Visualization of hysteresis in passive time-dependent responses of skeletal muscle in vivo by using DTI

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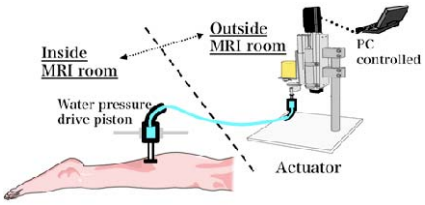
Introduction: The material properties of passive skeletal muscle are critical to proper function and are frequently a target for therapeutic and interventional strategies. A quasi-linear viscoelasticity model with a hysteresis in the material properties is used to study passive time-dependent responses of skeletal muscles in vivo [1]. In this model, viscoelasticity in muscle may cause hysteresis.

Diffusion tensor imaging (DTI) provides information regarding the movement as well as the direction and speed of tissue water, and it can also be used to visualize the hysteresis of passive time-dependent responses. The purposes of this study were to analyze in detail the water movement in skeletal muscles during pushing stimulation and visualize tissue deformation of the hysteresis in vivo by using DTI.

Material & Methods: Six healthy volunteers were asked to lie down in supine position and were subjected to magnetic resonance imaging of the lower extremities by using single shot DW-EPI and T2 images for anatomical information, respectively. A Signa LX 1.5 T (CN/I, GEMS) and two 5-inch surface coils were used. To estimate rapid water movement during pushing stimulation, low b diffusion-weighted imaging (DWI; b = 12.1 s/mm^2, 10-ms duration motion sensitizing gradients) were used. The 6 DWIs were acquired and calculated for DTI during pushing and decompressing phases. The other scanning parameters of the DWI were chosen as follows: effective TR, 6 s; TE, 49 ms; FOV, 160 mm × 160 mm; 96 × 96 matrix; slice thickness, 6-mm; receiver band width, 100 KHz.

Fig. 1. A schematic of the pushing stimulator



The facies posterior center of the lower leg was push stimulated using a 10-mm diameter piston (Fig. 1). The piston was pushed 15 mm/s into the body surface for 1 s, and after stasis for 0.5 s, it was pulled at the same speed. The slice to be examined was set at the same location as for the pushing stimulation, and DTIs were observed 14 times at 0.22-s intervals.

Because we observed clear differences in water movement during pushing and decompressing phases, we created color maps of eigenvalues. The DTI maps were plotted with the X components of the eigenvalue shown in red, the Y components in green, and the Z components in blue.

Results: Fig. 2 shows the T2 image (Fig. 2a) and a typical color map of the eigenvalues during pushing (Fig. 2b) and decompressing (Fig. 2c) phases. Deformation was found underneath the stimulated areas during the decompressing phase and in the wide area of the soleus during the pushing phase. Differences were also found in direction of water movement. X components phase was observed primarily during the pushing phase and Y and Z components during the decompressing phase. To determine the differences in deformation, regions of interest were set underneath and outward of the stimulated area to compare Lambda1. This value increased outward of the stimulated area during the pushing phase, whereas it increased underneath the stimulated area during both pushing and decompressing phases.

Discussion: In passive time-dependent responses of the skeletal muscles in vivo, these results showed varying deformation regions between the pushing and decompressing phases. In previous studies, the simulation was based on the assumption that same region was deformed during pushing and decompressing. This study showed that the differences in deformation regions and the direction of water movement were the factors responsible for the hysteresis.

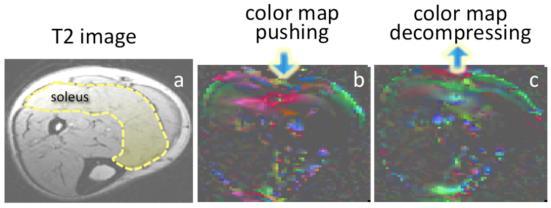


Fig. 2. Typical color maps of eigenvalues during pushing and decompressing phases

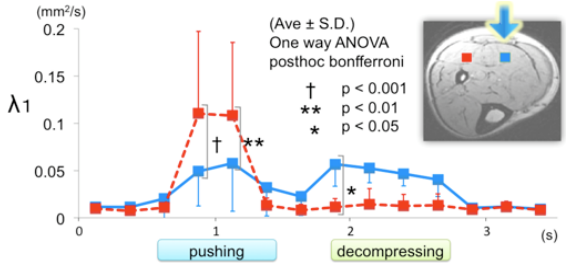


Fig. 3. Graph of Lambda1 in underneath and outward of the stimulated area

Reference: [1] Then C et al. Method for characterizing viscoelasticity of human gluteal tissue. J Biomech. 2012 Apr 30;45(7):1252-8.