Imaging Anisotropic Mechanical Properties of Lumbar Spinal Muscle Using MR Elastography

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INTRODUCTION: Low back pain (LBP) is the most common musculoskeletal problem globally, with the majority of cases being characterized as nonspecific mechanical LBP[1]. The undefined physiological source of this pain limits the effectiveness of many targeted treatment options, highlighting the need for improved diagnostic approaches. Though disc and muscle degeneration resulting from normal aging has been well documented and shown to alter mechanical function, current diagnostic imaging techniques are unable to distinguish this normal aging from pathology induced degradation[2]. Additionally, despite LBP being primarily mechanical in nature, spinal muscles are not typically evaluated using mechanical measures, further emphasizing the need for a method capable of assessing the mechanical structure and function of the lumbar spine. As ultrasound elastography, which has previously been used to assess muscle mechanics, is limited by low resolution, poor acoustic window, and artifact susceptibility[3], we propose the use of magnetic resonance elastography (MRE) for probing lumbar spine mechanics. MRE is an imaging technique used to measure the mechanical properties of soft tissue by inducing small-scale vibrations through a tissue of interest during an MRI. This technique is most commonly employed in the liver for the clinical assessment of fibrosis, but previous studies have shown that MRE is sensitive to changes in skeletal muscle mechanics resulting from different mechanical loading or disease states[4,5]. The MRE methods developed in this work will expand on previously reported spinal muscle MRE techniques by improving the spatial resolution and using an anisotropic inversion[6]. Due to the highly fibrous nature of muscle tissue, mechanical properties are dependent on muscle fiber orientation. Our group has previously established an anisotropic MRE protocol for resolving mechanical properties of skeletal lower-leg muscles using a transversely isotropic nonlinear inversion (TI-NLI)[7]. This improved inversion uses a combination of MRE data and fiber directions obtained from diffusion-weighted MRI to estimate the tensile modulus along the fiber direction and the shear modulus both along and perpendicular to the fiber direction. Here, we develop a novel protocol for lumbar spine MRE and conduct a pilot study with healthy, young adults to quantify spinal muscle mechanics. Ultimately, the goal of this work is to determine the feasibility of MRE to sensitively assess muscle viscoelasticity for the diagnosis and treatment of nonspecific LBP.

METHODS: All imaging was conducted using a Siemens 3T Prisma MRI with a 32-channel RF spine coil. Under IRB approval, we obtained informed consent and tested this protocol on 4 healthy subjects (2M, 2F, age 25±2). As shown in Figure 1A, participants are placed into the MRI scanner in a headfirst supine position. Vibrations were delivered at 50 Hz via a pneumatic actuator connected to a flexible passive driver placed beneath the lumbar spine, with legs elevated to ensure sufficient contact with the driver. An echoplanar imaging MRE sequence was used to map the induced displacements with imaging parameters including: TR/TE = 8400/53 ms; 400x400 mm^2 field-of-view; 200x200 matrix; 60 slices with 4 mm slice thickness. This resulted in full coverage of the lumbar spine (L1-S1) with high in-plane spatial resolution and an acquisition time of ~4 minutes. We also acquired a diffusion-weighted MRI scan with resolution and field of view matching the MRE, with 30 directions, b=400 mm^2/s, and an acquisition time of ~5 minutes to extract the muscle fiber direction at each point. Resulting phase images from MRE were processed to obtain maps of complex 3D wave motion, as shown in Figure 1B. The TI-NLI algorithm was used to resolve mechanical properties in a muscle group containing the erector spinae and multifidus including shear stiffness, damping ratio, and shear and tensile anisotropy, which are given as the relative increase in shear or tensile stiffness in the direction parallel vs. perpendicular to fiber orientation.

RESULTS: The OSS-SNR (octahedral shear strain signal-to-noise ratio), which is used to evaluate MRE data quality, was well above the minimal acceptable value for usable property estimation[8]. Across the 4 subjects tested, the average OSS-SNR was 6.7. While mechanical properties are expected to vary by subject and position, we found that our results were within a similar range of previously reported MRE data captured using isotropic methods[6]. Figure 2 shows the mechanical property maps from a representative subject with the following average property values across the region of interest: shear stiffness (1.34 kPa), damping ratio (0.2), shear anisotropy (0.26), and tensile anisotropy (0.54), indicating muscle tissue is stiffer along the fiber direction.

DISCUSSION: This pilot study demonstrated the feasibility of MRE as a sensitive measure of lumbar spinal muscle mechanical properties. The voxel-wise approach of MRE highlights the spatial variation in mechanical properties. The use of anisotropic MRE with TI-NLI resolves mechanical properties both parallel and perpendicular to fiber direction. The use of the proper mechanical model improves accuracy of MRE in anisotropic tissues, and the direction-dependent properties are more relevant for assessing muscle function through mechanics. This technique has many potential applications including the assessment of different loading conditions and disease states on the spinal muscles. Future work includes the collection of additional data in healthy participants and patients with nonspecific LBP to determine differences in muscle mechanical properties, including dynamic changes in muscle stiffness in different postures to interrogate mechanical function.

SIGNIFICANCE/CLINICAL RELEVANCE: This novel anisotropic MRE protocol, able to noninvasively assess spine mechanics, has the potential to serve as an early predictor of LBP vulnerability. Clinical translation of this imaging technique can improve the evaluation of nonspecific LBP and advance diagnosis and targeted treatment options.

REFERENCES: [1] Wu 2020; [2] Brinjikji 2015; [3] Schmidt 2025; [4] Basford 2002; [5] Smith 2023; [6] Creze 2018; [7] McGarry 2022; [8] McGarry 2011

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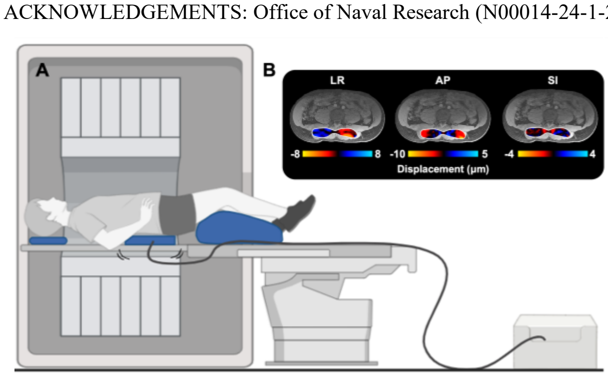

Figure 1. Lumbar spine MRE setup demonstrating passive driver positioning (A) and displacement fields in the left-right (LR), anterior-posterior (AP), and superior-inferior (SI) directions (B).

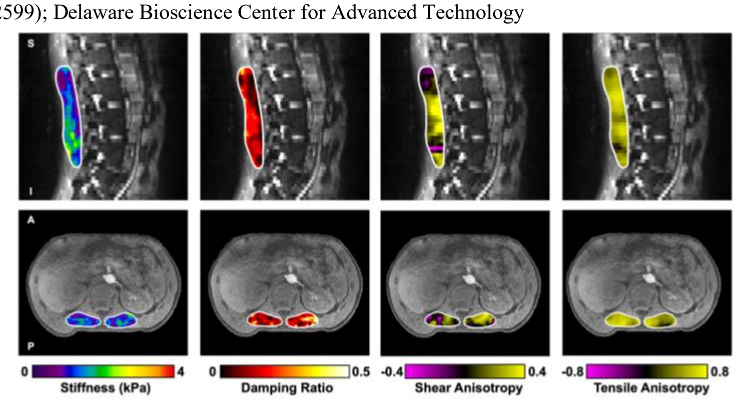

Figure 2. Representative maps of mechanical properties in the sagittal and axial view.