was loaded at different strain rates and tested to failure while RF data was collected at 5 MHz. For both tensile and compression testing, axial elastograms between successive RF frames were generated using cross-correlation and recorrelation techniques. When the ACL-bone complex was tested in the tibial alignment of the MTS system, compressive strains were found to dominate at the tibial insertion. Compressive strains were observed in the ligament proper when the transducer beam was aligned with respect to the insertion during loading. The distribution of tensile and compressive strain varied as a function of strain rate during testing and between loading and unloading. These preliminary results agree with those of prior FEA model predictions. In addition, a narrow band of high strain in the middle of the ACL was detected during compression that is considered to be a softer region of the ACL containing a highly collagenous structure. These preliminary results on ACL geometry and function indicate that elastography can provide important information in understanding the structure and function of both the ACL and the ACL-bone insertion. Ongoing studies focus on in-depth evaluation of the mechanical properties existing at the ACL and ACL-bone insertions.

I. INTRODUCTION

Elastographic imaging techniques, i.e., methods for the mapping of mechanical responses or properties using ultrasound or MRI images acquired before and after a mechanical excitation, were initially developed as an alternative tool for early tumor diagnosis based on the principle of palpation [1,2]. Since the early nineties, however, when techniques, such as elastography, were first introduced, the application of elasticity imaging has exponentially expanded, ranging from intravascular and cardiovascular applications in vivo to guidance of thermal therapy procedures and robotic surgery. One of the most interesting aspects of recent elastography uses is in the area of tissue biomechanics. In its initial applications, tissues such as the breast and prostate were assumed to be purely elastic, isotropic and incompressible, and therefore, the estimated strain, before and after a quasi-static single compression, would be directly linked to one of the two fundamental parameters, the Young’s modulus. As the applications expanded, the complexities of tissue mechanics were further taken into account. Tissues, such as the breast and the prostate but also the skeletal or cardiac muscle, are known to be viscoelastic [3], i.e., more than one parameter is needed to fully characterize their mechanical attributes. More importantly, some of these parameters are time-dependent and, therefore, the mechanical behavior needs to be studied with time.

In reported elastographic studies on articular joint tissues, theoretical models have mainly dealt with one of the most studied tissues in the field, articular cartilage [4-6]. Articular cartilage has been extensively studied due to its rapid erosion in arthritis patients. For example, poroelastography [4], or elastographic imaging of poroelastic tissues, estimates and images the in-plane strain ratio of the simulated cartilage during a sustained compression. The technique is capable of identifying and depicting the permeable interfaces of the tissue, the permeability of the solid to the fluid (or, the type of fluid contained in the solid matrix) and the Poisson’s ratio of the solid matrix at equilibrium, i.e., at no further variation of the strain ratio. The theoretical model has been verified in phantoms [7-8] while similar in vitro tissue results have been shown [5-6].

In this paper, the feasibility of elastography in the mechanical characterization of another important joint tissue, the anterior cruciate ligament (ACL), is examined. The ACL connects femur to tibia, and it is the tissue most commonly associated with sports-related injuries of knee ligaments (Fig. 1). Post injury, the ACL is usually reconstructed with a replacement tendon graft. While the mechanical properties of the ACL have been well characterized[11,14], those of the
healing tendon are not well known. Ultrasound elastography represents a novel method which may permit the in situ monitoring of changes in graft mechanical properties during healing. This critical knowledge will allow the design of physical therapy regimens aimed at promoting graft healing, as well as aid in appropriate graft and material selection in both biological and tissue engineered ACL replacement grafts[9].

The current study tests the feasibility of applying elastography to determine the mechanical properties of both the native ACL and the ACL-bone insertion sites which are critical for graft-to-bone integration. Current techniques include finite-element simulations [10,11] and mechanical testing measurements [11,14]. If proven successful, elastography may offer the advantage of a simple, practical and reliable technique for in vivo characterization of the mechanical behavior of the ACL. Specifically, the in vitro mechanical behavior of bovine ACL was studied, both during 1) applied compression and 1) tension using a mechanical testing device, as described below.

II. METHODS AND RESULTS

1. Elastography of bovine ACL in vitro during applied compression

The femoral insertion-ACL-tibial insertion complex (Fig 2(A)) was embedded in agar gel (Bacto agar, Fig. 2 (B)). The agar gel below and up to 1.5 cm above the sample have a compressive modulus of 30 kPa [12]. An additional 0.5 cm agar gel (40 kPa) was cast on top of the original gel. Samples were aligned parallel to the top surface of the gel, with both bony insertions facing downwards so as to not impede ultrasound wave propagation. The sample was compressed while a Terason ultrasound scanner (Teratech, Inc.) acquired RF data at 5 MHz. 2D RF data using a 3 MHz linear array were acquired continuously during the compression for a period of 3 sec. Sequences of ultrasound RF images were acquired at 54 frames/s (128 RF lines, sampling frequency: 10MHz). The axial displacement between successive frames was estimated and imaged using cross-correlation and recorrelation techniques [13] with a window size of 3 mm and a window overlap of 75%.

The elastographic convention for the sign of the strain estimate imaged is kept here, i.e., positive strain denotes compression while negative strain denotes tension in the axial direction. Axial displacements are estimated from two consecutive RF frames, using a 1D cross-correlation algorithm [2,13]. In this algorithm, time-shifts between two consecutive backscattered signals are determined by the cross-correlation of small sliding windows over the entire 2D ultrasound image. At high decorrelation noise, recorrelation techniques were employed [13]. Finally, the strain distribution is computed by differentiating the displacement map along the axial direction. For the numerical differentiation, a least-squares regression method was used.

In all specimens tested, the ACL, the interface between the ACL and the femoral or tibial bone were visible on the elastogram (Fig. 4). In the elastogram, bright areas indicate compressive strain. When manually compressed using the transducer, the interface appeared as a region subjected to highly concentrated tensile and compressive strain. In addition, inside the ACL, a narrow band of high strain in the middle and along the length of ACL (Fig. 4) was noted at certain amounts of compression that also corresponded to an area on the B-scan that was highly echogenic (Fig. 3). This may reflect the bundle-organization of the ACL and is the result of impedance mismatch between the anteromedial and posterolateral bundles of the ACL. These layers are also seen during the tensile stretching experiment (Fig. 6) and
2. Elastography of bovine ACL in vitro during tensile testing

Tibiofemoral joints were mounted on a MTS 858 Bionix Testing System (Fig. 1b). The femur and tibia were aligned along the tensile axis and the sample was submerged in saline during testing. The ACL was loaded at different strain rates and tested to failure while RF data was collected at 5 MHz with a Terason ultrasound scanner and processed off-line as in the compression experiment.

Ultrasound acquisition and elastographic processing was identical to that used in the compression experiments. Two different cases of displacement and strain estimation were studied: a) using successively acquired ultrasound data (incremental) and b) using a reference ultrasound frame for the strain estimation (non-incremental). Displacement and strain in (a) were estimated between successive RF data frames and with a period of 21 msec. The purpose was to obtain the temporal profile of the motion and deformation variation at the ligament and the insertion. Displacement and strain in (b) were estimated relative to reference frame e.g., at the beginning of the tensile stretching. The purpose was to obtain a map of the cumulative deformation at the ligament and the insertion.

It was found that the interface between the ACL and the femoral (FI) or tibial (TI) bone was visible on the ultrasound images (Fig. 5), and the largest displacement was observed in the ACL proper and femoral insertion (Fig. 6(a)). When the ACL-bone complex was tested in the tibial alignment on the MTS system, compressive strain was found at the tibial insertion, indicated by the bright regions on the elastograms (Fig. 6b).

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Compressive strains were also seen in the ACL itself, most likely because the transducer was aligned with respect to the insertion during loading. The distribution of tensile and compressive strain varied as a function of strain rate. The temporal variation in stress in response to increases in tensile strain indicated the higher displacement and increase in compressive strain at the interface (Fig. 7). Finally, Fig. 8 depicts tensile stretching of a second ACL specimen that is undergoing deformation under a different configuration with respect to the ultrasound image plane. However, the compressive strain (bright region, Fig. 8b) is again visible at the interface. Tensile strains (dark regions) can also be observed around the same interface.

III. DISCUSSION

The results of this study demonstrate the feasibility of elastography for the in vitro mechanical characterization of the bovine ACL and ACL-bone interface. Displacement images and elastograms alike indicate that the strain distribution at the insertions is highly complex, with both tensile and compressive strains localized at the insertion site. When tested under tension, the strain profile seen at the interface was predominantly compressive in nature, while tensile strains were found at the ligament itself. These preliminary quantitative results agree with those of finite-element analysis [10], where it was predicted that when the medial collateral ligament (MCL) is under tension, the principle stress component found at the femoral insertion is compressive. While the angle of insertion differs between MCL and ACL, fibrocartilage tissue, which is generally found in regions of compression, is the dominant tissue type seen at the ACL-bone and MCL-bone interfaces. Ongoing studies focus on validation of the elastographic findings through independent mechanical measurements and the use of higher resolution scanners in order to unveil the structure-function relationship existing at the ACL to bone insertion.

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V. REFERENCES

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