In vitro Demonstration of Shear Strain Distribution of the Human Gastrocnemius-Soleus Aponeurosis during Submaximal Isometric Contraction using Velocity-encoded Phase Contrast MRI

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Objectives: Recent literature has reported that the proximal region of the posterior aponeurosis-tendon complex (after MG insertion) is made up of two thin layers. Structurally, the proximal region differs from the distal region in that it exhibits bipennate arrangement with respective to the muscle fibers. During plantar flexions, the soleus (SOL) and the gastrocnemius (GM) muscles independently activate the fibers from the anterior and posterior sides, allowing the aponeurosis to transmit the contractile force to the skeleton. Such an anatomical arrangement renders the two layers of the aponeurosis subject to shear strain when the two muscle groups are activated to different extent. This report has utilized velocity encoded phase contrast cine magnetic resonance technique to track the movement, and subsequently calculate the spatial shear strain distribution along the proximal region of the aponeurosis-tendon complex (at the junction of the SOL and GM) during isometric contractions.

Materials and Methods: Four subjects participated in the study after IRB approval. Velocity encoded PC images were acquired on a 3T Trio Siemens scanner using a standard FLASH 2D PC sequence with VENC: 10 cm/s, TR/TE/FA: 13.3 ms/7.5 ms/20^o, 3 mm slice thickness, 290 Hz receiver BW/pixel, 3 segments, 2 averages, 128x256 matrix, 160 mm x 320 mm FOV in the retrospective gated mode to acquire 22 phases (temporal resolution: 80 ms) during 86 isometric contraction cycles. The leg was imaged using a multi-channel, phased array torso coil while fixated in a rigid cast with the ankle at 90^o. The plantar flexor force was measured during isometric voluntary contractions using a pre-calibrated optical strain gage located at the sole of the cast whose output was used to gate the scanner, recorded for force/displacement analysis, and also fed into a screen visible to the subject to provide feedback on the targeted % MVC force level. The periodicity (1714 ms) of contractions was maintained by providing a computer generated audio cue to the subject. This protocol was repeated for 10%, 20% and 40% MVC force levels for each subject. PC images and recorded force data were analyzed using an in-house developed algorithm (MATLAB) for pixel tracking and shear strain distribution. Shear strain was calculated ($\gamma = \Delta L / L$) by locating 11 pairs of pixels across the aponeurosis, with each pair positioned at the same height and 8 pixels apart. Temporal as well as spatial shear variations were obtained from each pair (Figure 1).

Results and Discussion: In all subjects, the GM muscle exhibited greater upward velocity and thus movement relative to the SOL muscle throughout the whole proximal aponeurosis region (Figure 2) and during the whole contraction cycle. The mean maximum displacement gap between the GM and SOL muscles were 0.272 ± 0.05 mm. Figure 3 is a representative data from one subject showing dynamics changes in strain for a given pair of pixels during one plantar flexion cycle. Based on temporal strain of each pair, spatial distribution of shear was obtained at all torque levels (Figure 4). Figure 4 is a representative data from the same subject showing the spatial distribution of shear strain at the peak contraction level, indicated by the black square. Across all subjects, shear stain was positive at all times, i.e. GM moved higher relative to SOL throughout the entire proximal region. Temporally, the maximum shear strain occurred at the peak torque level. The spatial shear distribution pattern differed among subjects, but identical within subjects at different % MVC levels, validating the repeatability of the measurement methodology. Qualitatively, it was

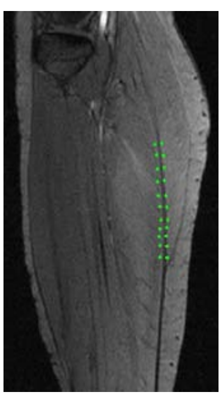

Fig. 1: Pixel Locations

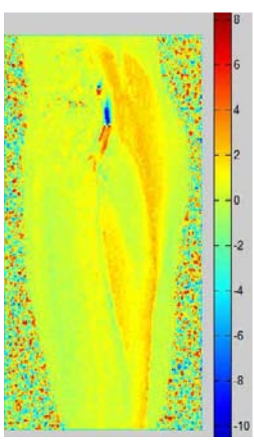

Fig. 2: Velocity Image

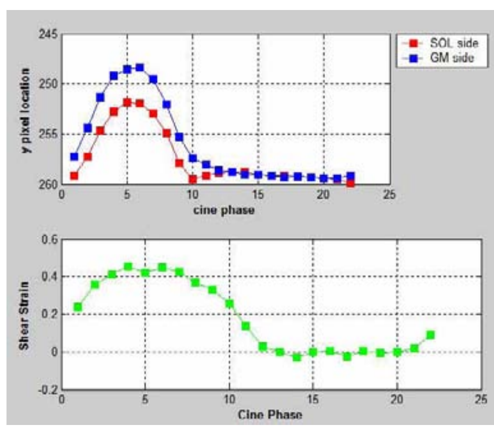

Fig. 3: Temporal Strain Distribution

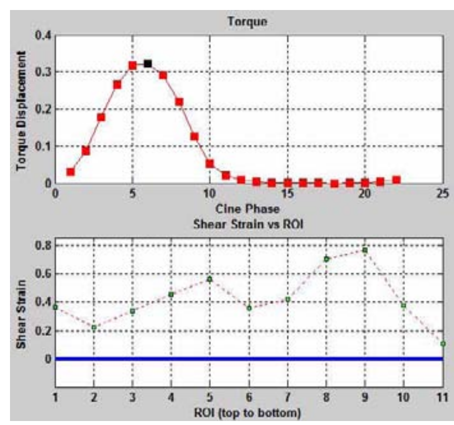

Fig. 4: Spatial Strain Distribution

observed that peak shear strain occurred at the distal portion of the aponeurosis near the MG insertion point (ROI 9 in Figure 4).

Conclusion: The PC MR technique has proven to be effective in quantifying small displacement changes between two adjacent pixels during isometric contractions for shear strain calculation in the proximal aponeurosis. The shear strain was non-uniformly distributed with higher value observed at the distal portion near the MG insertion point. Temporally, the maximum shear occurred at the peak torque level. Large absolute shear strain value reveals highly elastic nature of aponeurosis. Heterogeneity of shear strains along the aponeurosis may due to anisotropic material properties as well as variable muscle activation pattern. This noninvasive method for shear strain quantification may provide better understanding on tendon rupture etiology, and improvement on therapeutic strategies.