**In Vivo Assessment of Lower Limb Muscle Stress State Based on Shear Wave Elastography**

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**ABSTRACT** This study aims to explore the possibility of assessing muscle stress state using shear wave elastography (SWE). Eight healthy males participated in the measurements, and the Young’s modulus of 10 leg muscles of each participant were measured in six standard positions: lying, sitting, and four quasi-static walking postures. The contributions of each muscle in the four quasi-static walking postures were examined, and the relationship between the Young’s modulus and simultaneously recorded plantar pressure was preliminarily explored for the most significant muscles. Results indicate that ICC ranges from 0.941 to 0.998, and 95% CI is in the range 0.909–0.999, CV ranges from 1.45% to 9.5%, and SEM ranges from 0.026 kPa to 0.824 kPa for all the tested muscles. This indicates that the Young’s modulus of the muscles, measured by SWE, showed excellent retest reliability. In the lying and sitting positions, significant differences were observed in Young’s modulus of 9 muscles with the only exception of biceps femoris (BF). In the heel strike and push off positions, strong linear relationships were found between the plantar pressure and Young’s modulus of gastrocnemius medialis (GM) suggesting that muscle SWE measurement may be a good indicator of ground reaction forces. This study demonstrates that the SWE measures of the muscle Young’s modulus can be used to reliably reflect the quantitative change in the stiffness of a muscle at different positions, and may also be employed to estimate the ground reaction forces and muscle stress state. Although this is a great progress in studying muscle force, it is still a great challenge to measure the Young’s modulus of muscle and noninvasively evaluate the muscle force in vivo using SWE.

**INDEX TERMS** Shear wave elastography, muscle force, Young’s modulus, lower limb, in vivo.

I. INTRODUCTION

Muscles play the role of an actuator in a human musculoskeletal system, facilitating a range of complex movements. Mechanical characteristics of muscles during movements are research hotspots in biomechanics and bionics. In-depth study of the assessment of muscle force is conducive to extend the range of biomechanics and to promote the development of bionic mechanical design, biomedicine, competitive sports, and other disciplines [1]–[3]. Previous studies have examined the torque and stiffness of human muscles in lower extremities in vivo during passive stretching by using a dynamometer [4]–[6]. However, the aforementioned measurements are influenced by various factors, such as synergistic muscles, aponeurosis, tendons, and ligaments, and it is difficult to accurately evaluate the passive characteristics of a single muscle [7].

Methods for obtaining muscle force include direct measurement and indirect calculations. Most direct measurements are mainly used in invasive experiments and included cadaver and animal tests that are rarely performed in vivo [8]. Ward et al. implanted a pressure sensor into the tibialis anterior (TA) muscle of the New Zealand White rabbit, and studied the in vivo relationship between muscle stress and intramuscular pressure during dynamic muscle contractions. However, due to ethics and other reasons, it is difficult to
directly use the direct measurement method to carry out large-scale in vivo research, let alone in clinical use [9]. Thus, researchers mostly use indirect calculating methods such as electromyography (EMG) [10]–[12] and musculoskeletal models [13]–[15] to study muscle force evaluation. Although EMG can be used to quantify the status and functional information of muscles, there are numerous limitations in the assessment of muscle force. First, it is difficult to obtain an EMG signal that exactly corresponds to a single muscle because EMG is a superposition (in volts) of the action potential in numeral muscle movement units during contraction [16], not the variables related to muscle force, which demonstrated that the validity of muscle force assessment remains to be discussed by using EMG. Second, EMG fails to provide any information on passive muscle force. Additionally, the presence of neuromuscular fatigue alters the relationship between the surface electromyogram signal and the muscle force [17]. At present, the general research method of musculoskeletal model is to use the medical image data provided by CT, MRI or frozen section to establish the whole or part of human skeleton geometric model. The model uses the mechanical hinges with different degrees of freedom instead of joints to connect bones, and transforms the muscle into force line. And then, dynamics theory of multiple rigid bodies is used to analyze and solve the mechanical information of joints, muscles and related soft tissues. Hill’s “muscle contraction model” [18] and Huxley’s “rotational cross-bridge model” [19] are often used to assess the individual muscle force. Considering the various simplifications and hypotheses (the three-dimensional shape of muscle is ignored, and the muscle group is simplified into several straight lines; the standard model ignores individual differences) were introduced into the musculoskeletal model, Wheatley et al. [20], [21] improved the model, and proposed a new finite element model of skeletal muscle to realize the fluid behavior through the porous elastic theory for the first time, which can predict the intramuscular pressure and muscle force under the condition of passive stretching. These studies provided valuable information for the indirect evaluation of muscle force based on musculoskeletal model. However, the research of skeletal muscle model has not been applied in practice, so the reliability of muscle force evaluation based on skeletal muscle model is still uncertain. Thus, the in vivo and non-invasive assessment of muscle force, even a rough assessment, remains a main challenge in biomechanics.

Shear wave elastography (SWE) is a novel, real-time, and non-invasive technique that is used to estimate human tissue stiffness [22], [23]. SWE operates by subjecting the tissue to mechanical perturbations by using the acoustic radiation force generated by the ultrasonic beams. This induces shear waves that propagate within the tissue. As the shear waves propagate, they are captured by the ultrasound transducer at an ultra-fast frame rate. Algorithms such as cross-correlation algorithm are then used for estimating the propagation speed of these shear waves at each pixel. This shear wave speed (Vs) is related to the shear elastic modulus (μ) via a square relationship defined by muscle mass density (ρ), which is often assumed to be 1000 kg/m³:

\[ \mu = \rho V_s^2 \]  

(1)

The Young’s modulus (E) is the most relevant measure of stiffness of a given material. For isotropic locally homogeneous and quasi-incompressible biological tissues, the shear modulus is directly linked to the Young’s modulus:

\[ E \approx 3\mu \]  

(2)

However, because of its anisotropy, this equation cannot be theoretically applied to skeletal muscles. Interestingly, using an in vitro muscle preparation (swine), Eby et al. [24] demonstrated that, when the ultrasound probe is parallel to muscle fibers, muscle shear modulus is strongly linearly related to the Young’s modulus measured using traditional material testing.

Recently, SWE has been undergoing rapid development, and it constitutes the most promising evaluation tool that can be used to assess the mechanical parameters of skeletal muscles. A few studies have used SWE to indirectly evaluate muscle loading cases by measuring muscle elasticity, and it is evident that an increased loading of skeletal muscle is associated with increased stiffness of muscle [25]–[29]. Some in vitro experiments proved that muscle elasticity can be used to directly assess passive muscle force by using SWE, and a significant correlation exists between the Young’s modulus of muscle and passive muscle force [26], [30]. Although the aforementioned study provided valuable information for the evaluation of passive muscle force in vitro, there is a paucity of studies evaluating muscular force (including active muscle contraction and passive stretching force) via SWE in vivo and non-invasively. Is there a significant correlation between muscle Young’s modulus and muscle force? Is it possible to measure Young’s modulus of muscle and evaluate muscular force in vivo, non-invasively using SWE? All these problems need further study.

In the present study, important muscles around the knee joint were selected for examination. By using ultrasound elastography and mechanical testing technology, the parameters of the performance of muscle mechanics around the knee joint and the correlation between the parameters and muscle stress state were investigated. Additionally, the possibility of assessment of muscle force in vivo was also preliminarily explored by using SWE in the study. The study provides new ideas and potential methods for the assessment of muscle force in vivo and is also extremely significant for investigating knee joint stability, treatment, and prevention of knee joint movement damage.

II. METHODS

A. PARTICIPANT SELECTION

Eight healthy males (age, 26±2.5 years; weight, 65±7.02 kg; height, 175±5.5 cm) were recruited as volunteers to participate in the study. The exclusion criteria were as follows: (a) participants who had lower extremity surgery or
major trauma, (b) participants with history of various types of muscle disorders, such as muscles fibrositis, myasthenia gravis, and progressive muscular dystrophy, (c) participants with a history of systemic, metabolic, endocrine, and other diseases, (d) participants who had a history of neurologic diseases, and (e) participants with a family history of heredity. Additionally, the 2-minute step test was used to estimate the level of fitness [31], and there was no significant difference in the level of fitness of the 8 subjects. This study was carried out in accordance with the recommendations of the First Bethune Hospital of Jilin University. The protocol was approved by the First Bethune Hospital of Jilin University. All Participants gave written informed consent in accordance with the Declaration of Helsinki.

B. TESTED MUSCLES

Based on human anatomy and joint function kinematics, 10 main functional muscles of the knee joint of the right leg were selected as the test subjects. The selected muscles included vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), sartorius (SAR), gracilis (GRA), biceps femoris (BF), semitendinosus (SET), semimembranosus (SEM), gastrocnemius medialis (GM), and gastrocnemius lateralis (GL), as shown in figure 1.

C. TEST DEVICE

The Young’s modulus of the muscles selected for testing was measured with an Aixplorer ultrasound scanner (Aixplorer, SuperSonic Imagine, Aix-en-Provence, France) in the SWE mode by using the musculoskeletal pre-set to allow the measurement of large shear modulus values. A linear transducer of 2-10 MHz was used in the study. Maps of the SWE were obtained at 12 Hz with a spatial resolution of $1 \times 1$ mm $^2$ [32]. “Gen” mode was used for the consideration of resolution and penetration; “Med” mode was selected for frame rate considering spatial or temporal resolution. Meanwhile, in order to optimize superior texture, enhance edge delineation and reduce shadowing, the SuperCompound was used in this study.

Plantar pressure distribution and ground reaction force were measured by using an RS Scan International pressure plate ($2096 \times 472$ mm $^2$, 500 Hz sampling, 16,384 sensors with $0.5 \times 0.7$ cm $^2$, USBII interface; Olen, Belgium). Data were acquired and analyzed on Footscan7 Gait 2nd generation (RS Scan International, Olen, Belgium).

D. TEST PROCEDURE

The participants were instructed to perform six standard test positions involving lying (supine/prone), sitting, and quasi-static walking positions (heel strike; heel rise; push off; vertical tibia).

FIGURE 2. Measurement of rectus femoris, probe positions, and the corresponding Shear wave elastograms: (a) supine; (b) sitting.

First, in the lying (supine/prone) and sitting positions, 10 muscles selected for testing were located and marked in the anatomical position by using the B-mode such that the consistency of measuring positions was guaranteed as shown in figure 2, and this process took about 30s for each muscle. Then, we started the SWE testing. In order to reduce the influence of pressure artifact on the measurement results, the Young’s modulus scale was adjusted to $0$-$180$ kPa. Considering the influence of the probe scan angle between the probe and muscle fiber, the direction of the probe parallel to the muscle fiber should be selected to the maximum possible extent [24], [33]. Subsequently, the square-shaped elastography window (region of interest) position was fixed except at the upper and lower borders (risk of boundary effect) [34]. The size of the elastography window was set as $10 \times 10$ mm $^2$ as shown in figure 2. It took 5s to stabilize the elastography window for each measurement of elastic imaging, and then obtained the elastic image [35], [36]. By using Q-BOX (a circle with a diameter of 5 mm) [28], which is a built-in quantitative measuring tool, the maximum, minimum, and mean Young’s modulus values were measured. Additionally, the mean Young’s modulus value was used for data analysis in the study. In this study, SWE testing was performed on the same muscle sample by 5 experienced operators, and each operator performed one test, respectively. Among the 5 operators, three operators had more than 3 years of experience in SWE testing, and the other two had more than 2 years of SWE testing experience.
When participants adapted to the test conditions and could walk naturally, plantar pressure distribution testing was conducted for each participant. Participants were asked to walk on the ground 10 times where in the right foot was first placed on the pressure plate such that gait was consistent. In order to avoid the effect of muscle fatigue on the measurement results, participants rested for 3 min after every 5 measurements.

The plantar pressure distributions of each participant were analyzed via gait analysis, and the plantar pressure distributions of the right foot in the four quasi-static positions corresponding to normal walking are extracted and recorded, as shown in figure 3.

![FIGURE 3. Plantar pressure distribution testing.](image)

The fixed brackets were placed on both sides of the body, and the brackets gave the arms a support force, which was used by the subjects to adjust the range of ground reaction pressures and the pressure distribution of left and right feet to simulated the four quasi-static positions (heel strike; heel rise; push off; vertical tibia) according to the data recorded above, and keep as close as possible to the data recorded in actual walking. In each quasi-static position, Young’s modulus of each muscle was measured based on SWE (elastography window and measuring tool Q-BOX were set as above). Because the elastic imaging window needs to be stabilized for 5s before accurate elastic images can be obtained, it took 7–8s for each muscle to complete a measurement. In order to avoid the influence of muscle fatigue on the measurement results, subjects need to rest for 3 minutes after each measurement of a muscle. In each quasi-static position, each muscle was tested five times by five operators, respectively. Meanwhile, during the SWE testing, participants were required to maintain their posture as much as possible to the data recorded in actual walking. All the data analyses were performed using the IBM Statistical Package for the Social Sciences (SPSS) Statistics software version 21.0 (SPSS Inc., Chicago, IL, USA). As recommended by Hopkins (2000) [37], the reliability of the test results of muscle Young’s modulus was measured and assessed using the intra-class correlation coefficient (ICC 3,1, two way random, absolute agreement) with 95% confidence interval (95% CI), the coefficient of variation (CV), and the standard error in measurement (SEM). Generally, an ICC 3,1 value within ranges 0–0.40, 0.41–0.6, 0.61–0.79, 0.8–1.0 indicates poor, moderate, good, and excellent reliability, respectively. Meanwhile, considering the small sample size and to avoid the influence of the risk of type I error, in this study, Kendall’s W was used to for non parametric testing of the consistency of the operator’s standards for measuring the Young’s modulus of muscles and the variability between subjects. Coefficient of concordance W is between 0 and 1, and the closer W is to 1, the more consistent the evaluation standards of each operator are. The associated probability $p-<0.05$ of Kendall’s W tests was considered to have a significant difference between subjects. The Young’s modulus measurements of muscle samples were expressed as (X ± S). In order to avoid exaggerating the risk of type I error caused by the low sample size, the bootstrap method with repeated random sampling was used to enhance the results. A 1000 iteration of bootstrap resampling was performed using the mean Young’s modulus of muscles in the lying (supine/prone) and sitting positions [38]. In this study, the Bootstrap estimates of the mean muscle Young’s modulus in the lying (prone/supine) and sitting positions were performed. Statistical significance was set at $p < 0.05$.

The relationship between the Young’s modulus of the tested muscles and the plantar pressure was analyzed by conducting the least-squares linear fit as follows:

$$ E = E_0 + kF $$  \(3\)

where $E$ denotes the Young’s modulus of the tested muscles, $F$ denotes the plantar pressure, $E_0$ denotes the Young’s modulus of the slack muscle, and $k$ denotes the increase in Young’s modulus of the tested muscles per unit plantar pressure. The coefficient of determination ($R^2$), $E_0$, and $k$ of each regression line were calculated.

III. RESULTS

A. REPEATABILITY ANALYSIS OF YOUNG’S MODULUS MEASUREMENT

Bland-Altman plots are used to make the random effects analyses of the differences among five operators, as shown...
TABLE 1. Test-retest reliability of the Young’s modulus of muscles.

|       | RF   | VM   | VL   | SAR  | GRA  | BF   | SEM  | SET  | GM   | GL   |
|-------|------|------|------|------|------|------|------|------|------|------|
| prone/supine |      |      |      |      |      |      |      |      |      |      |
| ICC3,1 | 0.992 | 0.971 | 0.972 | 0.991 | 0.996 | 0.976 | 0.989 | 0.994 | 0.990 | 0.997 |
| 95% CI | (0.977, 0.998) | (0.923, 0.993) | (0.925, 0.993) | (0.975, 0.998) | (0.988, 0.993) | (0.936, 0.999) | (0.969, 0.994) | (0.983, 0.997) | (0.974, 0.998) | (0.991, 0.999) |
| CV(%) | 8.11 | 3.56 | 7.67 | 5.23 | 5.28 | 1.45 | 3.79 | 5.40 | 3.92 | 6.61 |
| SEM (kPa) | 0.095 | 0.043 | 0.105 | 0.206 | 0.215 | 0.026 | 0.061 | 0.096 | 0.090 | 0.153 |
| sitting |      |      |      |      |      |      |      |      |      |      |
| ICC3,1 | 0.971 | 0.951 | 0.984 | 0.998 | 0.996 | 0.984 | 0.992 | 0.990 | 0.994 | 0.995 |
| 95% CI | (0.923, 0.993) | (0.972, 0.988) | (0.956, 0.999) | (0.993, 0.999) | (0.989, 0.999) | (0.958, 0.999) | (0.978, 0.996) | (0.971, 0.998) | (0.984, 0.999) | (0.999, 0.999) |
| CV(%) | 2.37 | 1.48 | 2.13 | 7.87 | 6.80 | 3.78 | 5.70 | 2.34 | 4.76 | 7.19 |
| SEM (kPa) | 0.067 | 0.040 | 0.063 | 0.129 | 0.100 | 0.069 | 0.084 | 0.037 | 0.067 | 0.114 |

B. RELATIONSHIP BETWEEN THE YOUNG’S MODULUS OF MUSCLE AND POSITIONS

In the lying (supine/prone) and sitting positions, the overall change trend of Young’s modulus of the 10 tested muscles of the 8 participants were shown in figure 5. Bootstrap estimates of the mean Young’s modulus of 10 muscles are shown in Table 3. With the exception of BF, there are significant differences in Young’s modulus of the other 9 tested muscles in different positions ($p < 0.05$). Specifically, RF, VM, and VL muscles are in a state of relative relaxation in the supine position, and the Young’s modulus of the muscles is between 7.39 kPa and 8.66 kPa. Additionally, SAR, GRA, SET, SEM, GM, and GL are in a state of relative relaxation in the sitting position, and the Young’s modulus of the muscles is between 8.85 kPa and 10.34 kPa.
TABLE 2. The Kendall’s W tests results of the consistency of the operator’s standards for measuring the muscle Young’s modulus and the variability between subjects.

|       | RF  | VM  | VL  | SAR | GRA | BF  | SEM | SET  | GM  | GL  |
|-------|-----|-----|-----|-----|-----|-----|-----|------|-----|-----|
| prone | 0.981 | 0.963 | 0.974 | 0.988 | 0.947 | 0.941 | 1.000 | 0.996 | 0.998 | 0.978 |
| supine | 0.998 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 |
| sitting | 0.984 | 0.894 | 0.933 | 0.998 | 1.000 | 0.949 | 0.985 | 0.955 | 0.985 | 0.972 |
| heel strike | 0.996 | 0.975 | 0.986 | 0.951 | 0.979 | 0.984 | 0.995 | 0.996 | 0.964 | 0.948 |
| heel rise | 0.995 | 0.968 | 0.944 | 0.951 | 0.998 | 0.918 | 0.989 | 0.932 | 0.974 | 0.987 |
| push off | 0.972 | 0.973 | 0.964 | 0.994 | 0.991 | 0.971 | 0.989 | 0.927 | 0.974 | 0.928 |
| vertical | 0.872 | 0.971 | 0.995 | 0.983 | 0.972 | 0.957 | 0.901 | 0.979 | 0.990 | 0.983 |
| Tibia | 0.00019 | 0.00017 | 0.00022 | 0.00022 | 0.00022 | 0.00022 | 0.00022 | 0.00022 | 0.00022 | 0.00022 |

C. RELATIONSHIP BETWEEN THE PLANTAR PRESSURE AND YOUNG’S MODULUS OF MUSCLE

With respect to GM, the study preliminarily explores the quantitative relationship between plantar pressure and positions when participants are in the heel strike and push off positions. Specifically, GM contributes most significantly in the heel strike and push off positions. Meanwhile, the change trend chart of each muscle under four quasi-static walking postures is shown in the Supplementary Figure 1 in the supplementary materials.

IV. DISCUSSION

SWE is a quantitative technology that is used for the characterization of tissue mechanical parameters by measuring
remotely induced shear wave velocity [39]–[41]. The muscle shear modulus is calculated by real-time shear wave velocity and tissue density [42], and the accuracy of measurement is also verified in various tissues and membranes [27], [43]. Compared with the previous research on the measurement of Young’s modulus of muscle, the results showed that SWE has higher reliability and repeatability. The repeatability comparisons of different measurement methods were shown in Table 5.

Furthermore, the present study obtained higher repeatability measurements of the Young’s modulus of the muscles, and this was attributed due to the following aspects: (1) Based on the recommendation of manufacturer [53], the probe remained stable to avoid pressure artifact during SWE testing. Simultaneously, the influence of the probe scan angle (the angle between the ultrasound probe and muscle fiber) on the measurements is considered [24], [33], and the ultrasound probe was parallel to the muscle fiber to the
maximum possible extent. (2) Healthy males are considered for our study, and this avoids the influence of gender [54], age [55], [56], and diseases [57] on the Young’s modulus of muscle. (3) To ensure the consistency of measuring positions of subjects, the measuring positions of 10 muscles were located strictly based on anatomical positions and B-mode image of ultrasound. With respect to the VL, the probe is positioned to first perform longitudinal scanning on the quadriceps tendon and then moved towards the VL. When the rectus femoris fiber appears on the image, the probe is adjusted in the direction of the muscle fiber, and the distal end of the muscle is displayed on the right side of the imaging region (Fig. 2). The location method in the study is different from that of a previous scheme wherein the method involved positioning by distance [58], which is accompanied by measurement errors caused by the height difference. (4) In the case of quasi-static walking, a pressure plate is used to test the postural stability. If the pressure plate data fluctuates, the SWE testing is performed again.

The knee joint is the most complex and highly coupled joint in the whole body. In daily life, it is responsible for supporting the body and participating in most sports. Additionally, it shoulders the function of maintaining the dynamic balance of the body. In addition to the tendons and ligaments around the knee joint, muscles also contribute to its stability. Specifically, while walking, running, and performing other sports, the force on the muscles around the knee joint is crucial to control the stability of the knee. Several studies investigated muscles around the knee joint based on SWE although most studies were limited to the position of supine and prone to explore the effect of a few diseases on Young’s modulus of a single muscle [59], [60]. Additionally, changes in the Young’s modulus during stretching were also examined in a few studies [27], [61]. Thus, in order to comprehensively investigate the mechanical properties of the knee joint, our study considers more muscles (10 muscles) and test positions (7 positions) and explores the mechanical property of the important muscles around the knee joint and the relativity between them and muscle stress state.

The results of the study indicate that 10 muscle Young’s moduli are all within the range of 7.39 kPa – 10.34 kPa in which differences are small, and this is potentially due to the consistency of participants, i.e., healthy young males. In the lying (supine/prone) and sitting positions, there are significant differences in the Young’s modulus of the other 9 tested muscles in different positions (p < 0.05) with the exception of the BF. The results indicate that SWE measurements of Young’s modulus can be used to accurately reflect the loading cases changes in muscles involved in human motion, and the measurements were consistent with those in extant studies and prevalent anatomical knowledge [62]. The study explores the in vivo, and quantitative changes in the Young’s
TABLE 5. Repeatability comparisons of different measurement methods.

| Methods | Author | Muscle | ICC   | CV (%) | SEM (kPa) |
|---------|--------|--------|-------|--------|-----------|
| TE      | Perazzo et al. [42] | Biceps brachii | 0.912 | -      | -         |
|         | Nordez et al. [43] | GM     | 0.893 | 7.8    | -         |
| MRE     | Wang et al. [44]   | Lumbar paraspinal | 0.601-0.727 | -    | -         |
|         | Hong et al. [45]   | Lumbar paraspinal | 0.614-0.996 | -    | -         |
|         | Lacourpaille et al. [46] | RF, and VL et al. | 0.421-0.944 | 4.6-11.5 | 0.15-0.18 |
|         | Leong et al. [47]  | Upper trapezius | 0.78-0.83 | -      | -         |
|         | Dubois et al. [48] | RF, VM et al. | 0.87-0.91 | 8-11   | -         |
| SWE     | Moreau et al. [49] | Multifidus muscle | 0.72-0.95 | 11-19  | -         |
|         | Otsuka et al. [31] | RF, VL | 0.681-0.989 | 1.3-10.2 | -         |
|         | Cortez et al. [50] | GM, TA | 0.760-0.960 | 6.9-15.6 | -         |
|         | Koo et al. [27]    | TA     | 0.852-0.942 | -      | -         |
|         | This study         | The tested 10 muscles | 0.941-0.998 | 1.45-9.5 | 0.026-0.824 |

modulus of 10 muscles in quasi-static walking for the first time. As shown in figure 7, the gastrocnemius significantly contributes in the heel strike, heel rise, and push off positions. Specifically, GM contributes most significantly in the heel strike and push off positions, and this result is similar to that in studies on the EMG signal [62]. At the same time, this study also carried out EMG test verification to prove that the muscle activation modes of EMG signal between normal walking and quasi-static positions (heel strike and push off) are similar, see the Supplement 2 in the Supplementary Materials for details. SWE is used to analyze the real-time and quantitative changes in single muscle stiffness.

Based on the aforementioned results, our study explores the quantitative relationship between plantar pressure and positions when participants are in the heel strike and push off positions for GM. The test results indicate that Young’s modulus of GM increased linearly with increases in the plantar pressure in the quasi-static walking irrespective of whether it corresponded to heel strike or push off. However, with respect to the 2 quasi-static positions, significant differences are observed between the Young’s modulus of the muscle under plantar pressure of each unit, and the Young’s modulus of push off exceeded that of the heel strike. In a study by Vaughan et al. [62] EMG combined with human gait analysis is used to explore the functional state of major muscle groups of human body lower limbs during walking. With the flexion of the ankle joint and muscle elongation of the posterior group of the calf in the heel strike position, the results indicate that the quadriceps femoris, hamstring, calf muscles, and gluteus maximus exhibit evident discharge and that they are all involved in movement. Stretching is performed by the posterior group of calf muscles doing contractile contraction in the push off position, and the results indicate that the muscle discharge of the posterior group of calf muscles is the highest while the other muscles did not discharge evidently. In the same position, muscle force of the posterior group of calf muscles exceeds that in the heel strike position. The aforementioned conclusion explains the reason as to why the increase in Young’s modulus of the tested muscles per unit plantar pressure exhibits highly significant difference and why the measurement results of push off exceed than that of heel strike.

There were a few limitations in our study. First, this study obtained a strong linear relationship between the plantar pressure and Young’s modulus of GM only in the heel strike and push off positions. However, such linear relationship is not applied to some other positions, such as “vertical tibia”. Secondly, in the process of this study, we encountered some difficulties caused by the limitations of equipment, equipment, ethics, and other reasons. It is impossible to in vivo, non-invasively, and quantitatively obtain the single muscle force through other methods, so there is a lack of direct indices to measure the changes of muscle force. After a considerable amount of muscle Young’s modulus testing by using SWE and the Kistler three-dimensional dynamometer testing, and consider the two points: (1) The GM contributes most significantly in the heel strike and push off positions, (2) there is an approximate linear relationship between GM and plantar pressure, we finally selected plantar pressure as the indirect and rough indicator to measure the changes of muscle force of GM. Although there is a strong linear relationship between the plantar pressure and Young’s modulus of GM in this study, such relationship still has great errors (neglect the co-contraction of other muscles) and individual difference, which can’t be directly and quantitatively used to assess the muscle force currently. In order to make accurate
and quantitative assessment of muscle force, it is necessary to optimize the muscle force evaluation model (see Supplement 3 in the Supplementary Materials for details and the constants in the simplified model are different in each person). Thirdly, only a small number of young healthy males are recruited in our study, and the group is small and homogenous. And given that shear modulus of different gender [54], age [55], [56]and disease [57] were shown in extant studies, future studies need more tested samples to identify the effects of gender, age, and disease on SWE to assess the muscle state. Fourthly, since muscles are anisotropic, there are some errors that in using the Young’s modulus of local muscle measured by Q-BOX to represent the mechanical properties of the whole muscle, so it is necessary to consider using high density EMG to improve the detection accuracy in the future. Fifthly, soleus is a critically important muscle for human locomotion. In order to investigate the relationship between muscle elasticity and muscle loading, we only selected superficial leg muscles to as the SWE measuring accuracy of human superficial muscles has been well validated in many previous studies [28], [48], [56]. Whereas, many researchers have reported that tissue depth may seriously affect the accuracy of SWE measurement [63], [64]. With the further development of SWE technique, we plan to investigate the soleus muscle in our future studies.

V. CONCLUSION

SWE is a reliable, repeatable, and in vivo technique that is used to measure the Young’s modulus of muscles and assess the change of single muscle stress state in real time. Meanwhile, in the heel strike and push off positions, strong linear relationships were found between the plantar pressure and Young’s modulus of GM suggesting that muscle SWE measurement [6], [64]. With the further development of SWE technique, we plan to investigate the soleus muscle in our future studies.

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