3D Strain Rate Mapping of the Calf muscle and Correlation of Strain Rate Orientation to Muscle Fiber Direction.
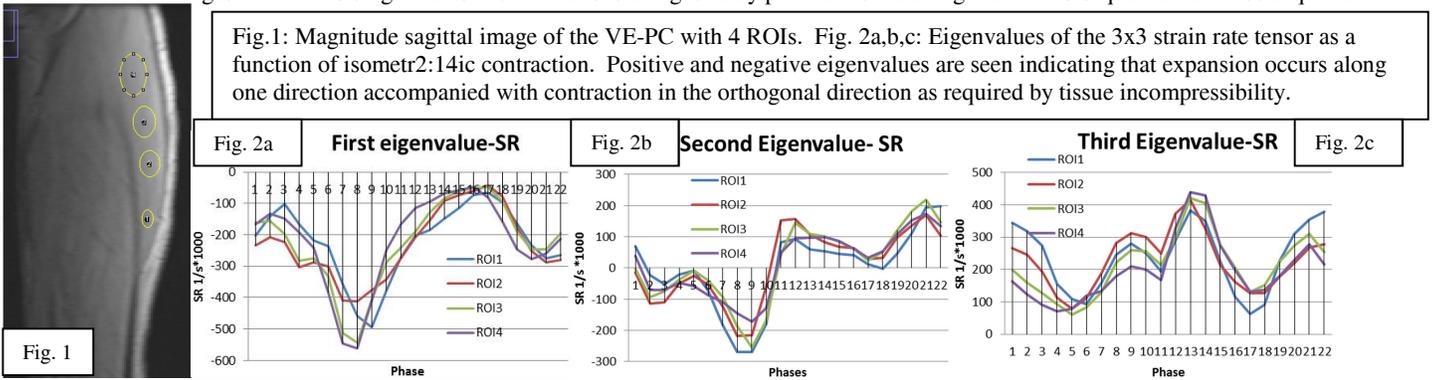
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Purpose: The objective quantification of regional muscle deformation is a valuable clinical tool to evaluate normal and diseased muscle. 2D Strain and strain rate are kinematic properties that have been used to characterize myocardial and lingual deformation. However, the strain rate is 3 Dal as the tissue deformations are 3 dimensional. 3D strain rate in cardiac muscle [1] and 3D strain in skeletal muscle [2] have been reported; the latter used spin tags and obtained a ROI rather than voxel based strain tensor.
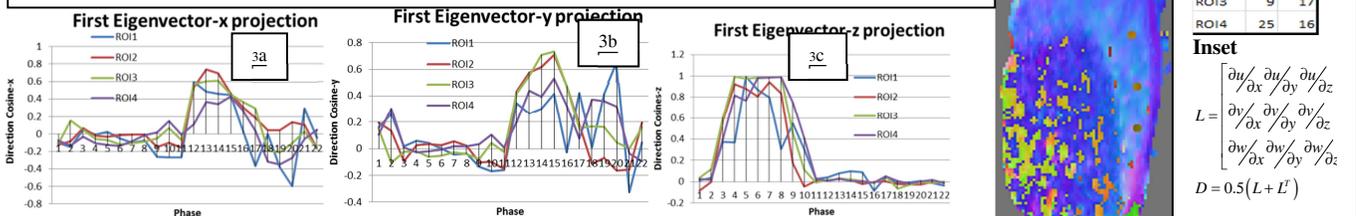
Aim: To map the 3D strain rate (SR) tensor from a series of velocity encoded (VE-PC) images acquired during isometric contraction.

Methods: Three subjects, recruited after IRB approval, were scanned on a 1.5-T GE whole-body scanner with a cardiac surface coil. The lower leg was placed a cast with a pressure transducer attached to the cast; the subjects foot pressed against the pressure transducer and the signal from the transducer was projected on a screen to provide feedback to the subject to exert force at 40% MVC. A gated VE-PC (water) imaging sequence (16.5ms TR, 7.7ms TE, 20° FA, 122Hz/pixel bandwidth, 10 cm/s velocity encoding in 3 directions, 4 views/segment, 22 phases, 2 excitations, 256x128 image matrix, 300×120-mm FOV, 3 contiguous slices 3mm (separate acquisition)/skip 0 , and 2:14 min scan time) in a sagittal orientation was used to acquire tissue VE-PC dynamic images of the lower leg during isometric contraction. SR tensor was calculated in 3D after the phase images were corrected for phase shading artifacts and denoised using a 2D anisotropic diffusion filter. The spatial gradient tensor, L, and strain rate tensor, L, is defined in the inset below. The 3x3 strain rate tensor was diagonalized and eigenvectors corresponding to the 3 eigenvalues were determined. DTI images with diffusion gradients in 32 directions and geometry parameters matching the VE-PC sequence were also acquired.

Fig.1: Magnitude sagittal image of the VE-PC with 4 ROIs. Fig. 2a,b,c: Eigenvalues of the 3x3 strain rate tensor as a function of isometr2:14ic contraction. Positive and negative eigenvalues are seen indicating that expansion occurs along one direction accompanied with contraction in the orthogonal direction as required by tissue incompressibility.

Results: Fig. 1 shows the magnitude image with four ROIs placed in the medial gastrocnemius. The three eigenvalues of the strain rate tensor are shown in Fig.2a,b,c. The first eigenvalue is negative (represents compression), and the third eigenvalue is positive (represents expansion) as anticipated for expansion in one dimension to be accompanied by a compression in the other dimension. The second eigenvalue potentially represents the deformation in-plane (fiber cross-section) and shows the least deformation (though not negligible). Contraction occurs between phases 3-8 while extension occurs in the rest of the phases. Thus the first eigenvector (corresponding to the negative eigenvalue) should be along the muscle fiber direction in the phases 3-8. This is borne out by the direction cosines (x,y, z projection) of the SR first eigenvector (Fig. 3a,b,c). High values for the direction cosine in phases 2-12 indicates that the SR vector is aligned along the muscle fiber (approximately in SI direction, Fig. 4).

Fig. 3a-c: Direction cosines of the 1st eigenvector (Fig. 2a). The z-axis projection is a maximum during the contraction phase confirming that the negative eigenvector is along the fiber direction (~ along SI). Fig. 4: Eigenvector map of a sagittal slice matching the VE-PC slice (predominant blue in the gastrocs indicates a SI fiber direction.

Table 1

	SR	DTI
ROI1	27	16
ROI2	29	13
ROI3	9	17
ROI4	25	16

Inset

$$L = \begin{bmatrix} \partial u/\partial x & \partial u/\partial y & \partial u/\partial z \\ \partial v/\partial x & \partial v/\partial y & \partial v/\partial z \\ \partial w/\partial x & \partial w/\partial y & \partial w/\partial z \end{bmatrix}$$

$$D = 0.5\left(L + L^T\right)$$

The fiber eigenvector colormap image is shown in Fig. 4 with 4 small brown ROIs along the medical gastrocs matching the ROIs in the VE-PC image. The angle with the y-axis determined from the DTI data was less than those estimated from isometric phases 4-8 of the SR 1st eigenvector (Table 1, angle in degrees) . This is in accordance with results using spin tags for the tibialis anterior muscle [1].

Discussion and Conclusions: 3D strain rate mapping is feasible despite the challenges of 3D spatial/velocity encoded acquisition. In this preliminary study, the SR and fiber eigenvector direction deviated (Table 1). The ability to perform 3D strain rate mapping and diffusion tensor imaging will enable a more detailed understanding of muscle mechanics and architecture. This will enable studies of MSK conditions in which the structural integrity is compromised and consequently, muscle function is impaired. **References**:[1]Selskog P. IEEE Trans Med Imaging. 2002 Sep;21(9):1105-9. [2] Englund et al. Am J Physiol Regul Integr Comp Physiol. 2011;300(5):R1079-9.