Robust method to measure tendon strain

J. C. Asmuth[1], N. A. Andarawis[1], N. J. Tustison[1], B. B. Avants[1], J. J. Sarver[1], L. J. Soslowsky[1], J. C. Gee[1]
[1]University of Pennsylvania, Philadelphia, PA, United States

Introduction:
Rotator cuff tears are a common injury to the shoulder and cause significant pain and disability. Research is ongoing to understand the causes and progression of rotator cuff tears with focus on a variety of factors, both intrinsic and extrinsic. Detailed knowledge of the intratendinous strain field provides a measure of the mechanical competence of the tendon adjacent to the tear and can be used to assess the probability of tear progression. This is an essential detail for determining treatment options [1]. MRI image-based measurement of tendon strain is challenging due to the low contrast and subtle nature of tendon intensities. Prior knowledge, such as modeling the tendon as a continuum, can lead to improved results. Texture Correlation (TC) is one method that has been previously investigated [2] where deformations are computed via local neighborhood correspondences within the image pairs. However, TC may lead to erroneous strain calculations because it does not constrain the solution to be well behaved and the inherent assumption of local translations is violated with large and non-linear deformations (as seen in the tendon). We present an alternative method to TC based on an intrinsically symmetric image registration (ISIR) algorithm [3]. ISIR computes a large deformation diffeomorphism (i.e., the mapping is one-to-one, differentiable and onto) that directly implements the continuum assumption and guarantees well behaved strain fields that can be steered by the addition of non-image features such as landmark points.

Method:
Cadaveric shoulders imaged with a surface coil using a 3.0T MRI scanner (Siemens, Erlangen, Germany) using a two-dimensional spin echo sequence (T_R=500 msec, T_E=14 msec). A special MRI-compatible device was used to fix the position of the shoulder joint and apply a static load to the tendon during the scanning process. Scapular-plane MR series (2 mm thickness, 0.156 mm/pixel) were taken under unloaded and loaded conditions. One image slice was selected from each series centered on the supraspinatus tendon's anterior band. The unloaded image is used as the 'fixed' reference. The loaded image is used as the 'moving' image. Deformation vectors are computed to relate pixel locations in the 'fixed' image to corresponding locations in the 'moving' image. The dense strain field is computed as follows: (1) B-spline curves are placed along corresponding tendon striations and boundaries in loaded and unloaded images pairs. (2) The corresponding B-spline curves are uniformly sampled to comprise a set of assumed landmark correspondences. (3) A dense deformation mapping is then computed using the ISIR algorithm based on the unloaded and loaded images as well as the landmark correspondences. (4) Finally, the strain field is computed from the deformation mapping.

Details:
(1) Splines are easier to manipulate than individual points and allow for easy user tracing of the natural striations visible along the tendon. A Matlab [4] program was developed to allow the user to manipulate clamped cubic B-splines overlaid onto each tendon image. (2) Each spline was converted to a sequence of 25 points for use as landmarks. (3) ISIR uses the ITK [5] toolkit and implements a multi-resolution framework to iteratively compute a smooth, invertible diffeomorphism between two images using intensity data and optionally supplied landmark points. (4) Principle strains are computed for the unloaded image from the deformation gradients.

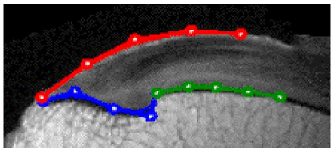

Figure 1a: Splines define tendon boundary

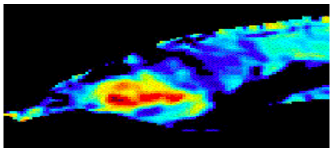

Figure 1b: Strain result with boundary initialization

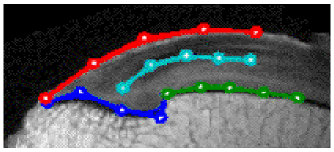

Figure 2a: Splines define tendon boundary and centerline striation

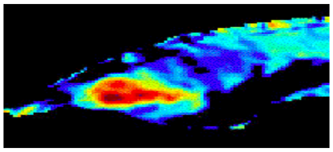

Figure 2b: Strain result with boundary and centerline initialization

Results:
To evaluate the feasibility of this method, strain fields were computed using the ISIR algorithm and a variety of spline initializations. Figure 1 shows a result based on boundary initialization alone. Slight improvement is achieved with the addition of a centerline, as shown in Figure 2. These strain fields are consistent with those predicted by two-dimensional finite element model analysis of the supraspinatus tendon [6]. Since placement of splines is subject to user variability, the robustness of the method to subtle variability is essential. Additional experimentation with varying the length and exact placement of the splines resulted in similar strain field results. Additional splines interior to the tendon did not improve the result. Of note is the result without spline initialization shown in Figure 3. The bifurcation of maximum principle strain is not consistent with the predictions of [6].

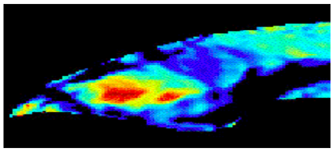

Figure 3: Strain result without spline initialization

Discussion:
Computation of strain fields using the method presented here produces qualitatively valid results and is robust to landmark placement. It is currently being applied to a study of two-dimensional strain in the supraspinatus tendon resulting from various types of anterior-side full-thickness tears and abduction angles. Tendon strains are not limited to one plane, however, and future work will involve extension of the method to three-dimensional strain field calculation.

References:
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[3] Avants, B. B., et al, *LNCS*, vol. 3752, pp. 247–58 [4] www.mathworks.com, [5] Ibanez, L., et al, *ITK software guide*, www.itk.org,
[6] Wakabayashi, I., et al, *J Shoulder Elbow Surg* 2003;12:612-7.

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