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Case Report

Quantifying spasticity in individual muscles using shear wave elastography

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ABSTRACT

Spasticity is common following stroke; however, high subject variability and unreliable measurement techniques limit research and treatment advances. Our objective was to investigate the use of shear wave elastography (SWE) to characterize the spastic reflex in the biceps brachii during passive elbow extension in an individual with spasticity. The patient was a 42-year-old right-hand-dominant male with history of right middle cerebral artery-distribution ischemic infarction causing spastic left hemiparesis. We compared Fugl-Meyer scores (numerical evaluation of motor function, sensation, motion, and pain), Modified Ashworth scores (most commonly used clinical assessment of spasticity), and SWE measures of bilateral biceps brachii during passive elbow extension. We detected a catch that featured markedly increased stiffness of the brachialis muscle during several trials of the contralateral limb, especially at higher extension velocities. SWE was able to detect velocity-related increases in stiffness with extension of the contralateral limb, likely indicative of the spastic reflex. This study offers optimism that SWE can provide a rapid, real-time, quantitative technique that is readily accessible to clinicians for evaluating spasticity.

Introduction

An estimated 795,000 Americans experience stroke every year [1], and stroke incidence is expected to increase as the population ages [2]. It is estimated that the prevalence of spasticity after stroke ranges from 18% to 39% [3–5], and spasticity-associated functional limitations create significant burdens on survivors and caregivers [6]. Health care costs for individuals

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with stroke who develop spasticity are estimated to be fourfold higher than those without spasticity [7]. However, high subject variability and indeterminate measurement techniques limit research investigation and treatment advances [8,9].

Though classically considered to have increased stiffness resulting solely from the over-active velocity-dependent stretch reflex, chronically spastic muscles associated with stroke appear to also have increased nonreflex stiffness when compared to the side of the body ipsilateral to the lesioned hemisphere, as well as healthy controls [9,10]. Clinically, spasticity is diagnosed and monitored using the 5-point Modified Ashworth Scale (MAS): a simple technique that requires no equipment, though is subjective, qualitative, and varies widely with muscle groups [11,12]. Though the precise mechanism behind spasticity is not known, we now recognize a variety of biomechanical changes within skeletal muscle connective tissue that likely limit the effectiveness of a simplistic tool, such as the MAS, for evaluating spasticity in chronic stroke [13,14]. Electromyography or biomechanical measures may offer more reliable, quantitative information, though are impractical for routine clinical use [14–16]. Furthermore, elevated muscle tone in persons with spasticity may not be related to activation of the muscle groups in question [17,18].

A variety of imaging-based elastography techniques have emerged with great promise for skeletal muscle evaluation, including ultrasound elastography and magnetic resonance elastography [18–22]. Strain elastography, a qualitative measure of relative stiffness, is also available but offers little advantage over the MAS, as neither offers a quantitative, objective measure [21,23,24]. The two quantitative imaging modalities, magnetic resonance elastography and ultrasound shear wave elastography (SWE), show good agreement in both phantoms and tissues, though SWE is especially promising for its flexibility, accessibility, and real-time results [25–27]. For this reason, SWE may be uniquely suited for evaluating pathologic alterations in stiffness of individual muscles, especially for quantifying spasticity [18,28–31].

This study evaluated the feasibility of using SWE to characterize the spastic reflex during passive elbow extension in an individual with spasticity caused by stroke. We hypothesized that SWE would capture heightened skeletal muscle stiffness, representing the spastic reflex, during passive elbow range of motion.

Methods

The subject was a 42-year-old right-hand-dominant male who experienced thromboembolic right middle cerebral artery occlusion, acutely treated with tissue plasminogen activator and endovascular recanalization. We evaluated him 10 months later, when he was receiving outpatient physiotherapy but no medical therapy for spasticity. His body mass index was 29.2 kg/m^2. He provided informed consent, and all study procedures were approved by the institutional review board. Prior to biomechanical and ultrasound testing, an experienced, licensed, neuromuscular occupational therapist evaluated upper limb function and spasticity using the Fugl-Meyer assessment and MAS.

We fixed an L7-4 linear-array ultrasound transducer (Philips Healthcare, Andover, MA) over the midbelly of the biceps brachii using a custom-molded apparatus. The apparatus attached to the subject's arm and maintained even, minimal, and continuous contact pressure between the ultrasound transducer and subject's arm via liberal coupling gel. We tested the side ipsilateral to the lesioned hemisphere first and aligned the ultrasound transducer with the long axis of the biceps. We encouraged the subject to remain as relaxed as possible for the duration of testing. The study included three sets of passive elbow extension trials from 90° to 165° extension (180°=full extension) using a Humac (Computer Sports Medicine Inc, Stoughton, MA) dynamometer to carefully control extension velocities at 5°/s, 20°/s, 40°/s, and 60°/s then repeating for subsequent trials. Synchronizing through the dynamometer, we obtained SWE measurements at 105°, 120°, 135°, 150°, and 165°, using the Verasonics (Verasonics Inc, Kirkland, WA) ultrasound system. To evaluate any lingering changes in stiffness, we obtained a series of measurements at 1-second intervals with the arm held at 165°. A focused ultrasound push beam with duration of 400 μs produced shear waves that were detected using plane wave imaging with a frame rate of 5.85 kHz for 14.8 ms.

Two-dimensional shear wave speed maps of the muscle were reconstructed using the time-of-flight approach based on local cross-correlation of the shear wave signal [32]. Shear wave speed is a quantitative measure of tissue stiffness and can be converted to shear modulus using the equation

$$\mu = c_s^2 \rho$$

where μ is shear modulus, c_s is shear wave propagation velocity, and ρ is density, which can be assumed to be 1000 kg/m^3 for all soft tissues [33]. We selected two regions of interest, for evaluating shear wave speed in the biceps and brachialis, as indicated in Figures 1 and 2.

Results

The subject had a Fugl-Meyer motor function score of 41 (normal: 66), with primary deficits in the contralateral upper forearm (25/35), wrist (3/10), and hand (9/14). His MAS for the right and left sides was 0 and 1.

A sample set of bilateral elastograms and associated shear wave speeds during 60°/s extensions for the ipsilateral side are presented in Figure 1. The results for the contralateral side are included in Figure 2, which demonstrates consistently higher stiffness when compared to the ipsilateral limb—an effect present throughout all trials, regardless of elbow extension speed, that is best demonstrated by the 165° plateau. Most notably, at higher velocities, the contralateral brachialis experienced a catch with increased stiffness, as in Figure 2B (trial 1; 105°)—an effect that dissipated with successive extension trials.

Discussion

This study represents one example from several pilot studies demonstrating the feasibility of using SWE to characterize the spastic reflex during passive elbow extension