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Reliability and quantification of gastrocnemius elasticity at relaxing and at submaximal contracted condition

Minsoo Jeon, Kyojun Youn, Shinseung Yang

Department of Rehabilitation Medicine, Chungnam National University Hospital, Jung-gu, Daejeon, Republic of Korea

Abstract

Aims: To investigate the feasibility of quantitative analysis of muscle stiffness by Acoustic Radiation Force Impulse (ARFI) imaging, to obtain the reference values at relaxing and contraction position of gastrocnemius medialis (GCM) and to evaluate the inter-observer and intra-observer reliabilities of shear wave velocities measurements in healthy skeletal muscles. **Material and methods:** The stiffness of the left GCM muscle of 15 healthy volunteers was measured by ARFI elastography in transverse scan while the ankle was in the relaxed position and in 30 degrees of plantar flexion with the submaximal isometric contraction. All subjects were examined by two experienced physiatrists with four years of experience. Reliability of ARFI measurements was assessed by means of the intraclass correlation coefficient (ICC). Interobserver and intra-observer reliabilities were statistically analyzed. **Results:** The mean shear wave velocity (SWV) of GCM at plantar flexion position with submaximal isometric contraction was significantly higher than that at relaxed position (first physiatrists: plantar flexion with submaximal isometric contraction 2.41±1.09 m/s, relaxed 0.84±0.28 m/s, second physiatrist: plantar flexion with submaximal isometric contraction 2.49±0.94m/s, relaxed 0.83±0.21), $p<0.05$. The inter-observer reliability was excellent for ankle-plantar flexion with submaximal isometric contraction (ICC=0.968), and good for relaxed position (ICC=0.891) respectively. The intra-observer reliability for ankle-plantar flexion with submaximal isometric contraction were excellent (ICC: first physiatrist 0.98 and second physiatrist 0.96) and that for relaxed position (ICC: first physiatrist 0.98 and second physiatrist 0.90) were also excellent. There was no significant correlation between SWV and body mass index. **Conclusions:** ARFI elastography is a reliable imaging modality for quantifying the stiffness of contracting muscles. Additionally, the characterization of pathological soft tissues by ARFI elastography would be a promising clinical practice for patients with musculoskeletal issues.

Keywords: Acoustic Radiation Force Impulse imaging; elastography; muscle stiffness; ultrasonography

Introduction

Upper motor neuron diseases such as cerebral palsy, stroke, and spinal cord injury are characterized by an exaggeration of the stretch reflex, spasms and resistance to passive movement across a joint. Various muscular diseases also progress to cellular histological degeneration resulted in the change of muscle elasticity. Assessment of muscle stiffness is important in terms of disease status evaluation and treatment planning. The characteristics of passive stretching response of individual muscles can be used for the evaluation of musculoskeletal dysfunction. Sonoelastography is one of the indirect clinical methods used widely. Subtle changes of mechanical properties causing stiffness originating from external damage or intrinsic degeneration could be detected.

Acoustic radiation force impulse (ARFI) imaging was developed to provide information about the local mechanical properties of tissue [1]. Such dynamic sonoelastography measured the propagation velocity of mechanical vibrations (i.e. shear waves) with imaging analyses to calculate the local Young modulus of soft tissues, where faster velocity indicates a greater Young modulus. Ultrasound elastography has been found useful in the differential diagnosis of cancer in liver, breast, kidney, spleen, prostate, pancreas, testes or thyroid [2-9].

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Corresponding author: Shinseung Yang. M.D.
Chungnam National University Hospital
266 Munwha-ro, Jung-gu, Daejeon, 35015
Phone: +82-42-338-2421, Fax: +82-42-338-2461
E-mail: ssyang74@cnuh.co.kr

In recent years, use of dynamic sonoelastography in the musculoskeletal area has been increased in research of muscle physiology [10-13] and in clinical conditions causing stiffness of muscles [14,15]. Elastography applications were developed to improve the diagnostic capability of traditional imaging techniques such as magnetic resonance imaging (MRI) and ultrasound by delineating the differential stiffness of healthy and unhealthy tissue [16].

In general, all methods measuring the viscoelastic property of tissue in ultrasonography included the measurements of deformation in response to given force or stress. Several techniques were used for assessing the musculoskeletal system: strain elastography (SE) [17], shear-wave elastography (SWE) [18], transient ultrasound elastography (TE) [19] and ARFI imaging [20-23].

Several studies to prove validity of dynamic elastography in muscles or tendon pathology in vitro [23-24] have been published and several studies were executed to quantify inter-operator and intra-operator reliability for technique of SWE using Supersonic Shear Imaging module (SSI) [13,25,26]. However, a limited number of studies regarding the reproducibility of the ARFI imaging technique in the skeletal muscle have been reported in the literature.

In this study we aimed to measure the quantitative stiffness of muscles by the ARFI imaging technique during active skeletal muscle contraction and to determine the reference values in the relaxing and submaximal contracted position. Also, we evaluated the intra- and inter-operator reliability in measuring the shear wave velocity (SWV) in both positions.

Material and methods

Subjects

Fifteen healthy subjects (4 female, 11 male) were enrolled in this study. All patients were informed about study procedures and provided written informed consent. The descriptive properties of the fifteen attendees, including their age, gender, heights, weights, body mass indexes (BMI) and the side of functional dominancy were recorded. The study was conducted within the ethical standards of the Declaration of Helsinki and was approved by the Ethics Committee the Institutional Review Board of the hospital (No. 2017-01-011-004).

Method

ARFI imaging was obtained with a high-end ultrasound machine (Siemens ACUSON S2000™, Siemens Healthcare, Erlangen, Germany) with a linear 9L4 transducer of 8MHz.

The examiner marked the reference point at the proximal one-third of the vertical line connecting femoral intercondylar midpoint and tibiofibular intermalleolar midpoint. From this point, the probe was moved medially to the highest midpoint of the left GCM. Transverse scan of medial GCM was performed with a minimal compression applied with the transducer weight at that marked site. The region of interest (ROI) of ARFI imaging in a square shape of 0.5 cm^2 was captured at depth of 2 cm from the surface during real-time B-mode imaging. The SWV was expressed as a meter per second (m/s) (fig 1).

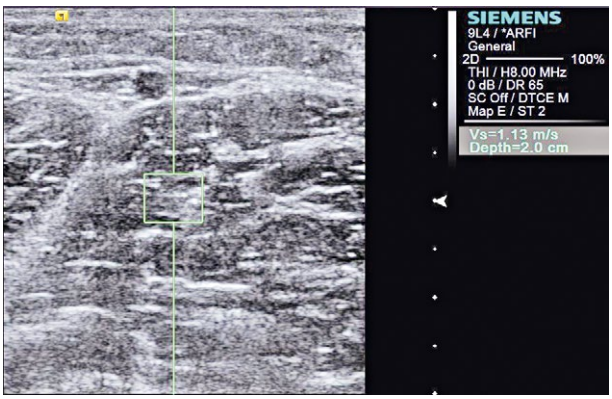


Fig 1. Typical example of shear wave velocity (SWV) measurement in the region of interest

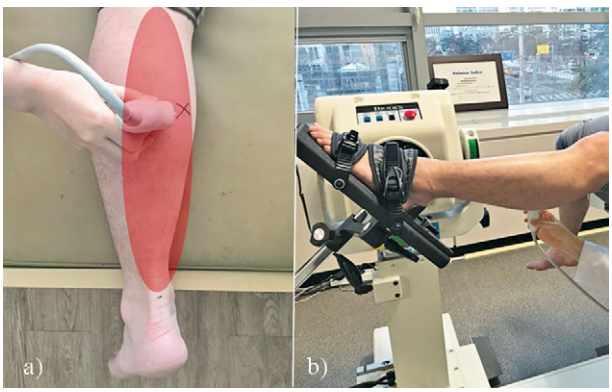


Fig 2. Measurement of medial gastrocnemius (GCM) with relaxed (a) and isometric contraction at the intensity of 80% of maximal voluntary contraction under visual feedback (b)

To assess the difference of SWV according to the muscle contraction, all subjects were scanned in two different positions. First, they lay in the prone position with feet hanging over the edge of the table, while the left ankle was in a relaxed position without any muscle contraction (fig 2a). Secondly, the subjects were seated on the special equipment with 90° flexion of hip, full extension of knee, and 30° plantar flexion of ankle. Left thigh was supported by an adjustable pad and secured with a Velcro strap to use isokinetic dynamometer (Biodex 4 medical, Shirley, NY, USA) (fig 2b). The subjects were required to perform isometric maximum voluntary contraction (MVC) of

GCM in that position and the maximum torque output was measured through three trials. ARFI images were captured at the specific marked point of GCM while the subject executed the isometric contraction at 80% intensity of MVC under visual feedback. Subjects were given a two-minute break between each trial of isometric contraction. SWV was measured three times at both different positions.

To assess the reliability of the ARFI imaging technique and to evaluate the inter-operator consistency, all subjects were examined by two physiatrists with four years of experience in elastography on the same day. Each physiatrist performed the acquisition of ARFI imaging in both positions and was blinded to the data of the other operator. After one week, a second measurement blinded to the first finding was performed to assess the intra-operator reliability.

Statistical analysis

All data were presented as means±standard deviation (SD). Mann-Whitney U test was used for comparison of mean SWV with ARFI imaging between the different ankle positions. Differences were considered statistically significant if p value is lower than .05. To know the inter-rater and intra-rater reliability, we used the intra-class correlation coefficient (ICC) and 95% confidence interval of the reliability analysis. All statistical tests were conducted by using the SPSS ver. 18.0 (SPSS Inc., Chicago, IL, USA).

Results

The demographic data of the participants are detailed in Table I.

SWV of ARFI imaging

The mean SWV of ARFI imaging of gastrocnemius measured by the first physiatrist at relaxed and at 80% intensity of maximal isometric contraction, were 0.84±0.28 m/sec and 2.41±1.09 m/sec, respectively. The values of SWVs measured by the second physiatrist at the same positions were 0.83±0.21 m/sec, 2.49±0.94 m/sec, respectively. The SWV during isometric contraction was significantly higher than that at the relaxed position (first physiatrist : Mann-Whitney U=1,925, p=0.000, second physiatrist : Mann-Whitney U=1,977, p=0.000) (fig 3)

The inter-operator reliability for measuring SWV of ARFI imaging was excellent for the contracted muscles and good for the relaxed muscles (Table II). The intra-operator reliability was excellent for both contracted and relaxing muscle (Table III).

Body mass index and SWV

The mean BMI was 23.28±2.23. Correlation between muscle elasticity and BMI did not demonstrate any significance at both relaxed (Pearson correlation coefficient =0.09, p=0.749) and submaximal isometric contracted state and in submaximal contraction (Pearson correlation coefficient =0.25, p=0.368), irrespective of gender (all p>0.005).

Table I. Demographic data of the volunteers

	Men (n=11)	Women (n=4)
Age (years)	31±1.49	31
Height (cm)	175.82±4.3	161.25±3.5
Body weight (kg)	75.23±5.44	53±3.56
BMI (kg/m²)	24.16±1.30	20.41±1.62

Values are presented as mean±standard deviation. BMI: Body mass index

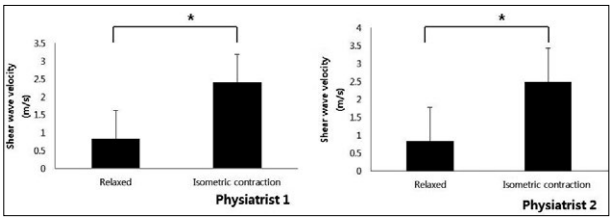


Fig 3. Shear wave velocity(SWV) values of gastrocnemius at relaxed position and at 80% maximal voluntary isometric contraction under visual feedback
*p<0.05 in Mann-Whitney U test

Table II. Inter-observer reliability of Shear Wave velocity with Acoustic Radiation Force Impulse imaging

	Cronbach`s alpha	Consistency
Relaxed position	0.891	Good
Isometric contraction	0.968	Excellent

Table III. Intra-observer reliability of Shear Wave velocity with Acoustic Radiation Force Impulse imaging

	Position	Cronbach`s alpha	Consistency
First Physiatrist	Relaxed position	0.976	Excellent
	Isometric contraction	0.979	Excellent
Second Physiatrist	Relaxed position	0.897	Good
	Isometric contraction	0.958	Excellent

Discussions

The aims of the present study were to obtain the reference values of SWV of GCM in a relaxed and submaximal contracted condition and to evaluate the inter-operator reproducibility and intra-operator repeatability of the SWV using the ARFI imaging technique in healthy people.

In our study, the mean SWV of relaxed medial GCM of two physiatrists were 0.84±0.28 m/sec, 0.83±0.21 m/sec respectively. Cortez et al using Supersonic Shear Imaging module (SSI) obtained SWV values in the GCM ranged from 1.89±0.32 to 2.38±0.58 m/s in the longitudinal plane, and from 1.54±0.22 to 1.94±0.29 m/s in the transverse plane [26]. In the study of Alfuraih et al, the SWV values of the rectus femoris ranged from 2.19 to 2.64 m/s in transverse view [27]. The reference values of elasticity were different although all studies were conducted in a relaxed position. These results may originate from the different equipment for measuring SWV and from the probe direction for capturing the image.

Due to the distinct anisotropic elasticity of muscle fibers, the reference value of elasticity could be changed according to the scanning direction. The slightly different reference values of SWV and reproducibility according to the scanning angle of the probe along the muscle fiber axis have been demonstrated in other studies [11,27]. For the convenience of the measurement during isometric muscle contraction, we measured the elasticity of muscle along the transverse plane. It was mentioned in other studies that it was more reliable to acquire data along the longitudinal plane than along the transverse plane but inter- and intra-rator reliability of transverse plane scanning was also significantly high in Alfuraih et al's study [26, 27].

The method measuring SWV of our study was also highly reliable at both relaxed and at submaximal contacted conditions. So, the data from this study could be clinical reference values in relaxing and at submaximal contracted condition and could be used to screen the pathological change of muscles or to evidence the muscle performance after strengthening or stretching muscles.

Kuo et al conducted a study to standardize the neck muscle stiffness in healthy individuals and to document a normal range of stiffness values with ARFI technique [28]. Also, Badea et al evaluated and documented the stiffness of masseter muscle in both healthy subjects and in those who had undergone neck radiation therapy [22]. In the future, more research is required to define the reference values of elasticity of clinically important muscles.

There were prior studies about the reproducibility of ultrasound SWV in skeletal muscle with various elastography techniques [11,25-27]. The authors reported a good intra-operator and inter-operator reproducibility in healthy relaxed muscles. Our results demonstrated that inter-operator reproducibility and intra-operator repeatability of the ARFI imaging technique were excellent in not only a relaxed condition but also in an active muscle contraction condition.

We found no significant correlation between the physiological parameters such as BMI and SWV at both relaxed or submaximal isometric contracted muscles. Interestingly, Berko et al demonstrated that the elasticity of the biceps brachii muscle was negatively correlated with BMI after exercise but not at a resting state whereas the elasticity of rectus femoris muscle was positively corelated with BMI only at rest state [28]. Kuo et al showed that trapezius muscle stiffness correlated with BMI significantly [29] in chronic neck pain. The authors opinion is that subjects with higher BMI combined with thicker muscle likely had stiffer muscles.

Yavuz et al evaluated the feasibility of ARFI to assess the stiffness of the bicep brachii muscle at different levels of isometric contraction [30] and Akkoc et al investigated the relationship between elastography and athletic performance but reported that no significant correlation was observed between muscle stiffness and maximum oxygen uptake (VO2max) or vertical jump [31]. Our results were similar to this previous study, reporting that SWV was positively correlated to the muscle contraction. Our opinion is that elastography may have a chance to be used as a tool to evaluate the muscle performance after strengthening or muscular training.

Nowadays various ultrasound elastography techniques are available and each equipment has advantages and limitations. Techniques of elastography are divided into quasi-static and dynamic elastography based on type of force applied. Strain elastography (SE) are corresponding to quasi-static methods and dynamic elastography includes ARFI imaging, Transient Elastography (TE) and Supersonic Shear wave Imaging (SSI). Strain elastography (SE) was the first developed and widely used technique which compared two separate areas in the same elastogram. The main limitations of SE are the problem of reproducibility caused from the control of the stress applied which remains operator-dependent, and the absence of a specific quantification [32].

Dynamic elastography which relies on shear waves propagation can produce higher resolution Young modulus map compared to SE. Among dynamic elastography, TE has been extended from one-dimensional measurement technique to two-dimensional imaging technique to allow the creation of elasticity maps by external mechanical vibrations. TE requires provides only a relative measure of stiffness (soft vs hard) whereas SSI provides an absolute measure of the shear modulus from just the tissue displacements. It has limitations at measuring the elasticity of deep organ in obese patients because transient impulse is not able to penetrate deeply enough. Supersonic Shear wave Imaging (SSI) was developed from the technology of 2D transient elastography but substituted the vibrator by the acoustic radiation pressure combining ultrasound ultrafast imaging. It produces more re-

liable and repeatable quantitative data with considerably less operator dependence. This equipment only allows a maximum shear wave velocity of 8.4 m/sec thus limiting its biomechanical application in the situation like strong muscular contraction causing too fast SWV to detect. In ARFI, a single ultrasound transducer generates an acoustic radiation force within the tissue to make shear wave and to measure quantitative tissue stiffness. ARFI measurements could be more reliable because tissue displacement is caused by fixed ultrasound waves, rather than by tissue compression by the sonographer. But the region of interest (ROI) in ARFI imaging is very small when compared to SSI [32,33]. Although the ARFI technique was known to have less operator dependency, compression from the transducer could affect SWV in the ARFI imaging. For minimizing this variant, the measurement must be performed with minimum compression from the ultrasound transducer with visual B-mode guidance in the same position.

If limited range of motion (LOM) of joint has occurred in certain clinical condition such as muscular dystrophy, collagen disorders, cerebral palsy, prolonged bed rest and chronic compartment syndrome, clinicians have some difficulties to differentiate the origin of LOM by conventional physical examinations. Conventional physical examination comprises gross measurement of the entire joint, muscle, tendon, or neurovascular complex. Measuring the viscoelastic properties of muscle or tendon itself using ultrasonic elastography might be helpful to differentiate the cause of LOM. Viscoelastic properties also provide a link to the histopathologic changes of muscle. Muscles of lower extremity such as gastrocnemius and hamstring of spastic patients become hard and stiff as histological changes occur over time [34]. The present study implies that the ARFI technique could be used to measure the change in muscle elasticity in vivo accompanying the histologic change. The clinician might detect sensitively the changes of muscle properties during rehabilitation through real-time and serial measurements of SWV with ARFI.

There are several limitations of this study. First, the number of attendees enrolled was small and only one muscle was selected in this study, so further studies are necessary to confirm our findings and improve the validity and reliability of this technique for other soft tissue such as other muscles or tendon. Secondly, we could not measure the serial change of muscles elasticity according to the gradually leveled isometric contraction. Thirdly, we only evaluated healthy subjects. Fourth, there may be unintentional movements of foot or/and knee joints during isometric muscle when a strong force is repeatedly applied to the footplate at the end of ankle plantarflexion.

Future studies are required to evaluate the clinical references of elastography of individual muscles and to correlate SWV with the clinical finding such as spasticity, range of motion and muscle power in patients with neurological or muscular lesions

Conclusions

Dynamic elastography with ARFI technique could be used to acquire reliable, real-time, non-invasive, quantitative data of muscle elasticity in vivo and to execute the clinical screening of pathological stiffness of muscles in patients with neurological and/or muscular diseases.

Conflict of interest: none

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