NONINVASIVE MEASUREMENT OF MENISCUS STRAIN USING HYPERELASTIC WARPING

*Sun, Q; **Burks, RT; **Greis, PE; *Phatak, NS; +*Weiss, JA
Departments of +*Bioengineering and **Orthopedics, University of Utah, Salt Lake City, UT

INTRODUCTION

The knee menisci are critical to the distribution of tibiofemoral contact stresses. This is demonstrated by the deleterious effects of injury or menisectomy on articular cartilage. Meniscus strains reflect load transfer and function in the normal and injured joint, and measurement of strain can be used to assess the efficacy of surgical repair techniques. However, *in vivo* measurement of strain in menisci is nearly impossible and *in vitro* measurements are difficult due to the limited access. The objective of this study was to validate the use of Hyperelastic Warping for noninvasive measurement of the deformation and strain distributions in the meniscus based on MR images.

MATERIALS AND METHODS

<u>Theory</u>: An image registration technique termed Hyperelastic Warping [1, 2] was used to determine deformation and strain in the medial meniscus from pairs of images representing distinct states of deformation. An image-based energy is formed in terms of the spatial intensity differences between a *template* image (representing an undeformed or reference state) and a *target* image (representing a loaded/deformed state). By minimizing the energy functional, a spatially varying force is produced to deform the template image into alignment with the target image. A hyperelastic constitutive model is used to regularize the problem and ensure a 1-to-1 mapping between template and target. The nonlinear optimization problem is solved using the finite element (FE) method.

<u>MR Image Acquisition:</u> A left cadaveric knee (male, 64 y/o) was mounted in a custom-built MR-compatible loading device. MR images (Fig. 1) of the knee were acquired at full extension (256x256 matrix, 14 cm FOV, 232 slices, 1 mm thickness) using a short TE dual echo 3D spoiled gradient technique [3] on a 1.5 T scanner (GE Signa Horizon). The first set of images (template) was collected in the unloaded configuration; a second set (target-1) was collected while an axial compressive load of 200 lb was applied to the knee; a third set (target-2) was taken with the axial compressive load plus an external-internal rotation of 30^o (about 16.75 N-m torque). The femur, tibia, articular cartilage and menisci were segmented manually from the template images and a FE model was constructed (Fig 2).

<u>Validation</u>: Due to limitations in measuring meniscus strain experimentally, Warping was validated by comparison to results of a FE model. A knee FE model was constructed from the template images with appropriate material properties, proper boundary conditions, and an axial compressive force. A transversely hyperelastic material model [4] was used for the meniscus (material coefficients C_1=0.729*MPa*, C_2=0, C_3=1.06 *MPa*, C_4=31.79, C_5=107.37*MPa*, K=14.11*MPa*, and λ*=1.023, obtained by fitting published data [5, 6]). Nonlinear FE analysis was performed to provide a "forward FE" solution. By applying the deformation map from the forward FE solution to the template image, a synthetic target image was generated. Using the template and synthetic target images, a Warping analysis was performed to predict deformations and strains in the medial meniscus. Validation was performed by comparing nodal displacements and fiber (circumferential) stretches between the forward FE and Warping solutions (Fig.3).

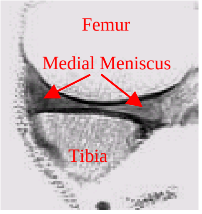

Fig. 1: Sagittal MR image slice from dual echo sequence.

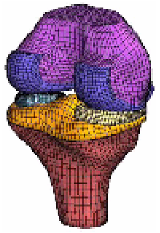

Fig. 2: Forward FE model of knee.

<u>Sensitivity</u>: To test how the material properties affect the Warping results, a study was performed to determine the sensitivity of the Warping solution to the material parameters. In this analysis, the material parameters in the standard model were varied by ±50%.

<u>Application</u>: Warping was used to predict the strains in the medial meniscus under a 200 lb axial compressive load using the template and target-1 images, and to predict the strains under a combination of the 200 lb load and a 30^o external-internal rotation using the template and corresponding target-2 images.

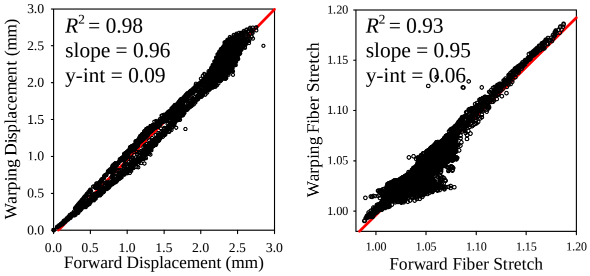

Fig. 3: Scatter plots of nodal displacement (left) and fiber stretch (right) for forward FE model versus predictions from Warping., with best-fit lines (red).

RESULTS

<u>Validation</u>: Warping predicted the displacement and stretch distributions from the forward FE analysis with an overall relative error of 6.31% and 0.69%, respectively. There was a highly significant correlation between the forward FE and Warping predictions (Figs. 3, 4). The slopes were slightly less than 1.0 and the y-intercepts were slightly greater than 0, indicating that Warping predictions of displacement and fiber stretch were generally lower than FE predictions.

<u>Sensitivity</u>: Warping predictions of strain were relatively insensitive to material parameters in measuring the meniscus strains from MR images (data not shown). Average relative errors were between 0.18 and 21% of the forward FE predictions, depending on the material coefficient.

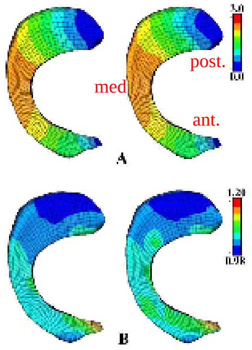

Fig. 4: Warping (left) and forward FE (right) solutions. A - Displacement. B - Fiber stretch.

<u>Application</u>: Peripheral circumferential strain values at the anterior, middle and posterior portions of the medial meniscus (near joint capsule) were 0.29%, 0.49% and 0.12%, respectively. The results showed significantly less strain in the posterior portion compared to the anterior and middle portions, which is consistent with an experimental study [6]. The 3rd principal (most compressive) strain shows a shift in location of max strain anteriorly and reduced compressive strains under 30 degrees external tibial rotation, as expected (Fig 5).

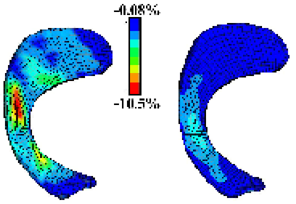

Fig. 5: 3rd principal strain for 200 lb load (left) and 200 lb load + 30° external rotation (right).

DISCUSSION

This research demonstrated that Hyperelastic Warping predicts strains in knee menisci with high resolution and accuracy. The Warping predictions of strain were insensitive to variations in assumed material properties. This is expected as the technique enforces the alignment of the image data in a "hard" sense using a Lagrange multiplier. Hyperelastic Warping shows promise for *in vivo* and *in vitro* measurement of meniscus strains. In conjunction with new imaging hardware such as open MR scanners, this technique enables noninvasive strain measurement under a variety of loading conditions.

REFERENCES

[1] Rabbitt RD, et al., SPIE 2573:252-65, 1995. [2] Weiss JA, et al., SPIE 3254:477-84, 1998. [3] Kim SE, et al., Proc. ISMRM 11th Annual Mtg, Toronto, P.1533, 2003. [4] Maker BN, et al., LLNL Tech. Report UCRL-MA, 1990. [5] Lechner K, et al., J Orthop Res, 18(6): 945-51, 2000. [6] Tissakht M and Ahmed AM, J Biomech, 28(4):411-22, 1995. [7] Jones RS, et al., Clin. Biomech. 11(5): 295-300, 1996.

ACKNOWLEDGEMENTS

NSF #BES-0134503 and Dept of Orthopedics, University of Utah.

51st Annual Meeting of the Orthopaedic Research Society
Poster No: 0478