FULL PAPER

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Three-Parameter Shear Wave Inversion in MR Elastography of Incompressible Transverse Isotropic Media: Application to In Vivo Lower Leg Muscles

Jing Guo,[1] Sebastian Hirsch,[1] Michael Scheel,[1] Jürgen Braun,[2] and Ingolf Sack[1]*

Purpose: To develop and demonstrate MR elastography (MRE) for the measurement of three independent viscoelastic constants of skeletal muscle according to the theory of linear elasticity of incompressible materials with transverse isotropy (TI).

Methods: Three-dimensional multifrequency MRE was applied to soleus, gastrocnemius, and tibialis anterior muscles in 10 healthy volunteers. The rotational wave fields were solved for complex-valued viscoelastic parameters μ_{12}, μ_{13}, and E_3 corresponding to two shear moduli (within the planes of isotropy and symmetry of TI materials) and Young's modulus (along the principal fiber axis).

Results: Anisotropy was represented by the inequality $\mu_{12} < \mu_{13} < 1/3E_3$ considering storage and loss properties of the soleus and gastrocnemius muscles, whereas storage shear moduli of tibialis were indistinguishable. Storage moduli were: 1.06 ± 0.12, 1.33 ± 0.10, 6.92 ± 0.95 kPa (soleus); 0.90 ± 0.11, 1.30 ± 0.15, 8.22 ± 1.37 kPa (gastrocnemius); 1.26 ± 0.16, 1.27 ± 0.11, 9.29 ± 1.42 kPa (tibialis), for μ_{12}, μ_{13}, and E_3, respectively. The muscles were different in their μ_{12} and E_3 values, whereas μ_{13} was less sensitive to the muscle type. Leg differences were observed in the soleus and gastrocnemius muscles.

Conclusion: Recovery of the full elasticity tensor in incompressible TI materials is feasible by three-dimensional inversion of the time-harmonic shear wave equation. The method is potentially useful for the clinical evaluation of skeletal muscle anisotropy. **Magn Reson Med 000:000–000, 2015. © 2015 Wiley Periodicals, Inc.**

Key words: magnetic resonance elastography; MRE; soleus; gastrocnemius; tibialis; anisotropic shear modulus; Young's modulus; transverse isotropy

INTRODUCTION

Skeletal muscle tissue is composed of anisotropic and highly hierarchic structures (1). The directional and geometrical representation of filaments, myofibrils, and myofibers determine the shape and constitution of the muscle across multiple scales. The alignment of microconstituents of skeletal muscle is important in function and gives rise to pronounced anisotropy of the muscle's macroscopic mechanical properties. As such, full assessment of muscle function requires knowledge of anisotropic mechanical parameters.

In vivo mechanical constants of muscle tissue can be measured by elastography (2,3). Elastography is sensitive to the shear modulus of biological tissue, which—as in the case of muscle tissue—communicates structural information across a wide range of scales (4). Unlike common imaging markers of MRI or sonography, elastography-measured shear modulus values vary largely upon muscle function (5–10). Many clinical elastography studies have demonstrated the sensitivity of shear elastic parameters to skeletal muscle disorders and dysfunctions (11–17).

However, fewer studies have addressed anisotropic shear elastic parameters of skeletal muscle (7,9,18–23). Unlike waveguide elastography, which can reveal the full orthotropic elasticity tensor (24,25), anisotropic elastography has only demonstrated the recovery of two shear moduli, one of which is parallel to the principal axis of a transverse isotropic material (TI), the other of which perpendicular to that axis (7,18,20,21,26–28). TI symmetry is an appealing model of living tissue's anisotropic mechanical properties since local rotational symmetry can be found in many biological tissues due to the prevalence of fibers. The full TI-elasticity tensor has five independent elements (29). However, the number of free constants reduces to three in case of incompressibility (20,22,30). Incompressibility appears to be a valid approximation for muscle tissue in light of the fact that the effective volumetric strain in highly porous tissues, like the brain or liver, is an order of magnitude smaller than the shear strain usually exploited in dynamic elastography (31,32).

Our study aims at the recovery of three independent viscoelastic constants of skeletal muscles by MRE. We therefore derive the rotational wave equation of pure shear in TI materials and solve this equation for two shear moduli and one Young's modulus. This method is validated by in vivo multifrequency MR elastography (MRE) of the gastrocnemius (Gas), soleus (Sol), and tibialis anterior (Tib) muscles in 10 healthy subjects. Because both legs are examined in the same scan, the variation of values can be tested across extremities and volunteers. The data are intended as a first reference to the full elasticity tensor of incompressible muscle tissue and may therefore provide the background for constitutive models of anisotropic biological tissue.

[1]Department of Radiology, Charité–Universitätsmedizin Berlin, Campus Charité Mitte, Berlin, Germany.

[2]Institute of Medical Informatics, Charité–Universitätsmedizin Berlin, Campus Benjamin Franklin, Berlin, Germany

*Correspondence to: Ingolf Sack, PhD, Department of Radiology, Charité–Universitätsmedizin Berlin, Charitéplatz 1, 10117 Berlin, Germany. E-mail: ingolf.sack@charite.de

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