Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://Elsevier.com/locate/radcr

Case Report

Quantifying spasticity in individual muscles using shear wave elastography

Sarah F. Eby BS[a,b,*], Heng Zhao PhD[c], Pengfei Song PhD[d], Barbara J. Vareberg OT[e], Randall R. Kinnick BS[c], James F. Greenleaf PhD[c], Kai-Nan An PhD[b], Allen W. Brown MD[e], Shigao Chen PhD[d]

[a] Mayo Medical School, Mayo Graduate School, and the Medical Scientist Training Program, College of Medicine, Mayo Clinic, 200 First St. SW, Rochester, MN 55905, USA
[b] Biomechanics Laboratory, Division of Orthopedic Research, Mayo Clinic, 200 First St. SW, Rochester, MN 55905, USA
[c] Department of Biomedical Engineering, College of Medicine, Mayo Clinic, Rochester, MN, USA
[d] Department of Radiology, Mayo Clinic, Rochester, MN, USA
[e] Department of Physical Medicine and Rehabilitation, Mayo Clinic, Rochester, MN, USA

ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form
29 December 2016
Accepted 2 January 2017
Available online 9 February 2017

Keywords:
Muscle spasticity
Stroke
Ultrasound
Skeletal muscle
Upper extremity

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

Competing Interests: The authors have declared that no competing interests exist.

* *Corresponding author.*
E-mail address: eby.sarah@mayo.edu (S.F. Eby).

http://dx.doi.org/10.1016/j.radcr.2017.01.004

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

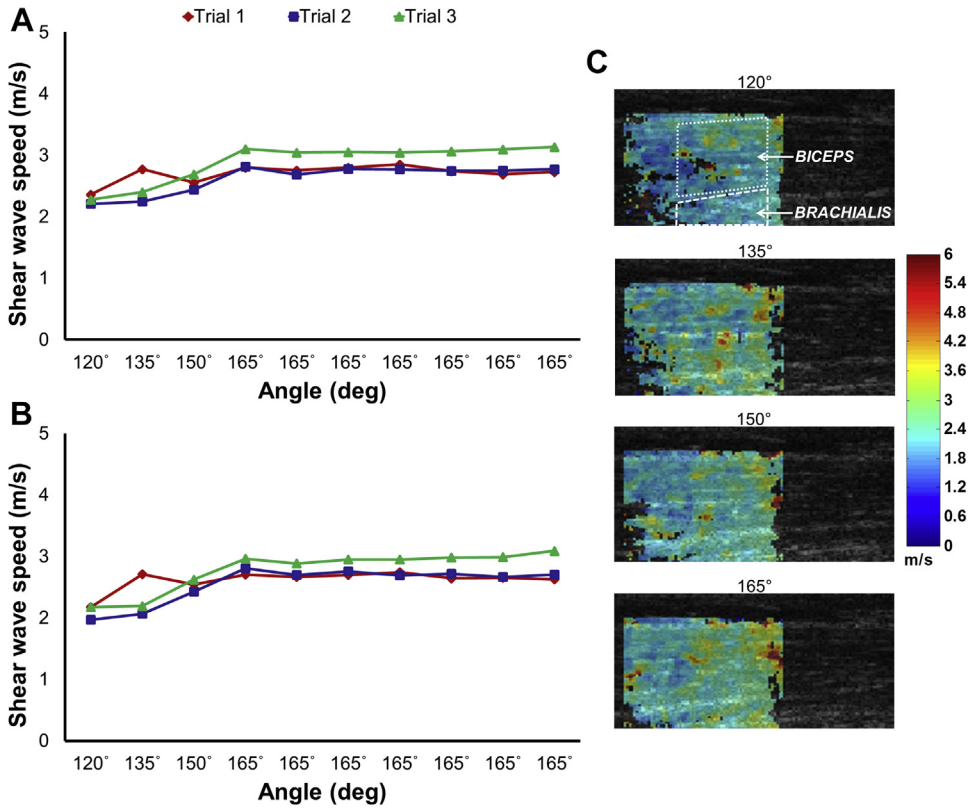

Fig. 1 – Shear wave speeds, ultrasound images, and elastograms for 60°/s ipsilateral elbow extension trials. (A) Ipsilateral biceps; (B) ipsilateral brachialis; (C) ultrasound images and elastograms from trial 1 with sample regions of interest demonstrated in the first panel.

following chronic stroke. Highly variable from 1 day to the next, and even throughout a given day, spasticity can be very challenging for clinicians to monitor and diagnose. Furthermore, patients experience spasticity significantly more often than clinicians and investigators are able to detect with currently available measures, thus limiting our ability to adequately treat their symptoms [34]. Though our subject did not experience profound spasticity or impairment, SWE was able to detect velocity-related increases in stiffness with extension of the contralateral limb, likely indicative of the spastic reflex. Additionally, an increase in passive stiffness appears unrelated to spasticity, as seen by the 165°-plateau region in Figure 2, though may have clinical and functional implications. This pattern of heightened stiffness for the contralateral side when the arm is held in extension was consistent throughout all trials and may facilitate using SWE as a clinical tool, noting that specialized dynamometers would not be necessary for obtaining measurements of the static arm. These findings show promise for future investigations and clinical applications using SWE to quantify and characterize the spastic reflex associated with stroke, as well as changes in passive mechanical properties.

Spasticity is classically defined as a velocity-dependent resistance to stretch; however, a variety of factors contribute to its clinical manifestation [13,14]. As a more thorough understanding of the neuromuscular sequelae of stroke and other pathologies affecting sensorimotor systems continues to evolve, a lack of precise, quantitative measurement techniques will continue to limit treatment and progress toward improving function and independence for individuals with spasticity. This study found brief periods of increased muscle stiffness during trials of increased extension velocity, possibly related to altered viscoelasticity of skeletal muscle following stroke. As is classically found with spasticity, this increased stiffness displayed conditioning effects with repeated elbow extension. Interestingly, SWE identified focal regions of marked elevations in stiffness and presumed contraction in the deeper brachialis muscle, while the overlying biceps brachii did not show concomitant elevations in stiffness. Previous techniques for evaluating spasticity are often limited in their ability to localize specific causative muscles, instead identifying muscle groups associated with a given joint's function. Future work should investigate how this differential activation may guide directed clinical intervention to improve function and quality of life.

This feasibility study has several limitations. We studied a single individual with stroke-related spasticity on a single day. Collecting electromyography or torque may provide additional information about the nature of muscle stiffness during a spastic event. Limitations with equipment synchronization prevented evaluation of extension velocities

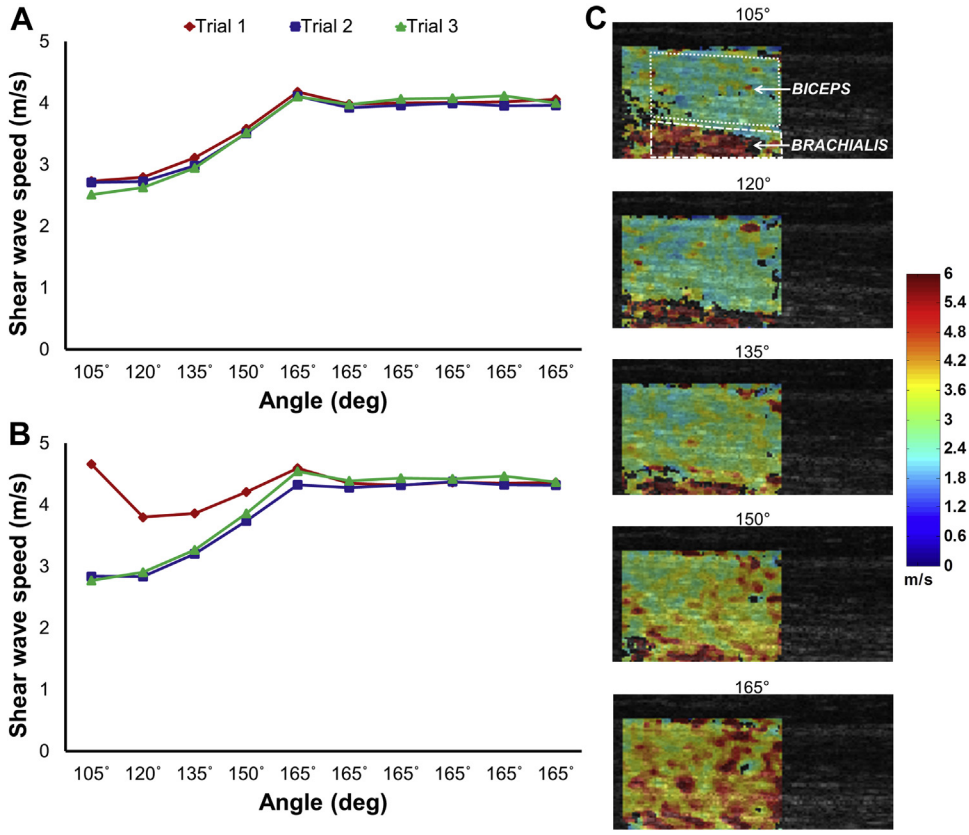

Fig. 2 – Shear wave speeds, ultrasound images, and elastograms for 60°/s contralateral elbow extension trials. (A) Contralateral biceps; (B) contralateral brachialis; note peak in stiffness, likely representative of spastic reflex, at 105° for trial 1 in the contralateral brachialis at 60°/s. (C) Ultrasound images and elastograms from trial 1 with sample regions of interest demonstrated in the first panel; note deep area of increased stiffness early in elbow extension that corresponds with peak shown in (B).

greater than 60°/s—relatively slow to consistently elicit a spastic reflex. Furthermore, an initial synchronization error prevented the collection of SWE values at 105° for the ipsilateral side, though we are confident these missed data points are of little significance. Difficulties with equipment transport limited our evaluation to an ambulatory, community-dwelling subject, and we likely measured chronic biomechanical changes in addition to the elevated stretch reflex that is a hallmark of spasticity. Fortunately, assessing individuals in the acute setting following stroke when the spastic reflex is more pronounced will become much more feasible as SWE technologies are increasingly utilized on commercially available clinical ultrasound machines.

SWE should continue to be used to evaluate spasticity in stroke, as well as a variety of other neuromuscular conditions, such as multiple sclerosis, spinal cord injury, and cerebral palsy, to further characterize the alterations to passive and active skeletal muscle stiffness with both acute and chronic spasticity. Additionally, future work should investigate the reliability and repeatability of SWE measures in spasticity, to ensure such a technique is truly superior to classic clinical evaluation tools, such as the MAS and others. This study offers optimism that SWE can provide a rapid, real-time, quantitative technique that is readily accessible to clinicians for evaluating spastic muscle.

Acknowledgments

This work was supported by the National Center for Research Resources and Mayo Clinic CTSA (grant number UL1RR024150); and the National Institute on Aging (grant number F30AG044075).

REFERENCES

[1] Roger VL, Go AS, Lloyd-Jones DM, Adams RJ, Berry JD, Brown TM, et al. Heart disease and stroke statistics–2011 update: a report from the American Heart Association. Circulation 2011;123:e18–209.

[2] Kolominsky-Rabas PL, Heuschmann PU, Marschall D, Emmert M, Baltzer N, Neundörfer B, et al. Lifetime cost of ischemic stroke in Germany: results and national projections from a population-based stroke registry: the Erlangen Stroke Project. Stroke 2006;37:1179–83.

[3] Sommerfeld DK, Gripenstedt U, Welmer A-K. Spasticity after stroke: an overview of prevalence, test instruments, and treatments. Am J Phys Med Rehabil 2012;91:814–20.
[4] Watkins CL, Leathley MJ, Gregson JM, Moore AP, Smith TL, Sharma AK. Prevalence of spasticity post stroke. Clin Rehabil 2002;16:515–22.
[5] Lundström E, Terént A, Borg J. Prevalence of disabling spasticity 1 year after first-ever stroke. Eur J Neurol 2008;15:533–9.
[6] Zorowitz RD, Gillard PJ, Brainin M. Poststroke spasticity: sequelae and burden on stroke survivors and caregivers. Neurology 2013;80:S45–52.
[7] Lundström E, Smits A, Borg J, Terént A. Four-fold increase in direct costs of stroke survivors with spasticity compared with stroke survivors without spasticity: the first year after the event. Stroke 2010;41:319–24.
[8] Platz T, Eickhof C, Nuyens G, Vuadens P. Clinical scales for the assessment of spasticity, associated phenomena, and function: a systematic review of the literature. Disabil Rehabil 2005;27:7–18.
[9] Mirbagheri MM, Settle K, Harvey R, Rymer WZ. Neuromuscular abnormalities associated with spasticity of upper extremity muscles in hemiparetic stroke. J Neurophysiol 2007;98:629–37.
[10] Sinkjaer T, Magnussen I. Passive, intrinsic and reflex-mediated stiffness in the ankle extensors of hemiparetic patients. Brain 1994;117(Pt 2):355–63.
[11] Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. Phys Ther 1987;67:206–7.
[12] Ashworth B. Preliminary trial of carisoprodol in multiple sclerosis. Practitioner 1964;192:540–2.
[13] Fellows SJ, Ross HF, Thilmann AF. The limitations of the tendon jerk as a marker of pathological stretch reflex activity in human spasticity. J Neurol Neurosurg Psychiatr 1993;56:531–7.
[14] Kumar RTS, Pandyan AD, Sharma AK. Biomechanical measurement of post-stroke spasticity. Age Ageing 2006;35:371–5.
[15] Sunnerhagen KS, Olver J, Francisco GE. Assessing and treating functional impairment in poststroke spasticity. Neurology 2013;80:S35–44.
[16] Pandyan AD, Price CI, Rodgers H, Barnes MP, Johnson GR. Biomechanical examination of a commonly used measure of spasticity. Clin Biomech (Bristol, Avon) 2001;16:859–65.
[17] Dietz V, Quintern J, Berger W. Electrophysiological studies of gait in spasticity and rigidity. Evidence that altered mechanical properties of muscle contribute to hypertonia. Brain 1981;104:431–49.
[18] Zhao H, Ren Y, Wu Y-N, Liu SQ, Zhang L-Q. Ultrasonic evaluations of achilles tendon mechanical properties poststroke. J Appl Physiol 2009;106:843–9.
[19] Debernard L, Robert L, Charleux F, Bensamoun SF. Analysis of thigh muscle stiffness from childhood to adulthood using magnetic resonance elastography (MRE) technique. Clin Biomech (Bristol, Avon) 2011;26:836–40.
[20] Debernard L, Robert L, Charleux F, Bensamoun SF, Bensamoun SF. Characterization of muscle architecture in children and adults using magnetic resonance elastography and ultrasound techniques. J Biomech 2011;44:397–401.
[21] Brandenburg JE, Eby SF, Song P, Zhao H, Brault JS, Chen S, et al. Ultrasound elastography: the new frontier in direct measurement of muscle stiffness. Arch Phys Med Rehabil 2014;95:2207–19.
[22] Gennisson J-L, Deffieux T, Macé E, Montaldo G, Fink M, Tanter M. Viscoelastic and anisotropic mechanical properties of in vivo muscle tissue assessed by supersonic shear imaging. Ultrasound Med Biol 2010;36:789–801.
[23] Park G-Y, Kwon DR. Sonoelastographic evaluation of medial gastrocnemius muscles intrinsic stiffness after rehabilitation therapy with botulinum toxin a injection in spastic cerebral palsy. Arch Phys Med Rehabil 2012;93:2085–9.
[24] Inami T, Kawakami Y. Assessment of individual muscle hardness and stiffness using ultrasound elastography. J Phys Fit Sports 2016;5:313–7.
[25] Bensamoun SF, Wang L, Robert L, Charleux F, Latrive J, Tho MH. Measurement of liver stiffness with two imaging techniques: magnetic resonance elastography and ultrasound elastometry. J Magn Reson Imaging 2008;28:1287–92.
[26] Dutt V, Kinnick RR, Muthupillai R, Oliphant TE, Ehman RL, Greenleaf JF. Acoustic shear-wave imaging using echo ultrasound compared to magnetic resonance elastography. Ultrasound Med Biol 2000;26:397–403.
[27] Oudry J, Chen J, Glaser KJ, Miette V, Sandrin L, Ehman RL. Cross-validation of magnetic resonance elastography and ultrasound-based transient elastography: a preliminary phantom study. J Magn Reson Imaging 2009;30:1145–50.
[28] Eby S, Zhao H, Song P, Vareberg BJ, Kinnick R, Greenleaf JF, et al. Quantitative evaluation of passive muscle stiffness in chronic stroke. Am J Phys Med Rehabil 2016;95(12):899–910.
[29] Eby SF, Cloud BA, Brandenburg JE, Giambini H, Song P, Chen S, et al. Shear wave elastography of passive skeletal muscle stiffness: influences of sex and age throughout adulthood. Clin Biomech (Bristol, Avon) 2015;30:22–7.
[30] Lee SSM, Spear S, Rymer WZ. Quantifying changes in material properties of stroke-impaired muscle. Clin Biomech (Bristol, Avon) 2015;30:269–75.
[31] Lee SSM, Gaebler-Spira D, Zhang L-Q, Rymer WZ, Steele KM. Use of shear wave ultrasound elastography to quantify muscle properties in cerebral palsy. Clin Biomech (Bristol, Avon) 2016;31:20–8.
[32] Tanter M, Bercoff J, Athanasiou A, Deffieux T, Gennisson J-L, Montaldo G, et al. Quantitative assessment of breast lesion viscoelasticity: initial clinical results using supersonic shear imaging. Ultrasound Med Biol 2008;34:1373–86.
[33] Sarvazyan AP, Rudenko OV, Swanson SD, Fowlkes JB, Emelianov SY. Shear wave elasticity imaging: a new ultrasonic technology of medical diagnostics. Ultrasound Med Biol 1998;24:1419–35.
[34] Sköld C, Levi R, Seiger A. Spasticity after traumatic spinal cord injury: nature, severity, and location. Arch Phys Med Rehabil 1999;80:1548–57.