Clinical Biomechanics 31 (2016) 20–28

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Use of shear wave ultrasound elastography to quantify muscle properties in cerebral palsy

Sabrina S.M. Lee [a,b,*], Deborah Gaebler-Spira [a,b], Li-Qun Zhang [a,b], William Z. Rymer [a,b], Katherine M. Steele [c]

[a] Rehabilitation Institute of Chicago, Chicago, IL, USA
[b] Northwestern University, Chicago, IL, USA
[c] University of Washington, Seattle, WA, USA

ARTICLE INFO

Article history:
Received 10 July 2015
Accepted 7 October 2015

Keywords:
Cerebral palsy
Muscle
Ultrasound
Shear wave elastography

ABSTRACT

Background: Individuals with cerebral palsy tend to have altered muscle architecture and composition, but little is known about the muscle material properties, specifically stiffness. Shear wave ultrasound elastography allows shear wave speed, which is related to stiffness, to be measured in vivo in individual muscles. Our aim was to evaluate the material properties, specifically stiffness, as measured by shear wave speed of the medial gastrocnemius and tibialis anterior muscles in children with hemiplegic cerebral palsy across a range of ankle torques and positions, and fascicle strains.

Method: Shear wave speed was measured bilaterally in the medial gastrocnemius and tibialis anterior over a range of ankle positions and torques using shear wave ultrasound elastography in eight individuals with hemiplegic cerebral palsy. B-mode ultrasound was used to measure muscle thickness and fascicle strain.

Results: Shear waves traveled faster in the medial gastrocnemius and tibialis anterior of the more-affected limb by 14% ($P = 0.024$) and 20% ($P = 0.03$), respectively, when the ankle was at 90°. Shear wave speed in the medial gastrocnemius increased as the ankle moved from plantarflexion to dorsiflexion (less affected: $r^2 = 0.82$, $P < 0.001$; more-affected: $r^2 = 0.69$, $P < 0.001$) and as ankle torque increased (less affected: $r^2 = 0.56$, $P < 0.001$; more-affected: $r^2 = 0.45$, $P < 0.001$). In addition, shear wave speed was strongly correlated with fascicle strain (less affected: $r^2 = 0.63$, $P < 0.001$; more-affected: $r^2 = 0.53$, $P < 0.001$).

Interpretation: The higher shear wave speed in the more-affected limb of individuals with cerebral palsy indicates greater muscle stiffness, and demonstrates the clinical potential of shear wave elastography as a non-invasive tool for investigating mechanisms of altered muscle properties and informing diagnosis and treatment.

1. Introduction

Cerebral palsy (CP) is the most common pediatric neuromuscular disorder, impacting roughly 3 out of every 1000 individuals (Yeargin-Allsopp et al., 2008). Movement and coordination are impaired among individuals with CP due to both altered neural control and secondary changes in muscle properties (Gage, 2009). These secondary changes in muscle are a primary target for treatment and commonly require expensive, invasive procedures for correction, such as multi-level orthopedic surgery. Quantifying the magnitude and functional impact of changes in muscle properties for individual patients with CP remains challenging, and hinders treatment planning.

Changes in muscle properties have been documented at nearly every level of the hierarchical structure of muscle in individuals with CP. From the sub-microscopic level, where changes occur in myosin heavy chain isoforms (Ponten and Stal, 2007), sarcomere lengths (Smith et al., 2011), and fiber types (Ito et al., 1996), to the whole muscle level where volume, cross-sectional area, and thickness are reduced (Barber et al., 2011). Such changes in muscle properties are significant and may negatively impact movement. For example, the muscles' passive resistance to stretch is commonly increased in CP, contributing to perceived muscle contracture and limiting joint range of motion. Increases in muscles' passive resistance to stretch can be attributed to increased collagen of the extracellular matrix (ECM) (Booth et al., 2001; Friden and Lieber, 2003; Smith et al., 2011), and changes in structural (Magid and Law, 1985) and intracellular (Friden and Lieber, 2003; Lieber et al., 2003) proteins.

There is widespread acceptance that muscles' passive properties are altered in individuals with CP (Barber et al., 2011; Friden and Lieber, 2003; Smith et al., 2011); however, obtaining quantitative in vivo measurements to support this assertion remains a challenge. Prior non-invasive methods to evaluate muscle or joint stiffness, such as torque–angle measurements (Barber et al., 2011; Sinkjær and Magnussen, 1994), compression elastography (Park and Kwon, 2012), and tendon indentation (Chardon et al., 2010) have provided important

* Corresponding author at: Department of Physical Therapy and Human Movement Sciences, Northwestern University, 645 N Michigan Avenue, Suite 1100, Chicago, IL 60611, USA.
E-mail address: s-lee@northwestern.edu (S.S.M. Lee).

http://dx.doi.org/10.1016/j.clinbiomech.2015.10.006
0268-0033/

measures in healthy individuals and those with impaired movements. By measuring the change in torque, as an estimate of change in force, and angle displacement, as an estimate of change in muscle length, during an external perturbation, estimates of muscle or joint stiffness can be obtained. Sinkjær et al. (1988) developed a method where this stiffness could be distinguished as passive, intrinsic, and reflex-mediated stiffness (Sinkjær et al., 1988) and applied this method to the ankle extensors of hemiparetic patients (Sinkjær and Magnussen, 1994) and individuals with multiple sclerosis (Sinkjér et al., 1993). However, these prior methods have multiple limitations including limited quantitative accuracy, muscle specificity, repeatability, ease of use in the clinic, and/or cost-effectiveness. Invasive methods have also been used such as biopsy or intraoperative measurements (Friden and Lieber, 2003; Smith et al., 2011); these provide invaluable information on stiffness mechanisms at the cellular and fiber level, but not at the whole muscle level where we are limited to measurements of passive stiffness.

Shear wave (SW) ultrasound elastography, which builds upon traditional elastography, allows quantitative in vivo measurement of tissue material properties (Bercoff et al., 2004). Using the same acoustic radiation forces as B-mode ultrasound, we use the SuperSonic Shear Imagine (Bercoff et al., 2004), a method that uses multiple ultrasound push beams to induce the SWs and subsequently, to measure the SW speed in muscle. The speed of these SWs is related to material properties, such that SWs travel faster through stiffer tissues. This technique has emerged as a reliable method to estimate material properties in a variety of tissues (Bouillard et al., 2012), including muscle (Bouillard et al., 2012; Eby et al., 2013; Lacourpaille et al., 2012). Several earlier studies have measured SW speed in muscles such as the biceps brachii (Bouillard et al., 2012; Lacourpaille et al., 2012), gastrocnemius (Chernak et al., 2013; Lacourpaille et al., 2012), and vastus lateralis muscles (Lacourpaille et al., 2012) in both healthy individuals and in individuals with neuromuscular dysfunction such as spasticity (Basford et al., 2002; Kwon et al., 2012; Lee et al., 2015). Using MRI to measure SW speed, Basford et al. observed the shear modulus in resting lateral gastrocnemius muscle of individuals with neuromuscular disease such as childhood poliomylelitis and spastic paraplegia, to be 2.4 times larger that of non-impaired muscle (Basford et al., 2002). Recently, SW speed in the biceps brachii muscle of the paretic side was found to be on average 69.5% greater than the non-paretic side in stroke survivors (Lee et al., 2015). Greater SW velocities in the gastrocnemius muscles of children with CP were also reported, compared to typically developing children with the ankle at 90°(Kwon et al., 2012).

Building upon these results, the goal of this study was to evaluate SW speed of the medial gastrocnemius (MG) and tibialis anterior (TA) in children with hemiplegic CP over a range of ankle positions and torques. We hypothesized that SW speed would 1) be greater in the more-affected limb than the less-affected limb of children with hemiplegic CP, 2) increase with muscle stretch as indicated by ankle position and increase with increasing fascicle strain, and 3) increase with decreased ankle range of motion.

2. Methods

2.1. Participants

Eight individuals (five males, three females; mean (SD) age: 9.4 (3.7) yrs; height: 1.31 (0.17) m; body mass: 33.3 (12.8) kg; Gross Motor Function Classification System (GMFCS) Levels: three subjects at I; five subjects at II) participated in the study. Children with CP were recruited from the Rehabilitation Institute of Chicago for participation in this study. Inclusion criteria were a diagnosis of spastic hemiplegic CP by a physician specializing in pediatric rehabilitation medicine, between the ages of 5 and 18 years, able to ambulate with or without walking aids, and no botulinum toxin injections or surgical procedures to MG or TA within the past year. Although the inclusion criteria specified a diagnosis of hemiplegic CP, one subject (S7) had a stroke at five years of age; however, due to similar movement impairments, he was included in the study. The physician also identified which side was the impaired or more-affected side from visual and manual inspection (e.g., muscle weakness, loss of selective control, increased tone, decreased range of motion, skeletal deformity). The Institutional Review Board of Northwestern University approved all protocols and consent from the subjects was obtained prior to testing.

2.2. Experimental protocol

Ultrasound images were captured over a range of ankle positions. A small rotary actuator, "The IntelliStretch Rehabilitation Robot" (Rehabtek LLC, Glenview, IL) was used to continuously monitor ankle angle and torque throughout the experiment. Each subject was seated in the IntelliStretch with his or her knee in maximum extension and their foot strapped to the device (Fig. 1a). Tracking both knee and ankle positions were important since the MG crosses both joints and knee position will impact the magnitude of MG stretch. Maximum extension was chosen rather than a standardized joint angle to account for different resting muscle lengths. Since resting muscle length is variable among individuals with CP, maximum knee extension would indicate the MG muscle is at its longest length. Thus, this position would be comparable between subjects.

B-mode and SW ultrasound elastography measurements of TA (Fig. 1b) and MG were made with the ankle in five positions (neutral, maximum dorsiflexion, maximum plantarflexion, and two intermediary angles) with the muscles at rest. Intermediary angles were chosen at which torque values were one-third and two-thirds of the torque measured at maximum dorsiflexion and plantarflexion for the initial tested limb. These two torque values were then used for finding the two intermediary angles for the contralateral limb at which the torque values were matched. Three trials in randomized order were performed in each position. Ultrasound images were captured using an Aixplorer Ultrasonography System (SuperSonic Imagine, Aix-en-Provence, France) with a linear transducer array (4–15 MHz, SuperLiner 15-4, Vermon, Tours, France) (Bercoff et al., 2004). Technical details of this SuperSonic Imagine technology have been described previously (Bercoff et al., 2004). A customized neoprene sleeve held the transducer in place to minimize translation or tilt of the transducer. The transducer was orientated parallel to the fascicle plane at the mid-belly region of each muscle. The region of interest, from which the SW velocities were measured, was placed over the mid-region of the muscle belly (Fig. 1b). Images were taken separately for the TA and MG of each leg, for a total of 60 trials (2 legs, 2 muscles, 15 trials/muscle). Subjects were instructed to remain relaxed during this study, but to test if muscle activation also increased with ankle position, we monitored electromyography (EMG) signals (Trigno EMG, Delsys, Inc., Boston, MA) from the MG and TA in three subjects. For those three subjects, there was no evidence of increased muscle activity.

2.3. Ultrasound processing

A custom-written software in Matlab (Mathworks, Nathick, USA), adapted from the propriety company software, was used in this study. The mean SW speed is calculated from a circular region with varying diameters selected by the experimenter from the 12 mm by 12 mm region of interest (Fig. 1b). In our software, instead of using the circular region, all the values from the region of interest were used except for areas outside of the muscle belly, which were manually cropped. This way, the maximal area for including SW speed values was achieved. The spatial average of SW speed was then calculated across the cropped region of interest for each muscle. The company software, Q Box, provides each SW speed with 'quality factor' values that indicates the accuracy of the SW speed measurement. This is related to the cross-correlation algorithm that the company software uses to track the propagation of SWs through the tissue. The mean SW speed is calculated from SW speed