A FIRST-ORDER TEXTURE CORRELATION ALGORITHM AND IMAGE ROUGHNESS PARAMETER TO QUANTIFY SOFT TISSUE DEFORMATION USING MRI

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INTRODUCTION

Texture correlation is a promising, non-contacting technique for measuring displacement fields between a pair of consecutive (i.e. reference and loaded) digital images [1]. This technique utilizes a pattern matching algorithm that assumes a pixel within an image to be identified by a unique intensity pattern (or texture) in a subset of pixels surrounding it, and that this subset undergoes a displacement that represents the displacement of the corresponding material element. A recent study has shown that MR images of tendon can exhibit suitable texture and reproducibility for tracking pixel displacement using this technique, suggesting the possibility for strain measurement in a variety of tissues [2]. However, the utility of MR texture correlation analysis may vary amongst tissue types depending on their underlying structure, composition, and contrast mechanism, which give rise to variations in texture with MRI. In this study, we investigate the utility of a texture correlation algorithm with 1st-order displacement mapping terms for use with MR images, and suggest a novel index of image "roughness" as a way to decrease errors associated with the use of texture correlation for strain measures from MRI.

METHODS

MR images of porcine intervertebral discs (n=3) and canine knee menisci (n=2) were used to study algorithm accuracy. 3D volume data sets were obtained of the intervertebral discs with a 7.1T scanner (234 x 234 x 469 microns) using a standard spin-echo sequence, and representative 2D axial slices selected for analysis. In axial images of the disc (Figure 1a), the outer anulus fibrosus region exhibits a distinct layered pattern, whereas the central nucleus pulposus region is relatively homogeneous. 3D data sets of menisci were similarly obtained using a 9.1T scanner (98 x 98 x 120 microns). MR images of the meniscus (Figure 1b) reveal a layered pattern throughout the tissue.

The previous MRI texture correlation study utilized a zeroth-order displacement tracking algorithm which assumes square subsets to remain square between images. In this study, a 1st-order texture correlation algorithm was implemented following Vendroux and Knauss [3]. Briefly, the algorithm uses 1st-order displacement mapping terms, piecewise continuous bicubic spline interpolation, a least-squares correlation coefficient, and an optimized Newton-Raphson search procedure to track pixel displacement between consecutive images. The higher-order mapping terms account for linear subset deformations between images, resulting in higher displacement field accuracies. The measurement accuracy of the coded 1st-order algorithm was compared against a zeroth-order algorithm (with displacement estimates refined to the nearest 1/8th pixel using discrete bicubic spline interpolation) as a function of strain magnitude and image noise, using a pixel subset size of 21 x 21 pixels with both the intervertebral disc and meniscus MR images.

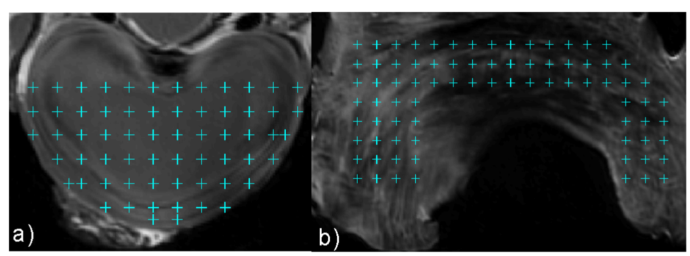

Figure 1. Representative 2D MR images of (a) porcine intervertebral disc and (b) canine meniscus. Markers (+) indicate pixel locations where displacements were tracked.

Tissue deformation was simulated by applying a displacement gradient to each MRI in two dimensions, equivalent to 1%, 6%, 10%, and 16% biaxial strain. In addition, unique sets of Gaussian-distributed noise were superimposed on the 6% strain reference and deformed image pairs. Signal-to-noise ratio (SNR) was defined as the mean signal within the region of interest to the standard deviation of the superimposed noise for each image. A grid of points was tracked in images of each tissue type (n=63 for each disc image, n=80 for each meniscus image), and accuracy was compared (i.e., radial error defined as the square root of the sum of perpendicular axial errors).

Accurate displacement tracking using texture correlation requires that the features (i.e. intensity variations, or "texture") within a pixel's subset be distinct from background noise. As a first step towards a quantitative index of texture, a "roughness" of MRI image features was defined as the ratio of subset intensity SD to the SD of the background, which we termed the roughness index, β. Radial error and corresponding values of β were evaluated for each tracking point within image pairs and for various levels of SNR.

RESULTS & DISCUSSION

Figure 2a shows the mean and SD of the radial displacement error for varying levels of simulated strain across all images. As expected, the zeroth-order algorithm exhibits increasing error with increasing strain magnitude, whereas the 1st-order algorithm does not. Displacement error increases markedly with increasing levels of superimposed noise (decreasing SNR) for both algorithms (Figure 2b and 2c), particularly below SNR levels of 20. The 1st-order algorithm was found to reduce average error and SD by 30-90% as compared with the zeroth-order algorithm for varying SNR levels and 6% strain.

In general, the disc images exhibit much higher average errors than the meniscus, particularly at lower levels of SNR. This suggests that the texture of the pixels tracked in the disc differs substantially from that in the meniscus. Upon closer examination, we found these errors to be higher in the homogeneous nucleus pulposus region of the disc (error = 5.8±6.7 pixels; SNR=12.8, n=35), as compared to the outer anulus fibrosus regions (0.53±0.72 pixels, n=28). Thus, the homogeneity of the nucleus pulposus gives rise to large errors, particularly for low SNR levels. The meniscus images did not exhibit this drastic spatial dependence of error.

To understand how the roughness index, β, is distributed within a typical MR image, β values were calculated for each pixel within the disc and meniscus images described above with superimposed noise (SNR=40), as shown in Figure 3. The homogeneous nucleus pulposus region of the disc can be identified by lower β values as compared with the outer anulus fibrosus region. The meniscus exhibits higher overall values of β, and shows less difference in β with spatial position. Figure 4 illustrates the relationship between roughness index and radial error for both tissue types and varying superimposed noise. The roughness index shows correlation with displacement error independent of tissue type or noise conditions. Indeed, there is a very strong dependence of radial error on β for both tissues, with values of β less than 5 associated with displacement errors greater than 1 pixel.

This represents a first attempt to quantify texture within MR images and understand how it relates to error in displacement tracking using a 1st-order texture correlation algorithm. By quantifying the amount of texture for a given MR image, the roughness index can be used to estimate *a priori* how test conditions and tissue type may contribute to acceptable measurement accuracy. This may prove to be a valuable tool toward the goal of determining high-resolution strain fields within biological tissues using texture correlation.

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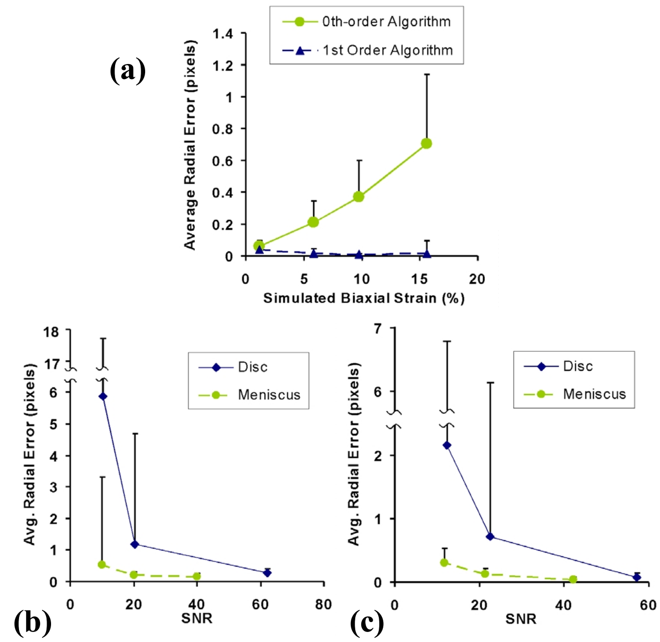

Figure 2. (a) Mean and SD of radial error as a function of strain (n=349 for each data point; no superimposed noise); Error versus SNR (6% biaxial strain; for disc, n=189; meniscus, n=160) for (b) zeroth-order algorithm, (c) 1st-order algorithm

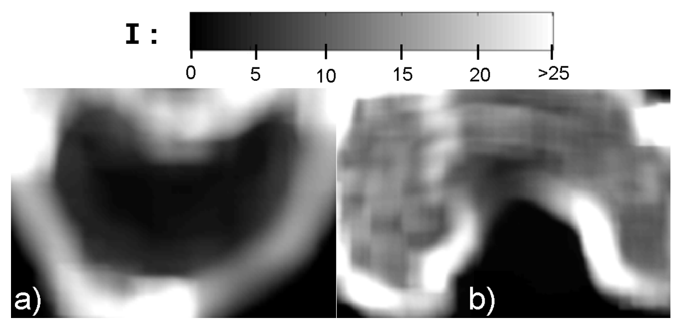

Figure 3. Roughness index, β, mapped for representative MR images of (a) intervertebral disc and (b) meniscus (SNR = 40).

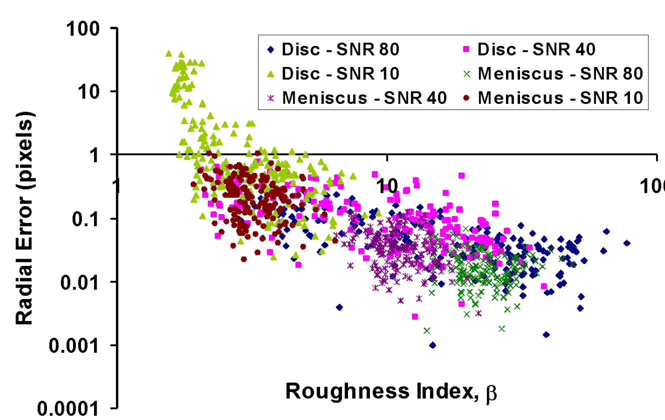

Figure 4. Radial error as a function of roughness index, β (6% biaxial strain).