Reliability of Shear Wave Elastography for the Assessment of Gastrocnemius Fascia Elasticity in Healthy Individual

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Abstract

The mechanical properties of deep fascia (i.e. an index of stiffness) strongly affect the development of muscle pathologies, and muscular actions, such as compartment syndromes. Actually, a clear understanding of the mechanical characterization of muscle deep fascia still lacks. The present study focuses on examining the reliability of ultrasonic shear wave elastography device (USWE) in quantifying the shear modulus of gastrocnemius fascia in healthy individual and the device's abilities to examine the shear modulus of gastrocnemius deep fascia during ankle dorsiflexion. Twenty-one healthy males participated in the study (age: 21.48±1.17 years). The shear modulus of the medial gastrocnemius fascia (MGF) and lateral gastrocnemius fascia (LGF) were quantified at different angles using USWE during passive lengthening. The operators took turns to measure each subject's MGF and LGF over 1-hour period and by operator B with a 2-hour interval. In the intra-operator test, the same subjects participated at the same time 5 days later. The intra-rater [Intra-class correlation coefficient (ICC) = 0.846-0.965)] and inter-rater (ICC = 0.877-0.961) reliabilities for measuring the shear modulus of the MGF and LGF were rated as both excellent, and the standard error in measurement (SEM) was 3.49 kPa, the minimal detectable change (MDC) was 9.68 kPa. Regardless of the ankle angle, the shear modulus of the LGF were significant greater than that of the MGF ($p < 0.001$). The significant increase in the shear modulus both of the MGF and LGF were observed at neutral position compared to the relaxed position. This results indicate that the USWE is a technique to assess the shear modulus of gastrocnemius fascia and detect its dynamic changes during ankle dorsiflexion. USWE can be used for biomechanical study and intervention experiments of deep fascia.

Introduction

Gastrocnemius deep fascia (GDF), as a support band or separate boundary, is mainly responsible for maintaining the general shape of the muscle to build up support and prevent adhesion between muscles [1]. Its main function is to provide and transmit force for connective tissue, thereby regulating human posture and movement [2]. Previous study have showed that the repeated stress transmitted to the muscle deep fascia during relaxation and activation of the extremity muscles (eg. jumping, running). The deep fascia may remodel to accommodate the stresses produced, such as reduce the inherent stiffness [3]. Anatomical studies demonstrate that GDF is composed of three layers of connective tissue with different orientation and densities [4–5]. It connects to the underlying muscles [5]. These not only strengthen the ability of fascial tissues to bear strain (including the force produced by intra- and inter-muscle contraction) in all directions, but also transmit the forces to adjacent tendons or muscles in an effective way [6]. From the point of biomechanics, deep fascia play an important role in movement restriction and proprioception. In addition, this restriction has been observed in fascia connection models and cadaveric models, such as between deep fascia of the medial gastrocnemius and the pelvis[7–8]. This also means that when fascia tissue is stretched in one part, it may cause restriction, tension or pain in another parts of the body [9]. Previous studies have shown muscle fascia is an uninterrupted viscoelastic membranous tissue which can modify muscles elasticity. The less of fascial tissue stiffness in the transverse direction not only contribute to maintaining intramuscular pressure, but also allow for underlying muscle's radial expansion [3, 5, 10]. The increase of GDF stiffness is associated with pain or soreness of gastrocnemius (e.g. gastrocnemius myofascial pain), even muscle injuries [1]. The application of soft tissue manipulation can relax the fascia, thereby improving joint flexibility and decreasing pain [11]. However, we found no studies in which the elasticity of GDF had been measured in vivo. Therefore, a detection technique to quantify the shear modulus of GDF in a reliable, quick and objective manner may provide useful information for develop adapted recovery strategies and curative effect of fascia therapy.

The shear modulus of GDF can be assessed with techniques and methods such as palpation, magnetic resonance elastography (MRE) [12–13]. However, palpation, used by clinicians to assess the whole soft tissue stiffness, is a useful and valuable tool, but it only provides qualitative information about the tissue stiffness (soft or hard) and dichotomic (presence or absence). The MRE needs the subject to stay in the designated place for a long time, and restrict their position during measurement. Thus, these methods and techniques can not meet the requirements of dynamic and quantitative monitoring of the shear modulus of GDF performance. Dynamic monitoring the mechanincal properties of fascia is contributed to understanding more information about diagnosis, monitoring disease progression and treatment response [14]. Ultrasonic shear wave elastography (USWE) is an quantitative and effective technique to evaluate the elastic properties of soft tissues, such as muscle, tendon, and fascia [15–18, 19]. USWE can be used to estimate the elastic properties of a local target area through shear wave speed, insight will be gained into how the body responds to various forces and the effects of treatments. The elastic properties of soft tissues have been measured using USWE in various conditions (e.g. at rest, before and after stretching, during and after exercise) [15–18]. Compared with MRE, USWE is more suitable for use in a sports medical and rehabilitation medical setting.

Our previous studies have shown that USWE is a effective and reliable technique for estimate the elastic properties of muscle and tendon, such as gastrocnemius and Achilles tendon, and reflecting the biomechanical properties of muscle and tendon [17]. In addition, USWE was also used to evaluate the passive behavior of plantar flexors during passive dorsiflexion. They found that the shear modulus of inter-muscle is inhomogeneous and displays differences in shear modulus during passive dorsiflexion [20]. However, USWE has not used to quantify the elastic properties measurement of shear modulus of GDF, including the changes in deep fascia shear modulus during passive dorsiflexion. In addition, in order to accurately reflect the situation, progress and therapeutic effect of the disease in clinical test, diagnosis and treatment, subjects usually have to undergo multiple evaluations by two or more testers, such as researchers, different doctors and therapists. Therefore, it is important to estimate the reliability of USWE (intra- and inter-rater). Unfortunately, we are not found of any study examining the reliability of the USWE for the measurement of GDF elasticity. To collect valid and reliable data in both clinical and research contexts, it is necessary to determine the degree of consistency and agreement regarding quantitative USWE measurements.

In summary, the primary objective of this study was to estimate the intra and inter-rater reliability of the USWE in quantifying the shear modulus of GDF at different angles during passive lengthening. The operators took turns to measure each subject’s MGF and LGF over 1-hour period and by operator B with a

2-hour interval. In the intra-operator test, the same subjects participated at the same time 5 days later. As a secondary objective, the change of elastic properties of GDF during various ankle angle was also investigated. We hypothesized that the the shear modulus of GDF increased with ankle dorsiflexion, and regardless of the ankle angle, the shear modulus of the MGF were significant greater than that of the LGF.

Methods

Ethical approval. This study was approved by the Ethics committee of Luoyang Orthopaedic Hospital of Henan Province (No. KY2019-001-01). The present study follows the principles of the Helsinki Declaration. All participants fully informed on the related matters of the study such as purpose, process, and signed a written informed consent.

Subjects. Twenty-one male volunteers (age: 21.48±1.17 years, height: 1.71±0.05 m, weight: 61.25±5.57 kg) without history of lower limbs injury were invited to participate in this study. This study was performed at Luoyang Orthopaedic Hospital of Henan Province, China.

Equipment. The procedures for muscle fascia shear modulus measurement were similar with our previous studies [15-18]. The equipment was an ultrasonic instrument (Aixplorer Supersonic Imagine, version 6.0, Aix-en-Provence, France) with built-in shear wave elastic imaging technology, and a 40-mm linear-array transducer (SL15-4) was used to capture USWE ultrasound image and quantify shear modulus of the medial gastrocnemius fascia (MGF) and lateral gastrocnemius fascia (LGF). Settings of the AixPlorer ultrasonic scanner were set as follows. Maps of the shear modulus were obtained at 12 Hz. The shear wave elastography mode was musculoskeletal mode. USWE Options was in penetration mode. The opacity was 85%. The gain is 90%. The smoothing level was 5. The persistence was off. The shear modulus ranged from 0 to 800 kPa. The B-scan depth was 3.0 cm [15-16]. The Q-box diameter of MGF and LGF were set as 1 mm. The size of ROI had to be set to 10*10mm, and ROI were positioned along the longitudinal section of the MGF and LGF [15,17].

Procedures. Only the dominant leg of participants were studied [15-18], and participants were asked to rest for 10 minutes before testing. In addition, participants were asked to lie down in the prone position on the treatment bed, the feet were fully extended and slightly away from the bed, the knee fully extended, and their upper limbs naturally placed on both sides of the body [15]. The customized and movable knee ankle foot orthosis was used to fix the ankle. The shear modulus of the MGF and LGF was quantified at neutral position and relaxed position of the ankle joint (neutral position (90°) representing the ankle joint was fixed at the neutral anatomical position, relaxed position representing the ankle joint was fully relaxed). The angle of ankle joint was measured by a hand-held goniometer. To ensure the ankle joint angle of subsequent repeated measurements were consistent with the first time, the exact angle of the ankle joint in the relaxed position was recorded after the first positioning. Shear modulus of MGF and LGF were measured around the proximal 30% between the calcaneus and the popliteal fossa medial and lateral, respectively. The length were measured by tape measure [15-18]. The placement direction of the scanner was parallel to the line connecting the calcaneus and the medial or lateral of the popliteal fossa.

To ensure an identical scanner placement in all USWE measurements, the measuring location and direction of the scanner was marked by waterproof marker. For more accurate experimental measurement, participants refrain from high-intensity exercise for 48 hours before testing, and they were asked to keep the body fully relaxed throughout the duration of testing.

All participants received a USWE examination from the experienced physical therapists (P.W.Y and Z.J.P.) with 4 years of experience performing ultrasonography. In addition, the USWE examination was supervised by a sonographer (Z.Z.J) with 13 years of experience. Shear modulus was quantified with AixPlorer ultrasonic scanner positioned on the skin markers at neutral position and relaxed position of the ankle joint. To ensure that the musculotendon restore its original elastic properties and unload the tension on the GDF between angle switching, shear modulus at each joint angle were measured at 5-min intervals [21]. According to our previous studies [22-24], first, enough ultrasound gel was applied in the skin markers. Second, the transducer midpoint was placed in the markers, and active the B-mode to ensure the muscle belly was assessed, and then rotated at orientated longitudinally until the gray-scale image displayed the appearance of the muscle (Fig.1). Third, the mode of USWE was activated, the transducer was kept motionless for more than 8 s and frozen the image until the color in the ROI was uniform and several fibers were continuously visible [15-18]. Three images were captured at each measurement site of muscle fascia. Image quality was closely monitored throughout all measures.

Two operators (PWY and ZJP) took part in the inter-operator investigation. The operators took turns to measure each subject's MGF shear modulus and LGF shear modulus according to the aforementioned program over 1-hour period and by operator ZJP with a 2-hour interval. In the second test, the same subjects participated at the same time 5 days later, which is repeated by operator PWY for the intra-operator investigation. Subjects were asked to maintain their normal activity but avoid high-intensity physical activities, such as long-distance running [25]. The measurement results of each subject were recorded by LYY.

Data analysis. Statistical analysis was performed using SPSS Version 19.0 (SPSS, Chicago, IL). All data were expressed as mean ± standard deviation. Data normality was tested by the Shapiro-Wilk test. The intra- and inter-rater reliability was evaluated by calculating the intraclass correlation coefficient (ICC). The intra-rater (measurements taken on 2 occasions separated by 5 days) and inter-rater (measurements by 2 operators) reliability were examined using ICC (3,1) and ICC (3,2) [26]. The standard error of the mean (SEM) was calculated by the formula SEM = standard deviation$\times\sqrt{(1 - ICC)}$, the coefficient of variance (CV) was calculated by the formula CV= (Standard deviation/ mean) ×100%, while the minimal detectable change (MDC) was computed by the formula MDC = $1.96\times SEM\times\sqrt{2}$. ICC values<0.50 is indicative poor, between 0.5 and 0.75 is moderate, between 0.75 and 0.9 is good, greater than 0.9 were excellent [26]. For the passive joint shear wave data, Two-way analysis of variance (ANOVA) tests (ankle angle × fascia) with repeated measures were performed, followed by post hoc comparisons using two-sided, paired, Bonferroni-corrected t tests. $p<0.05$ was considered significant.

Results

Intra- and inter-rater reliabilities of the shear modulus of the MGF and LGF.

The ICC, MDC, CV, SEM for intra- and inter-rater reliability for mean shear modulus in MGF and LGF can be found in Table 1 and Figure 3. Intra-rater (ICC = 0.846–0.965) and inter-rater (ICC = 0.877–0.961) reliability were good to excellent for the shear modulus of MGF and LGF. The SEM (kPa) was 1.41 to 3.49, the MDC (kPa) was 3.92 to 9.68, CV (%) were 21.50 to 27.69.

Changes in the shear modulus of the MGF and LGF.

Regardless of the ankle angle, the shear modulus of the LGF were significant greater than that of the MGF ($p < 0.001$, Figure 2). The significant increase in the shear modulus both of the MGF and LGF were observed at neutral position compared to the relaxed position ($p < 0.001$, Figure 2).

Discussion

The present study is the first to document that USWE is a reliable technique to quantify the change of GDF shear modulus. The results showed that the good (0.90 > ICC > 0.75) to excellent (ICC > 0.90) intra- and inter-rater reliabilities of measurements made using the USWE, and relatively low values of MDC and SEM also prove the accuracy of the assessment. The shear modulus of GDF (included LGF and MGF) increased significantly when the ankle at neutral position compared to the relaxed position. Regardless of the ankle angle, the shear modulus of the LGF were significant greater than that of the MGF.

This is the first study to document excellent intra- and inter-rater reliabilities of elastic properties of GDF (included LGF and MGF) using the USWE in healthy males. Previous other studies of the same type only investigated the reliability of the elastic properties of muscles, fascia and tendons using the USWE. For example, Otsuka et al.,(2019) used USWE to investigated muscle contraction-driven changes in deep fascia mechanical property, they found that high reliability of fascia lata in the longitudinal direction (ICC=0.618–0.989) [19]. Le et al used USWE to quantify the elastic properties of gastrocnemius muscle during passive dorsiflexion with excellent reliability (ICC = 0.92–0.96) [27]. Saeki et al (2017) studied the reliability of USWE in assessing the elastic properties of MG and LG in three different dorsiflexion angles [28]. The findings revealed that the reliability of USWE in various ankle angles were excellent (ICC = 0.76–0.91). It means that the USWE had the ability to estimate the changes of the measuring MG and LG. However, the elastic properties of MGF and LGF was not measured. The findings of the present study were similar to those studies for quantifying muscles elastic properties using USWE. In addition to using ICC values to evaluate intra- and inter-rater reliability, our study also computed the SEM (1.41 to 3.49 kPa) to further verified the reliability of our study. The relatively low values of SEM proved the precision of measuring MGF and LGF.

We found that the inter-rater reliability (ICC = 0.846–0.965) seems to be consistent with intrarater reliability (ICC = 0.877–0.961) at the same site. This results are similar to previous reports. Chen et al (2020) reported similar results that the intra-rater reliability (ICC=0.860–0.938) was consistent with inter-rater reliability (ICC=0.904–0.944) for measuring the elastic properties of the thoracolumbar fascia using the USWE [29]. This means that the measurement of gastrocnemius fascia using ultrasonic shear wave elastography is reliable, which does not change with the time spent and the operator. In addition, our findings revealed that the CV of the MGF and LGF were 21.50% to 27.69%, which were a slightly higher than that of reported in previous similar studies. Lima et al. (2017) reported the CV values of MG was 17.29% to 20.95% during rest, and the similar finding were observed by Chino and Takahashi (19.4%) [30]. It could be related to probe load or the operator dependency like the probe may not completely parallel to the muscle fascia[31-32]. However, as the present study found high reliability of the shear modulus of MGF and LGF in the longitudinal direction (inter-rater ICC: 0.846–0.965, intra-rater ICC: 0.860–0.938), the data of the muscle deep fascia were all classified as acceptable. Furthermore, we also reported the MDC. From the clinical and experimental standpoint, the MDC as the smallest statistically significant change in measurement results, it could reflect the precision of real change and serve as a reference for future study. In terms of our results, the shear modulus of GDF should be greater than 9.68 kPa to reflect real changes with retested tests.

The study showed a new findings for the shear modulus between MGF and LGF. Our finding showed that the significant increase in the shear modulus both of the MGF (45.30%) and LGF (52.29%) were observed at neutral position compared to the relaxed position. The shear modulus variation value from neutral position compared to the relaxed position is greater than the MDC (9.68 kPa), which revealed that the elastic properties change from the relaxed position was caused by real change rather than experimental errors. The above indicated that the stretching level of MGF and LGF was not identical during passive ankle dorsiflexion. Differences of stretching levels between MGF and LGF might be due to the difference in recruitment and size (such as: cross-sectional area, volume, rotation angle) patterns of MG and LG, and also may be associated with their passive force-length relationships[33-36]. The actual examination of the functional significance and biomechanical effect of the apparent difference in elastic properties between MGF and LGF is a very interesting research topic, which in turn may suggest modifications of traditional exercise protocols. It is beyond the scope of the this study as it requires a more appropriate research design. In addition, To our knowledge, there are no literatures had reported the elastic properties of GDF from the perspective of a healthy individual, thus, it was difficulty to compare our findings directly with the results of previous studies. However, previous similar results revealed the passive tensile response of the elastic properties of gastrocnemius muscle similar with our results at the same location. Liu et al (2021) found that the stiffness of gastrocnemius medius increased as the ankle dorsiflexion increased (ankle movement from plantar flexion 40°to dorsiflexion 30°)[37]. Le Sant et al (2017) demonstrated that an increase of shear modulus at the level of the lower leg muscles (including gastrocnemius muscle) during passive dorsiflexion performed with the knee fully extended [20]. These results are in line with the physiologic stiffening of the muscles to resist the force applied during passive stretching. Previous studies have shown that the fascia lata can act as a spring, contributing to myofascial force transmission, elastic energy storage, and limb stability [38-39]. Otsuka et al found the shear modulus of fascia lata increased according to the passive mechanical stress, and the relative amounts of shear modulus changes are not identical between fascia lata and muscles [19]. Therefore the change in shear modulus in the muscle and its fascia could be associated with risk for muscles/tendons injury [40].

Previous study have suggested the existence of force transmission among fascia, muscle and tendons [41-42]. The USWE measurements performed in this study were focused on one targeted myofascial and provide an indirect assessment of its passive tension. The specific influence of other synergetic muscles fascia should be estimated in the further study.

Limitations

There were some potential limitations of the present study. First, this study established a method for assessing the shear modulus in the MGF and LGF. We only recruited healthy subjects as a preliminary experiment. Further studies need to be conducted to evaluate the regional difference in the deep fascia elasticity in patients with muscle strains. Second, we did not use the EMG to monitor the MG and LG activity to ensure whether the muscle contracts during whole experiment. Indeed, every participant was asked to keep relaxed and there was no sign of muscle contraction on real-time ultrasound images. Thus, we believe that each subject followed the oral instructions and remained relaxed.

Conclusions

USWE is a technique to estimate the shear modulus of gastrocnemius fascia. The shear modulus change more than 9.68 kPa can be considered as a true change rather than error. Moreover, this tool is capable of detecting the change of gastrocnemius fascia between neutral position and relaxed position, which provides the possibility for further studies the dynamic changes of gastrocnemius fascia.

Declarations

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Table

Table 1 Intra- and inter-tester reliabilities of USWE for mean shear modulus of MGF and LGF.

	Measurement position	Ankle angle	Test 1 (kPa)	Test 2（kPa）	MDC (kPa)	CV (%)	SEM (kPa)	ICC (95%CI)
Intra-tester	MGF	R	31.16±8.95	31.20±7.51	4.16	24.07	1.50	0. 896 (0.762-0.957)
		N	68.79±17.77	69.60±15.07	8.35	21.65	3.01	0.965 (0.915-0.985)
	LGF	R	43.93±10.51	43.70±12.10	6.71	27.69	2.42	0.846 (0.659-0.935)
		N	84.02±18.15	81.21±17.46	9.68	21.50	3.49	0.941 (0.862-0.976)
Inter-tester	MGF	R	31.16±8.95	30.37±7.07	3.92	23.28	1.41	0.961 (0.907-0.984)
		N	68.79±17.77	67.86±16.98	9.41	25.02	3.40	0.877 (0.723-0.948)
	LGF	R	43.93±10.51	43.66±10.46	5.80	23.96	2.09	0.950 (0.881-0.979)
		N	84.02±18.15	78.42±17.05	9.45	21.74	3.41	0.936 (0.850-0.974)

R: Relaxing position , N: Neutral position.

LGF: Lateral gastrocnemius fascia, MGF: Medial gastrocnemius fascia.

MDC: Minimal detectable change, CV: Coefficient of variation, SEM: Standard error in measurement,

ICC: Intra-class correlation coefficient.

Figures

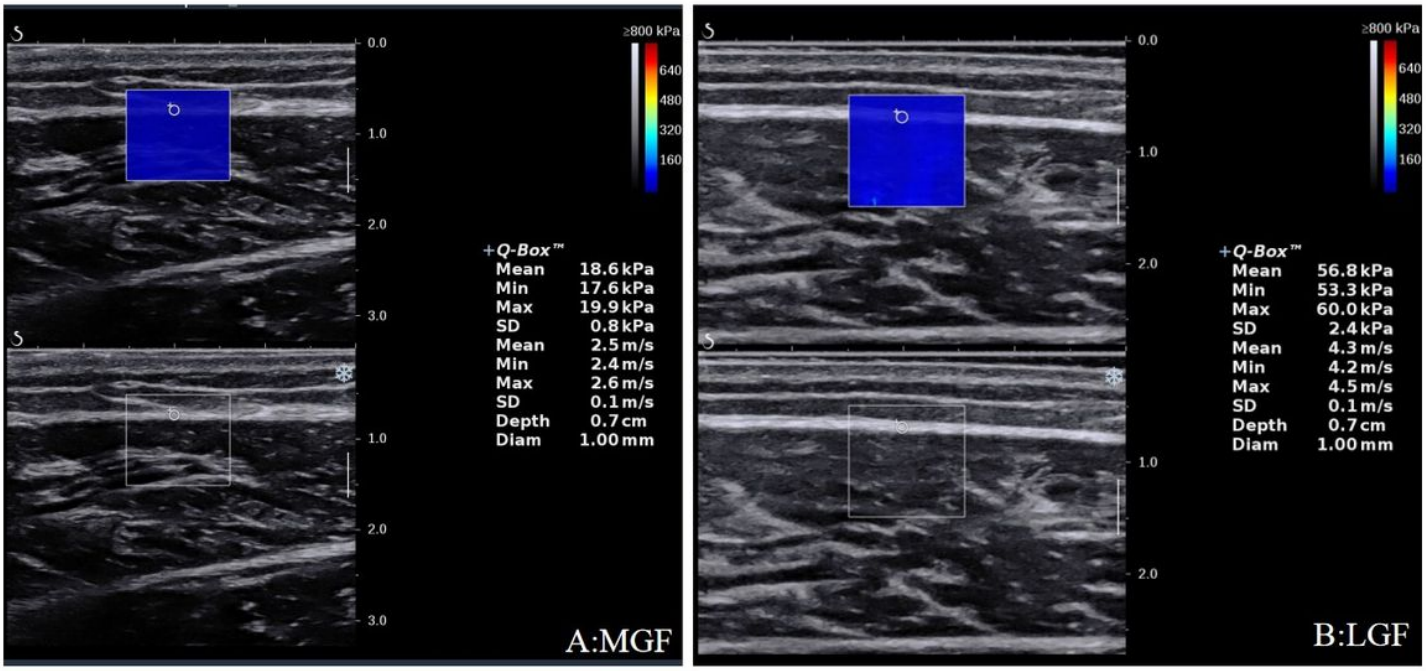

Figure 1

Typical maps of the elastic properties of MGF and LGF in the longitudinal directions. The color-coded box presentation of muscle fascia elasticity is shown in the upper images. The longitudinal grey-scale sonograms of muscle fascia are shown in the bottom images. The Q-BoxTM is shown on the right. MGF : the medial gastrocnemius fascia, LGF (B): the lateral gastrocnemius fascia.

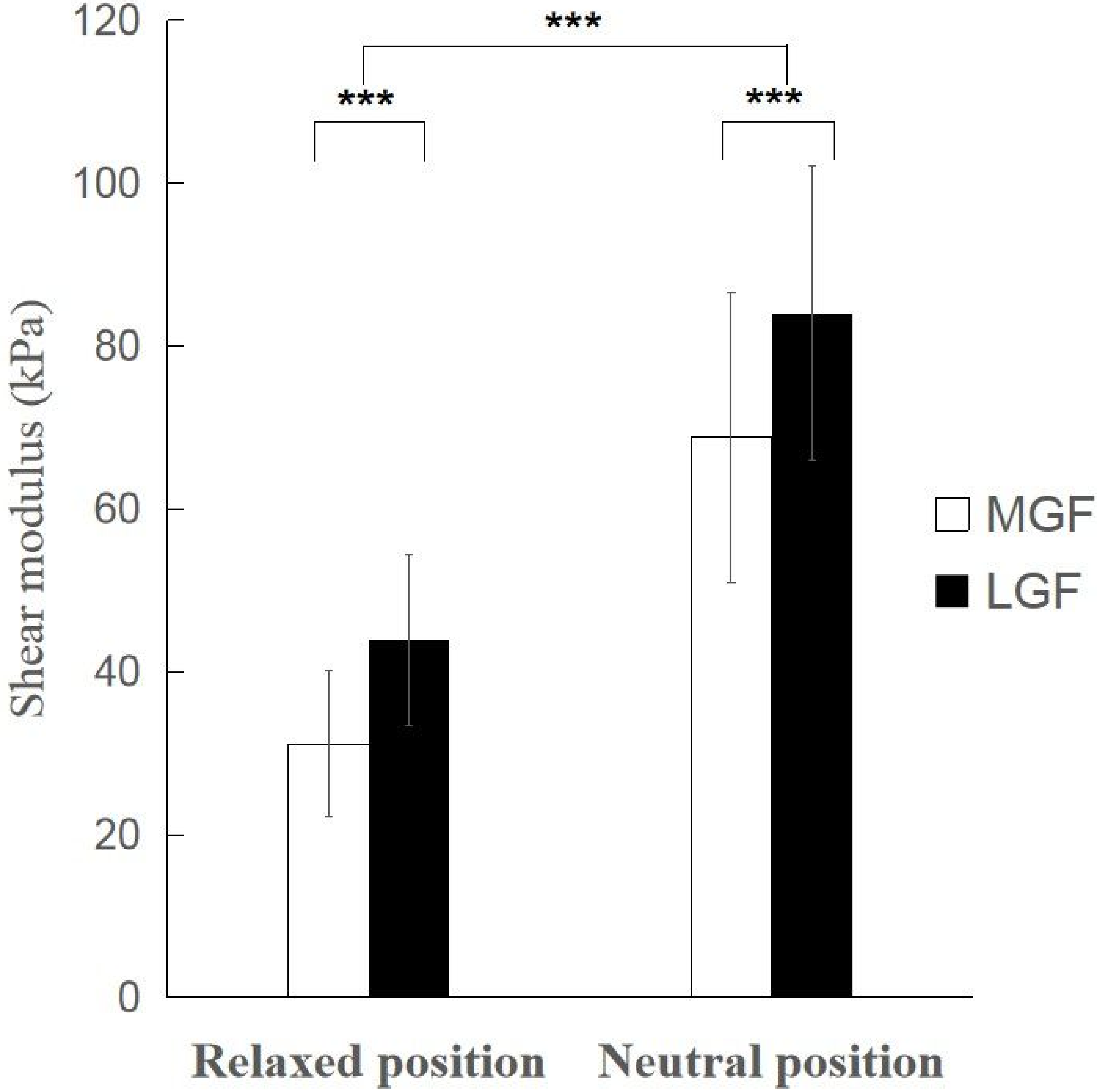

Figure 2

Variations in elasticity of the MGF and LGF at relaxed position and neutral position of passive ankle joint with the knee fully extended. *** P<0.001.

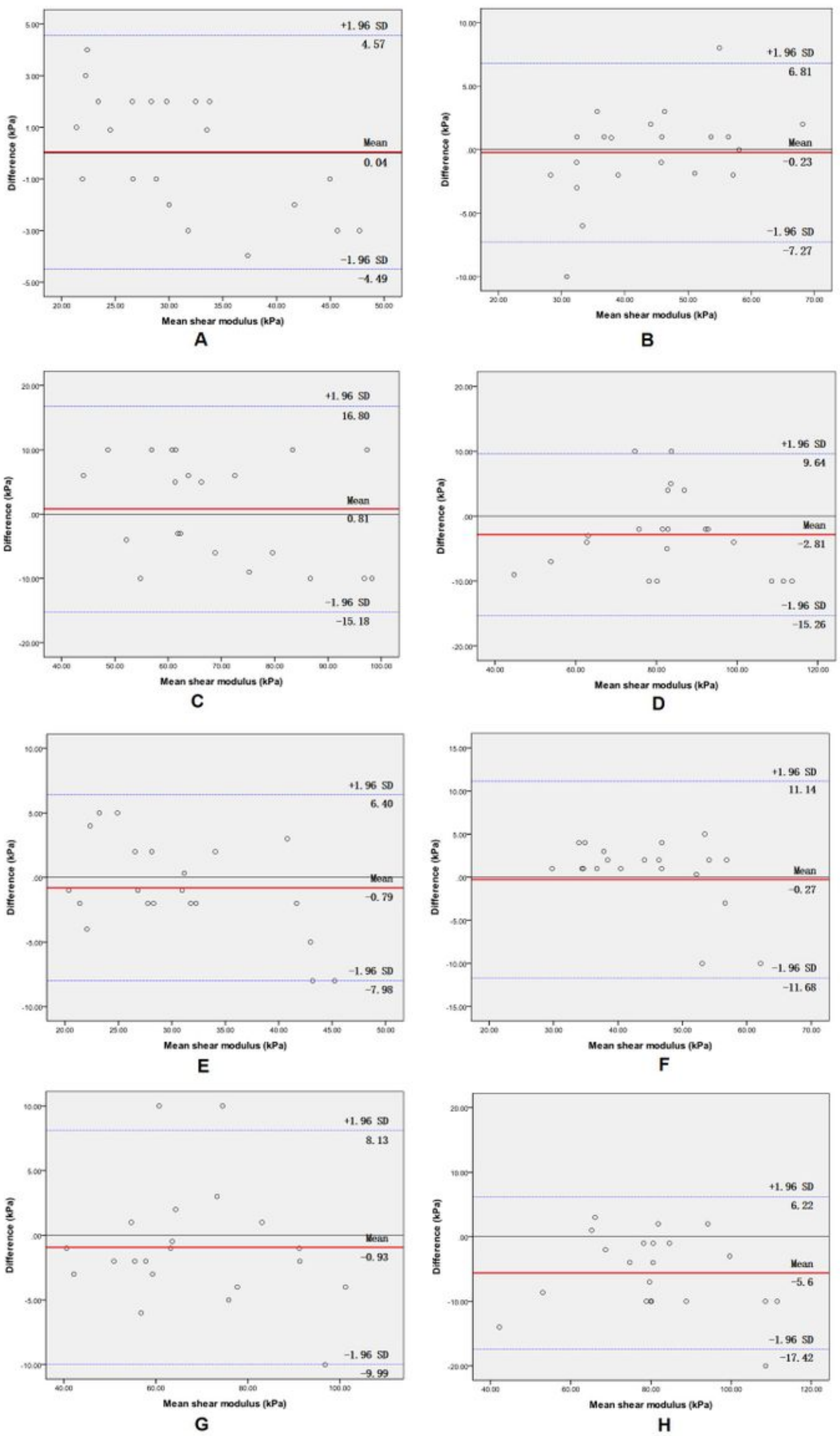

Figure 3

Bland and Altman plots of intra- and inter-operator reliabilities of MGF and LGF shear modulus. The difference in MGF and LGF shear modulus between day 1 and day 5 is plotted against mean MGF and LGF shear modulus for each participant in the MGF (A: at relaxed position, C: at neutral position) and LGF (B: at relaxed position, D: at neutral position). The difference in MGF and LGF shear modulus between operator A and operator B is plotted against mean MGF and LGF shear modulus for each participant in the

MGF (E: at relaxed position, G: at neutral position) and LGF (F: at relaxed position, H: at neutral position). In each picture, the continuous line is the mean difference and the dotted lines represent two SD above and below the mean difference.