Application of Shear Wave Elastography for the Gastrocnemius Medial Head to Tenis Leg

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ABSTRACT

Introduction: Muscle strain of the gastrocnemius medial head mainly occurs at the musculotendinous junction (MTJ), and stiffness is a risk factor. Shear wave elastography (SWE) measures the elasticity by determining the propagation velocity. This study aimed to measure the elasticity of the normal muscle and aponeurosis in MTJ of the gastrocnemius medial head using SWE, thus obtaining important information regarding the gastrocnemius medial head.

Materials and Methods: Forty-one volunteers (82 legs) were recruited, and the gastrocnemius medial heads were examined at the following four points; three points on the aponeurosis, namely at the center of MTJ (*Central*), 10-mm proximal (*Proximal*) and 10-mm distal (*Distal*) to MTJ, and at one point on the muscle belly (*Muscle*). Measurement values were compared among the points, between males and females, and between younger and middle-aged subjects. Correlations between the elastic modulus and age were also examined.

Results: The elastic moduli in *Proximal*, *Central*, *Distal*, and *Muscle* were 2.82 ± 0.53 m/s, 3.43 ± 0.83 m/s, 4.83 ± 1.56 m/s, and 2.25 ± 0.43 m/s, respectively. The elastic moduli significantly differed between the points of aponeurosis, with *Distal* having the highest modulus followed by *Central*. Elastic moduli were significantly greater in males than in females in *Distal* and *Muscle* and in younger subjects than in middle-aged subjects in *Muscle*. No significant correlations between the elastic modulus and age were observed for any point.

Conclusions: SWE could be a feasible method for quantifying the elasticity of muscle and aponeurosis in MTJ of the gastrocnemius medial head.

Key words: shear wave elastography; gastrocnemius muscle; musculotendinous junction; muscle; tendon; ultrasound; anatomy

INTRODUCTION

Muscle strain of the gastrocnemius medial head is a common diagnosis and was first reported as "tennis leg" by Powell (Powell, 1883). This condition mainly occurs at the musculotendinous junction (MTJ) in the gastrocnemius medial head middle-aged patients during sports activities (Bianchi et al., 1998; Bryan Dixon, 2009; Delgado et al., 2002; Flecca et al., 2007; Koulouris et al., 2007; Miller, 1977) and is characterized by a muscle tear and rupture of the aponeuroses or intramuscular tendons (Pollock et al., 2014). Muscle strain has a high recurrence rate of 13%–23% (Carling et al., 2011; Ekstrand et al., 2011; Hawkins and Fuller, 1999; Hawkins et al., 2001). The possible risk factors for recurrence include a history of injury, premature return to sports activity, inadequate rehabilitation, and incomplete recovery (Arnason et al., 2004; Engebretsen et al., 2008). Local stiffness at the site of previous injury is also a factor that leads to recurrent injury (Hagglund et al., 2013). The stiffness is caused by a scar tissue that is produced after a muscle strain; this has a different elasticity from normal tissue, and thus, increases the risk of injury recurrence (Blankenbaker and Tuite, 2010; Cheng et al., 2012; Hayashi et al., 2012). Although stiffness is commonly subjectively evaluated by palpation, there is no method to objectively assess stiffness.

Ultrasound elastography is a device that can evaluate tissue stiffness as its elastic modulus. Shear wave elastography (SWE) measures the propagation speed of a shear wave in the tissue (Yamakoshi et al., 1990). Because elastic modulus is proportional to the square of the propagation speed, the elasticity can be calculated by measuring the propagation velocity. Shear waves propagate along the muscle fiber longitudinally rather than perpendicularly, and transducers that are oriented parallel to the muscle fiber obtain the most reliable measurement of muscle elasticity (Gennisson et al., 2003; Gennisson et al., 2010). Furthermore, the elastic modulus measured by SWE correlates with tissue elasticity when the transducer is placed parallel to the muscle fiber orientation (Eby et al., 2013). Using this method, the transducer orientation of the supraspinatus muscle fibers, which are pennate, was determined and the supraspinatus muscle elasticity was feasibly measured using SWE (Itoigawa et al., 2015). As indicated by these previous studies, it is essential to position the transducer along the fiber direction of the skeletal muscle on the ultrasound image, and the muscle elasticity can then be measured using SWE.

Based on this background, we hypothesized that an SWE image can be used to quantify the muscle elasticity and aponeurosis in MTJ in the gastrocnemius medial head, thus providing information regarding the key characteristics of a normal gastrocnemius. First, we determined the orientation of the normal gastrocnemius medial head in cadavers to optimize the ultrasound probe positions for SWE imaging. Second, we investigated the elasticity of normal MTJ of the gastrocnemius medial head in vivo. Finally, we compared the differences in elasticity between male and female subjects and between younger and middle-aged subjects.

MATERIALS AND METHODS

Gross anatomy

Six lower legs in three embalmed cadavers were used to observe the detailed orientation of the muscles. The skins and subcutaneous tissues were removed, except for the gastrocnemius medial head. The gastrocnemius medial head were observed from a superior view (dorsal side) and then cut from the posterior side of the medial femoral condyle to the calcaneus (at approximately the longitudinal center of the gastrocnemius medial head) to observe the muscle fibers in a cross-section in the craniocaudal direction.

Participants

Forty-one subjects (82 legs) were initially recruited to this study. However, 16 legs were excluded because of a history of calf muscle strain or Achilles tendon rupture; finally, 66 legs were investigated, of which 30 were of young subjects aged <30 years and 36 were of middle-aged subjects aged ≥30 years. The mean age of the subjects was 31.7 years (range, 18–48 years); 44 legs were from males and 22 were from females. This study was approved by our institutional review board, and informed written consent was obtained from each participant.

Material properties using SWE

An ACUSON S3000 Ultrasound System (Siemens, USA) with a linear array transducer at 4–9-MHz frequency was used. The depth was set to 3 cm, the range of interest (ROI) size to 1 × 1 mm, and the maximum velocity to 10 m/s. When emitting a push pulse at any region, a colored elastogram image was obtained over the B-mode imaging. The color distribution on the elasticity map represented the elasticity of the tissue: blue represented soft tissue and red represented hard tissue. ROI was selected on the elastogram image, and the elastic modulus of that ROI was measured.

Measurement protocol

Each subject was examined in the prone position in a relaxed state. The joint angles were set to approximately 15° in the knee flexion and 15° in the ankle plantar flexion by placing the subject's feet on a pillow. Based on our anatomical findings, the probe was placed on MTJ of the gastrocnemius medial head parallel to the muscle fibers and perpendicular to the skin. The elastic moduli were evaluated using SWE at three points on the aponeurosis and one point on the muscle. The points on the aponeurosis were at MTJ of the gastrocnemius medial head (*Central*), at 10-mm proximal (*Proximal*) and 10-mm distal (*Distal*) to MTJ along the aponeurosis. The elastic modulus was also measured at 10-mm proximal from MTJ in the muscle belly of the gastrocnemius medial head (*Muscle*).

The measurement values were compared among the three points on the aponeurosis, between males and females, and between younger subjects aged <30 years and middle-aged subjects aged ≥30 years. Correlations between the elastic modulus and age were examined for each point of the aponeurosis and muscle.

Statistical analysis

Repeated-measures analysis of variance (ANOVA) followed by Tukey post hoc tests were used to investigate the differences among the points on the aponeurosis. Unpaired *t*-tests were used to investigate the differences between the sexes and subject ages. Correlation coefficients were calculated between the elastic modulus and age for both males and females. Results were considered significant when the P value was <0.05. Statistical analyses were performed using the GraphPad Prism version 6.0 (GraphPad Software, San Diego, CA).

RESULTS

Gross anatomy

The gastrocnemius medial head originated on the posterior side of the medial femoral condyle and ran distally and slight laterally. It transferred from muscle fibers to the aponeuroses at the center of the gastrocnemius medial head on MTJ. The aponeuroses of the gastrocnemius gradually merged with those of the soleus a few centimeters distal from MTJ, shifted to the Achilles tendon, and attached to the calcaneal tuberosity (**Fig. 1A**). The sagittal cross-section of the muscle on MTJ formed an "inequality sign shape" with the aponeuroses and the distal end of the muscle fibers at the center of the gastrocnemius medial head (**Fig. 1B Red dotted lines**). Both muscle and aponeurosis mostly ran parallel to the skin. It was considered that this triangle could be used as a landmark for probe orientation to reveal the direction parallel to the muscle fiber and aponeurosis on the ultrasound image.

Material properties of the aponeurosis and muscle using SWE

Based on the anatomical findings, the probe was placed on MTJ of the gastrocnemius medial head to descript the "inequality sign shape" formed by the aponeuroses and the muscle fibers (**Fig. 2A Red dotted lines**) and adjusted until the maximal fiber length was displayed to achieve proper probe alignment based on a previous reported method for SWE (Itoigawa et al., 2015) (**Fig. 2A**). This image enabled the measurement of the elastic moduli (derived from the shear wave propagation speed) in all subjects (**Fig. 2B**). The elastic moduli (mean ± standard deviation) were 2.82 ± 0.53 m/s in *Proximal*, 3.43 ± 0.83 m/s in *Central*, 4.83 ± 1.56 m/s in *Distal*, and 2.25 ± 0.43 m/s in *Muscle*. The elastic moduli of each group (in the order *Proximal*, *Central*, *Distal*, and *Muscle*) were as follows: males, 2.79 ± 0.52 m/s, 3.51 ± 0.93 m/s, 5.15 ± 1.58 m/s, and 2.29 ± 0.46 m/s; females, 2.87 ± 0.55 m/s, 3.28 ± 0.55 m/s, 4.19 ± 1.08 m/s, and 2.15 ± 0.36 m/s; aged <30 years, 2.88 ± 0.60 m/s, 3.44 ± 0.83 m/s, 4.72 ± 1.51 m/s, and 2.36 ± 0.51 m/s; aged ≥30 years, 2.76 ± 0.46 m/s, 3.42 ± 0.83 m/s, 4.93 ± 1.49 m/s, and 2.15 ± 0.32

m/s. The elastic modulus of *Distal* was significantly greater than that of the other two points on the aponeuroses, and the elastic modulus of *Central* was significantly greater than that of *Proximal* ($p < 0.001$) (**Fig. 3A**). The elastic moduli of *Distal* ($p < 0.001$) and *Muscle* ($p < 0.032$) were significantly greater in males than in females. The elastic modulus of *Muscle* was significantly greater in younger subjects than in middle-aged subjects ($p < 0.001$, **Figs. 3B, C**).

Correlations between the elastic modulus and age (in the order *Proximal*, *Central*, *Distal*, and *Muscle*) were as follows: men, R^2 = 0.073, 0.009, 0.000, and 0.173 and women, R^2 = 0.003, 0.079, 0.221, and 0.018 (**Fig. 4**). No remarkable correlations were observed for any point.

DISCUSSION

This study demonstrated that the elastic moduli of the muscle and aponeurosis in MTJ of the gastrocnemius medial head could be measured using SWE. DeWall et al. examined the shear wave elastic modulus of the triceps surae from the Achilles tendon to the gastrocnemius.(DeWall et al., 2014) and reported that the elasticity was greater in the distal portion than in the proximal portion. However, they did not clarify where the elastic modulus had changed. We focused on MTJ of the gastrocnemius, which is a site prone to muscle strain (Bianchi et al., 1998; Bryan Dixon, 2009; Delgado et al., 2002; Flecca et al., 2007; Koulouris et al., 2007; Miller, 1977), and found that the elasticity significantly varied in the area of only a few centimeters of MTJ. The change in the elasticity in the junction between the muscle and aponeurosis may be associated with a risk of muscle strain.

Moreover, the present study established a method for measuring the elasticity in MTJ of the gastrocnemius medial head. We conducted this study in healthy subjects as a preliminary experiment. As a next step, it should be applied to patients with muscle strains. If SWE can detect the level of stiffness after the muscle strain, it can be potentially used to objectively predict the appropriate time to return to sports activities, thus prevent recurrent injury. In this study, the elasticity of the male aponeurosis was significantly greater than that of the female aponeurosis in the *Distal* and *Muscle* points. Males have greater musculotendinous stiffness compared with females, which was measured by calculating the stiffness from the muscle torque and displacement (Blackburn et al., 2006; Kubo et al., 2003). Our results were consistent with these studies. Bell et al. revealed that estrogen was negatively correlated with musculotendinous stiffness.(Bell et al., 2012) Thus, female hormones may be a factor affecting stiffness.

Some previous studies investigated the relationship between age and muscle stiffness (Domire, 2009; Eby et al., 2015). Domire et al. measured the elasticity of human tibialis anterior muscle in subjects with an age range of 50–70 years using magnetic resonance elastography and found that there was a significant relationship between age and tissue stiffness.(Domire, 2009) Eby et al. examined the elasticity of human biceps brachii muscles using SWE and found that the elasticity gradually increased in older subjects (>60 years).(Eby et al., 2015) In the present study, no significant correlations were observed between the elastic modulus and age up to 40 years. Considering these results, the muscle may become stiffer in subjects aged between 40 and 50 years.

This study had some limitations. Measurements were conducted by one examiner, and the reliability was not examined. However, Hatta et al. evaluated the reliability of SWE measurements for the elasticity of the supraspinatus muscle using intraclass correlation coefficient and obtained excellent results.(Hatta et al., 2015) We used a similar measurement method, although this was applied to a different muscle. Another limitation was that the number of female subjects was lower than that of males. However, according to the power analysis, a sample comprising 39 males and 19 females had >80% power to detect an effective size of two standard deviations, and this was sufficient. Next, we examined only healthy subjects. Although this study was conducted as a preliminary study for measuring the stiffness in patients with a muscle strain, further investigations are required to determine the application for patients with a muscle strain.

CONCLUSIONS

This study demonstrated that SWE was able to measure the elasticity of the muscle and aponeurosis in MTJ of the gastrocnemius medial head. Moreover, the elastic modulus of the gastrocnemius aponeurosis increased in its distal point and the elasticity of female gastrocnemius aponeurosis and muscle was significantly lower than that of male gastrocnemius aponeurosis and muscle.

CONFLICT OF INTEREST

The authors have no conflict of interest relationships to report.

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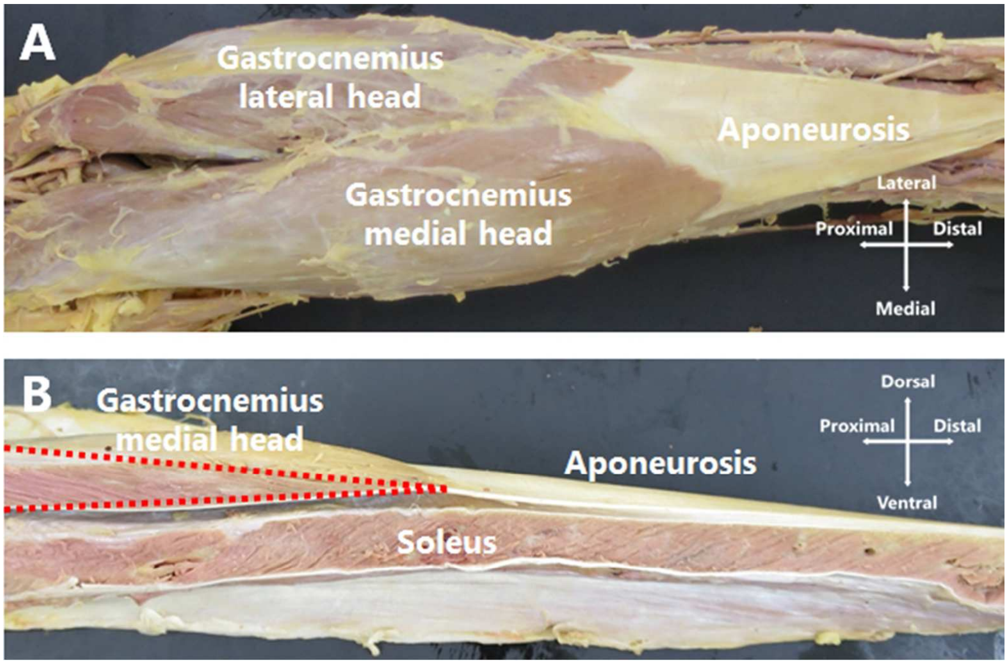

Figure 1. Gross anatomy of the gastrocnemius medial head. (A) Posterior view of the right lower leg. (B) Sagittal cross-section cut from the posterior side of the medial femoral condyle to the calcaneus. "inequality sign shape" (Red dotted lines) with the aponeuroses and the distal end of the muscle fibers is formed at the center of the gastrocnemius medial head.

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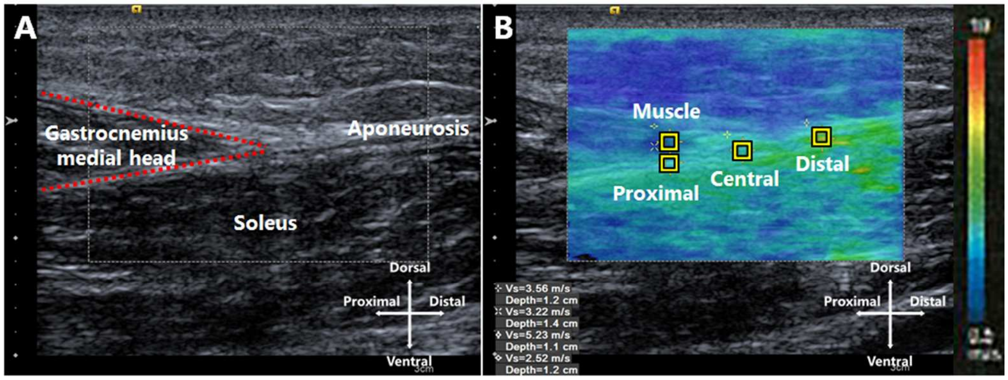

Figure 2. Ultrasound imaging of the musculotendinous junction (MTJ) of the gastrocnemius medial head. (A) The B-mode image. The probe was placed on MTJ to descript the "inequality sign shape" (Red dotted lines) formed by the aponeuroses and the muscle fibers and adjusted until the maximal fiber length was displayed to achieve proper probe alignment. (B) The B-mode image with overlaid elastogram.

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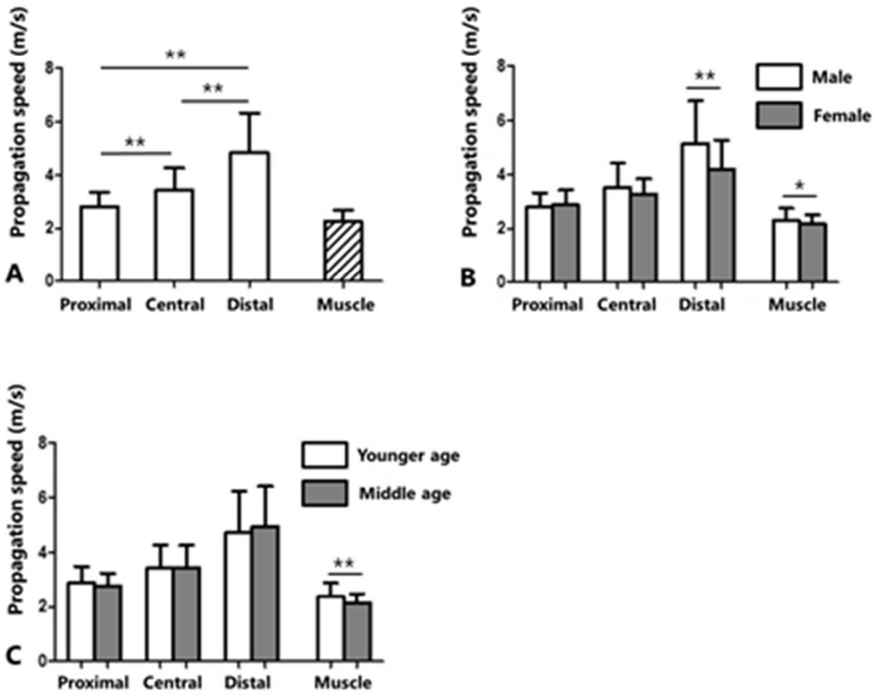

Figure 3. The elastic modulus (propagation speed) of three parts of the aponeurosis and muscle (*p < 0.05, **p < 0.01). (A) The differences between the parts of the aponeurosis and the muscle. (B) Differences between the males and females. (C) Differences between younger and middle-aged subjects.

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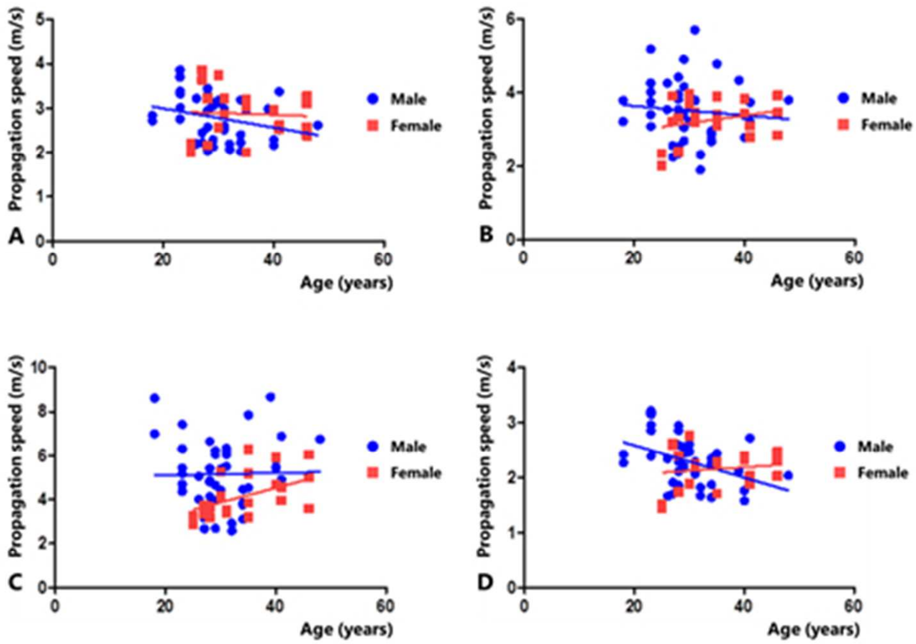

Figure 4. Correlations between the elastic modulus (propagation speed) and age. (A) Proximal. (B) Central. (C) Distal. (D) Muscle.

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