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Noninvasive in Vivo Study of the Morphology and Mechanical Properties of Plantar Fascia Based on Ultrasound

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ABSTRACT The overall distributions of the plantar fascia thickness and Young's modulus in the ten subjects were systematically investigated in this paper using two-dimensional ultrasound and shear wave elastography (SWE). The statistical analyses showed that $ICC_{1,1}$ of the plantar fascia thickness and Young's modulus ranged from 0.950 to 0.991, with the 95% CI in the range of 0.953–0.996. This result indicated that the thickness and Young's modulus exhibited excellent retest reliability. The conclusion that both the thickness, d, and Young's modulus, E, of the plantar fascia showed a simple and specific spatial dependence on the characteristics of the gradient distribution can be drawn. As the plantar fascia extends from the calcaneus to the five toes, both the thickness, d, and Young's modulus, E, of the five bundles of plantar fascia showed a downward trend of a negative exponential function, and the thickness, d, and Young's modulus, E, were the largest at the tubercle of the calcaneus and closest to the lowest value at the tubercles of the five metatarsal bones. The coefficient of determination (R^2) of the fitting curve of thickness, d, and Young's modulus, E, was higher than 0.959 in all ten subjects. The distribution characteristics of the plantar fascia thickness, d, and Young's modulus, E, showed good consistency in the healthy subjects in this paper. The conclusions of this paper may provide more accurate references and a basis for material mechanics data for plantar fascia diseases (such as fasciitis) and foot mechanical models (such as finite element models).

INDEX TERMS Shear wave elastography, plantar fascia, morphology properties, mechanical properties.

I. INTRODUCTION

The plantar fascia (PF) is a fibrous tissue with a fan-shaped base, which starts from the medial calcaneal tubercle and ends at the five metatarsal bones. It has the function of carrying the foot load, changing the rotation angle of the skeleton and dispersing stress throughout the metatarsus. Especially in the "pulley mechanism", plantar fascia is the most important structure to stabilize arches, buffer concussion and protect the plantar muscles, tendons and joints [1]–[3]. Once the structure undergoes morphological or mechanical changes, the plantar fascia will produce lesions, and the most common disease of the plantar fascia is plantar fasciitis.

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Plantar fasciitis, also known as plantar aponeurositis, is a common plantar lesion that accounts for 11% to 15% of all foot diseases [4], [5]. Although plantar fasciitis is a self-limited disease, it often seriously affects the quality of life of patients [6]. The main symptoms are pain and discomfort in the foot when walking or standing, and the pain is especially noticeable when it is experienced in the morning. After excessive walking or strenuous activity, the patient's pain is aggravated, even when standing at rest [7]. In recent years, with the development of aging society and changes in lifestyle, the proportion of patients with plantar fasciitis has been increasing. The injury mechanism and early diagnosis of plantar fasciitis have attracted the attention and research of a large number of scholars.

Traditionally, plantar fasciitis has been described as a local inflammatory response; however, pathological studies have found that the main characteristics of plantar fasciitis are degenerative changes of the plantar fascia with minor injury to local fascia and attachment and less inflammatory cell infiltration [8], [9]. Lemont *et al.* [8] inferred that the injury mechanism of plantar fasciitis is chronic degenerative changes of the plantar fascia caused by excessive abnormal force of the plantar fascia and not inflammation. Some studies suggest that the underlying cause of plantar fasciitis is abnormality of the morphology and material mechanical properties of the plantar fascia [9]–[12]. Wearing *et al.* [13] speculated that the essential cause of the lesion is the abnormal morphology of the plantar fascia after loading. Jung *et al.* [14] reported that the changes in the mechanical properties of the plantar fascia were related to compression deformation, stress and strain of the plantar fascia under different static and dynamic conditions, especially since the changes in the elasticity of the plantar fascia under the calcaneus and metatarsal head directly affects the function of the foot. Therefore, comprehensive and in-depth study of the morphology and material properties of the plantar fascia from the perspective of biomechanics can provide a richer theoretical basis for the injury mechanism and early diagnosis of plantar fasciitis.

Currently, traditional methods for obtaining the morphology and mechanical properties of plantar fascia include direct measurements and indirect calculations. Most direct measurements are used mainly in invasive experiments and include cadaver and animal tests that are rarely performed in vivo. Furthermore, it is difficult to conduct large-sample tests with a living body for ethical reasons and other considerations [1], [15]. Therefore, researchers at home and abroad mostly study the plantar fascia by indirect calculation methods, such as via an exercise test or finite element simulation [16]. The human exercise test obtains the plantar pressure distribution by a pressure measuring device, but the information of the plantar fascia morphology, material properties and stress state cannot be directly obtained [7], [17]. Although the inverse finite element method is also used to analyze the mechanical properties of the plantar fascia [18]–[20], the fascia tissues are assumed to be isotropic and homogeneous linear elastic materials. These conditions limit the reliability of research results. Therefore, there are few studies on the noninvasive in vivo morphology and material mechanical properties of the plantar fascia.

SWE is a novel, real-time, and invasive technique that is used to measure human tissue stiffness. 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. Studies on the evaluation of tissue elasticity by responses of soft tissues to various disturbances have been carried out by many researchers. Most elasticity imaging techniques, including vibration elastography imaging, compression elastography, magnetic resonance elastography, transient elastography, acoustic radiation force imaging, SWE, etc., are developed. These techniques have practical value in the diagnosis and identification of diseases, such as breast, thyroid and prostate tumors. However, there are still few studies on the evaluation of plantar fascia elasticity. Lee *et al.* [10] used compression elastography to perform semiquantitative elastography on the plantar fascia of patients with plantar fasciitis and normal subjects, suggesting that ultrasound elastography can provide mechanical information to early fascia morphology changes and a new method for the early diagnosis of plantar fasciitis. SWE is a novel ultrasound technique for quantitatively characterizing the mechanical parameters of tissues through the remote control of shear wave propagation. A variety of ultrasound-based elastography techniques have been compared with magnetic resonance elastography, and the results shows good agreement in a variety of tissues and phantoms. Based on the SWE technique, some researchers performed in vivo and quantitative detection of plantar fascia Young's modulus at the beginning of the plantar fascia (near the calcaneus) [21], [22]. Although the above experiments provide valuable information for the study of the mechanical properties of the plantar fascia, there are no studies on the overall distribution of mechanical properties, such as the morphology properties (plantar fascia thickness) and material properties (plantar fascia Elastic modulus). As the plantar fascia is mainly in tension during foot movement, Young's modulus is widely used to evaluate the overall Elastic modulus of plantar fascia. Using two-dimensional ultrasound and SWE technology, this paper comprehensively and deeply studied the overall distributions of the plantar fascia thickness and Young's modulus and explored the correlation between the two properties, which provided a richer theoretical foundation for the pathogenesis of plantar fasciitis and foot biomechanics (foot biomechanical study).

II. METHODS

A. SUBJECT SELECTION

To avoid the influence of subject selection on the measurements, ten healthy males (age, 26 $\pm$ 2.5 years; weight, 65 $\pm$ 7.02 kg; height, 175 $\pm$ 5.5 cm) with similar body conditions were recruited as volunteers to participate in the study. The exclusion criteria were bone spur at the attachment of the calcaneal tubercle, heel pain, ankle injury and operation, and systemic inflammatory disease, such as joint disease, rheumatoid arthritis, diabetes, and hyperlipidemia. Each subject was asked to avoid longer-than-usual standing, walking, or running for a week prior to the ultrasound examination. The testing procedure and method of study were approved by the ethics committee of the First Bethune Hospital of Jilin University, and informed consent was obtained from each volunteer. This study was performed in accordance with the Helsinki Declaration.

B. TEST DEVICE AND PROCEDURE

Young's modulus of the plantar fascia was measured with an Aixplorer ultrasound scanner (Aixplorer, SuperSonic

Imaging, Aix-en-Provence, France) in SWE mode using the musculoskeletal preset to allow the measurement of large shear modulus values. A linear transducer of 10-2 MHz was used in the study. Each subject was examined while lying prone with the knee fully extended, upper limbs naturally flattened on both sides of the body, feet naturally hanging over the edge of the examination bed, and ankles in a neutral position (Fig. 1a). First, the plantar fascia was placed on the left edge of the imaging area to image the plantar fascia at the calcaneus using B-mode, and the probe location (at this time) was defined as the scan starting point. The plantar fascia thickness was measured every at 0.5 cm to complete the morphology test (Fig. 2a). Subsequently, the elastic measurement via SWE was performed, and the width of the square-shaped elastography window (region of interest (ROI)) was as large as possible, and the height was set to include the complete plantar fascia. Using Q-Box^{TM}Trace, which is a built-in quantitative measuring tool, the border of plantar fascia was illustrated to measure Young's modulus of the plantar fascia (maximum, minimum, and mean value, unit: kPa) at every 1 cm (Fig. 2b). Additionally, the mean Young's modulus value was used for the data analysis in the study.

Then, according to the B-mode image, the plantar fascia thickness and Young's modulus were measured by moving half a probe at a time along the direction of the plantar fascia. The above steps were repeated to measure the five bundles of plantar fascia ending at the metatarsal bones, as shown in Fig. 1b. The measurements of the thickness and Young's modulus of the plantar fascia were repeated 5 times at the position of each probe.

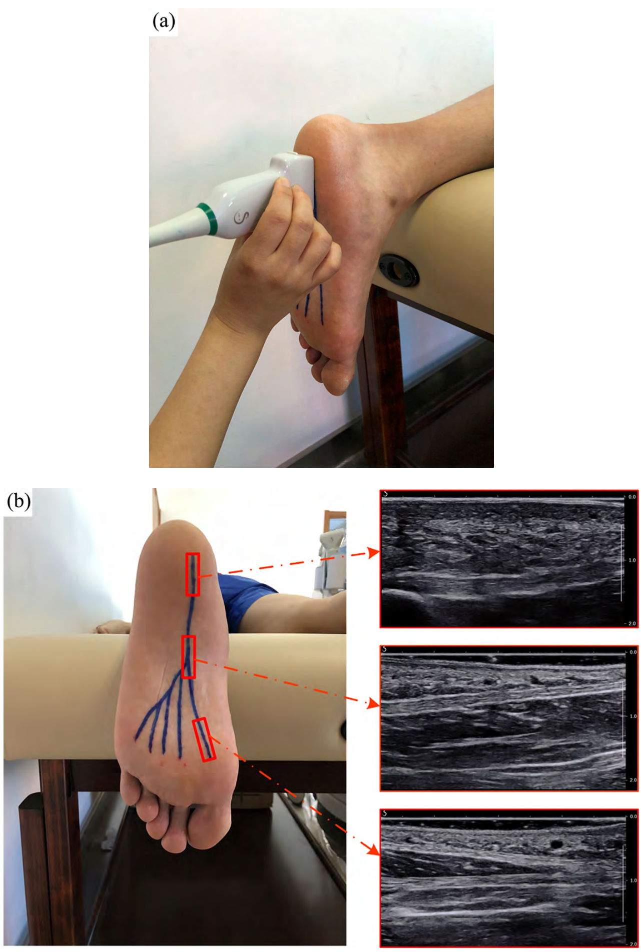

FIGURE 1. **(a) Test position of the subject, and (b) representative two-dimensional images of the front, middle and back of the plantar fascia.**

C. DATA ANALYSIS

All data analyses were performed using the IBM Statistical Package for the Social Sciences (SPSS) statistical software version 21.0 (SPSS Inc., Chicago, IL, USA). The 95% confidence interval (95% CI) and intraclass correlation coefficient (1, 1) ($ICC_{1,1}$) were used to measure and assess the reliability of the test results of the plantar fascia thickness and Young's modulus measurements. Generally, an $ICC_{1,1}$ value within the ranges 0–0.40, 0.41–0.6, 0.61–0.79, and 0.8–1.0 indicate poor, moderate, good, and excellent reliability, respectively.

The variation trend in d and E of the plantar fascia from the calcaneus to the five metatarsals was analyzed by exponential function (first-order exponential decay), and the coefficient of determination (R^2) of each fitting curve was calculated.

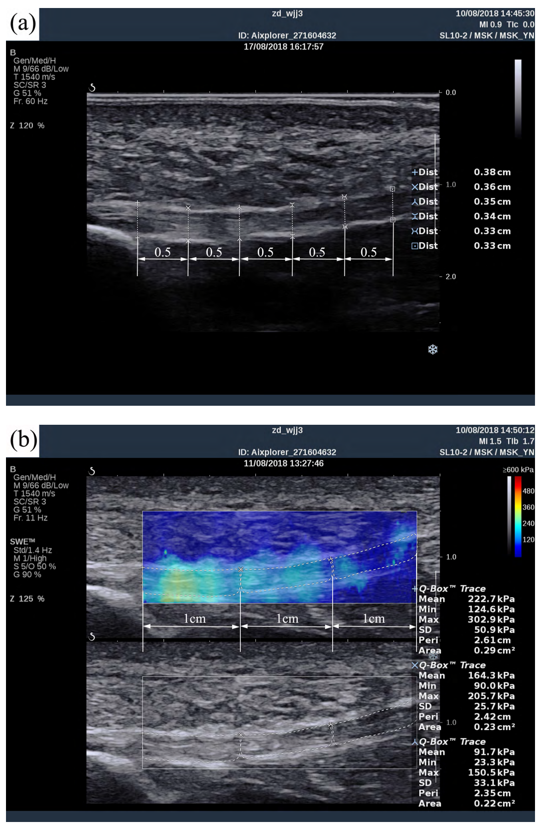

FIGURE 2. **Method of plantar fascia ultrasonic measurement: (a) thickness measurement, and (b) Young's modulus measurement.**

III. RESULTS

A. REPEATABILITY ANALYSIS OF PLANTAR FASCIA THICKNESS AND YOUNG'S MODULUS

The test-retest reliability results of the plantar fascia thickness and Young's modulus of the 10 subjects are listed in Table 1. The results indicate that the $ICC_{1,1}$ ranged from 0.964 to 0.991 and the 95% CI was 0.967–0.996 for the plantar fascia thickness. The $ICC_{1,1}$ of the plantar fascia Young's modulus ranged from 0.950 to 0.985, and the 95% CI for this was 0.953–0.991.

TABLE 1. The test-retest reliability results of plantar fascia thickness and Young's modulus of the 10 subjects.

Subjects	*d*		*E*	
	$ICC_{1,1}$	95% CI	$ICC_{1,1}$	95% CI
#1	0.985	(0.981,0.993)	0.973	(0.976,0.984)
#2	0.979	(0.971,0.989)	0.952	(0.967,0.986)
#3	0.991	(0.979,0.992)	0.985	(0.971,0.990)
#4	0.977	(0.974,0.989)	0.961	(0.963,0.987)
#5	0.964	(0.971,0.982)	0.950	(0.953,0.979)
#6	0.984	(0.967,0.988)	0.967	(0.956,0.982)
#7	9.986	(0.973,0.992)	9.976	(0.954,0.978)
#8	0.985	(0.983,0.996)	0.981	(0.975,0.991)
#9	0.984	(0.985,0.991)	0.982	(0.973,0.986)
#10	0.987	(0.980,0.994)	0.985	(0.981,0.991)

$ICC_{1,1}$: Intra-class correlation coefficient; 95% CI: 95% confidence interval.

B. SPATIAL DISTRIBUTION OF D, THE THICKNESS OF THE PLANTAR FASCIA

The spatial distribution diagram of the thickness of the plantar fascia, *d,* of subject #1 is shown in Fig. 3. The results indicate that the plantar fascia thickness, *d,* was the largest at the tubercle of the calcaneus, and as the plantar fascia extends from the calcaneus to the five toes, the thickness, *d,* of the five fascia bundles decreased and approached the minimum at the tubercles of the five metatarsal bones. From the calcaneus to the five metatarsals, the successive decline in plantar fascia thickness, *d,* can be described by a negative exponential function, as shown in Fig. 4a, and the spatial distribution of the plantar fascia thickness, *d,* for the other 9 subjects showed a similar trend (Fig. S1). Table 2 demonstrates that the coefficient of determination (R^2) for the fitting curve of thickness, *d,* was higher than 0.959 for all ten subjects. The thickness of the plantar fascia, *d,* at the tubercle of the calcaneus was in the range of 0.279-0.39 cm, while the thickness, *d,* of the first bundle of the plantar fascia at the toe ranged from 0.126 to 0.164, the thickness, *d,* of the second bundle of the plantar fascia at the toe ranged from 0.090 to 0.139, the thickness, *d,* of the third bundle of the plantar fascia at the toe ranged from 0.098 to 0.135, the thickness, *d,* of the fourth bundle of the plantar fascia at the toe ranged from 0.07 to 0.115, and the thickness, *d,* of the fifth bundle of the plantar fascia at the toe ranged from 0.04 to 0.1, as shown in Fig. 5a.

C. SPATIAL DISTRIBUTION OF YOUNG'S MODULUS OF THE PLANTAR FASCIA, E

Fig. 3 shows the spatial distribution of the Young's modulus, *E,* of the plantar fascia for subject #1. It can be seen from the figure that the plantar fascia Young's modulus, *E,* is the largest at the tubercle of the calcaneus and, as the plantar fascia extends from the calcaneus to the five toes, Young's modulus, *E,* of the five plantar fascia bundles rapidly decreases and reaches to the lowest value at the tubercles of the five metatarsal bones. From the calcaneus to the five metatarsals, a successive decline in plantar fascia Young's modulus, *E,* can be described by a negative exponential function, as shown in Fig. 4b, and the spatial distribution of plantar fascia Young's modulus, *E,* of the other 9 subjects demonstrates a similar trend (Fig. S1). Table 2 demonstrates that the coefficient of determination (R^2) of the fitting curve of Young's modulus, *E,* is higher than 0.961 for all ten subjects. The plantar fascia Young's modulus, *E,* of the tubercle of calcaneus is in the range of 168-304 kPa, Young's modulus, *E,* of the first bundle of plantar fascia at the toe ranges from 40 to 61.375 kPa, Young's modulus, *E,* of the second bundle of plantar fascia at the toe ranges from 27.6 to 37.5 kPa, Young's modulus, *E,* of the third bundle of plantar fascia at the toe ranges from 27 to 43.08 kPa, Young's modulus, *E,* of the fourth bundle of plantar fascia at the toe ranges from 17 to 28.897 kPa, and the Young's modulus, *E,* of the fifth bundle of plantar fascia at the toe ranges from 14.7 to 25.93 kPa, as shown in Fig. 5b.

D. DISCUSSION

Plantar fasciitis is a type of self-limiting disease that always recurs after illness, and it is lighter in one period of time and heavier in another period. Although it is not life-threatening, it seriously affects the quality life of patients. Meanwhile, chronic plantar fasciitis can seriously destroy the biomechanical equilibrium of the structure of the plantar fascia, so it is important to study the abnormal morphological and mechanical properties of the plantar fascia for the purpose of achieving an early diagnosis of plantar fasciitis [23], [24]. The traditional method for diagnosing plantar fasciitis has been replaced by new diagnostic techniques, such as ultrasound, magnetic resonance imaging (MRI) and computed tomography (CT), because of the certain subjectivity and uncertainty of the condition. Ultrasound has advantages of a simple operation, high timeliness, and noninvasiveness, so it is more easily accepted by most patients. In this study, repeatability analysis was used to evaluate the accuracy of the thickness and Young's modulus of the plantar fascia. The intraclass correlation between the thickness and Young's modulus of the plantar fascia, $ICC_{1,1}$, ranged from 0.950 to 0.991 and the 95% CI was 0.953 to 0.996, which indicated that the thickness and Young's modulus of the plantar fascia exhibited excellent retest reliability. The results show that ultrasound is a reliable, repeatable technique to be used to measure the morphology and mechanical properties of the plantar fascia. Furthermore, it is expected that ultrasound would be a promising tool to study the pathogenesis and provide early diagnosis of plantar fasciitis, and could be applied to clinical rehabilitation practice.

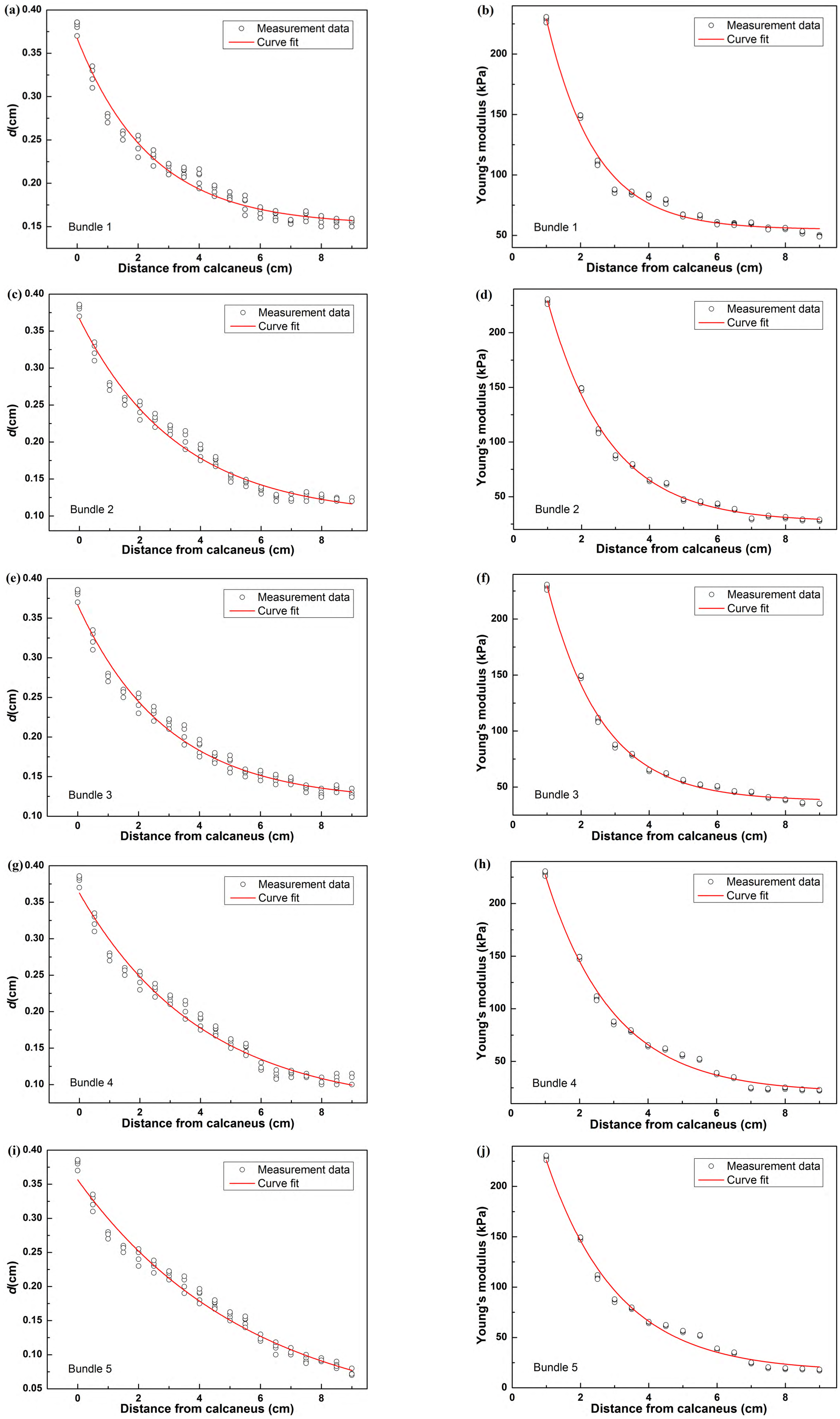

FIGURE 3. The curve of the thickness, *d*, and Young's modulus, *E*, of the plantar fascia from the calcaneus to the five metatarsals of subject #1: (a) thickness, *d*, of the first bundle, (b) Young's modulus, *E*, of the first bundle, (c) thickness, *d*, of the second bundle, (d) Young's modulus, *E*, of the second bundle, (e) thickness, *d*, of the third bundle, (f) Young's modulus, *E*, of the third bundle, (g) thickness, *d*, of the fourth bundle, (h) Young's modulus, *E*, of the fourth bundle, (i) thickness, *d*, of the fifth bundle, and (j) Young's modulus, *E*, of the fifth bundle.

TABLE 2. The determination coefficients, R2, of the fitted curves of d and E of the plantar fascia from the calcaneus to the five metatarsals.

Subjects	$R^2(d)$					$R^2(E)$				
	Bundle 1	Bundle 2	Bundle 3	Bundle 4	Bundle 5	Bundle 1	Bundle 2	Bundle 3	Bundle 4	Bundle 5
#1	0.975	0.980	0.982	0.978	0.979	0.987	0.995	0.995	0.990	0.988
#2	0.971	0.981	0.980	0.980	0.978	0.995	0.994	0.993	0.994	0.995
#3	0.986	0.987	0.986	0.983	0.985	0.980	0.970	0.974	0.978	0.980
#4	0.985	0.978	0.980	0.985	0.984	0.989	0.993	0.990	0.992	0.995
#5	0.989	0.986	0.988	0.988	0.991	0.993	0.984	0.982	0.984	0.986
#6	0.988	0.981	0.976	0.980	0.981	0.961	0.968	0.965	0.969	0.967
#7	0.991	0.984	0.980	0.988	0.989	0.994	0.996	0.996	0.995	0.993
#8	0.981	0.987	0.990	0.980	0.984	0.983	0.980	0.976	0.987	0.984
#9	0.984	0.988	0.988	0.988	0.980	0.994	0.977	0.976	0.980	0.982
#10	0.989	0.964	0.959	0.969	0.978	0.987	0.972	0.978	0.981	0.982

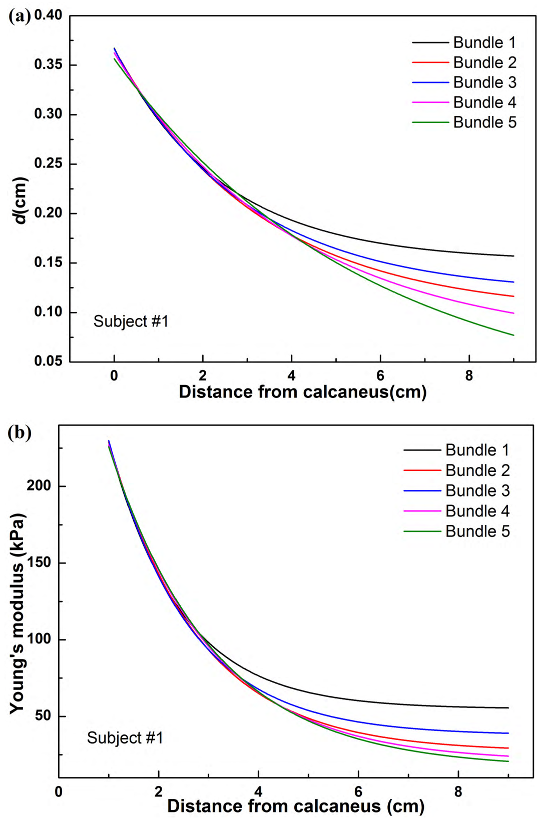

FIGURE 4. Distribution of thickness and Young's modulus for the plantar fascia of subject #1: (a) thickness, and (b) Young's modulus.

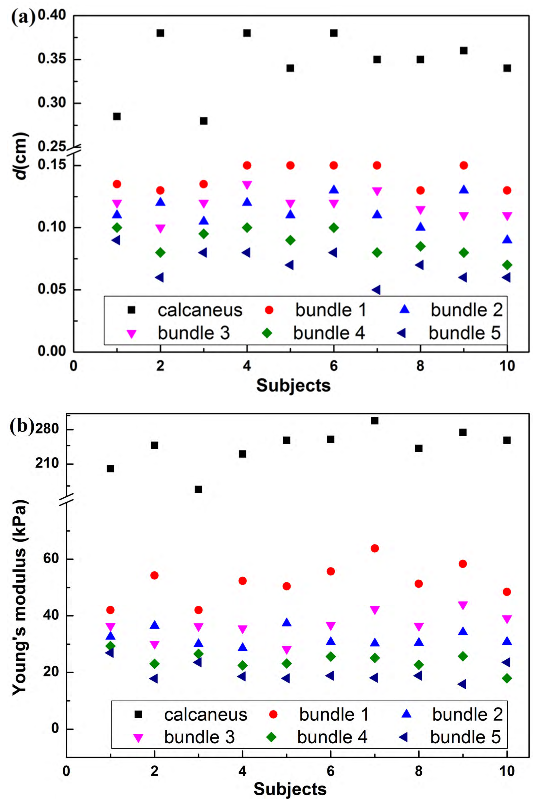

FIGURE 5. Distribution of plantar fascia thickness and Young's modulus at the tubercle of the calcaneus and metatarsal bone of the 10 subjects: (a) thickness, and (b) Young's modulus.

In the measurement of the thickness of the plantar fascia, researchers have performed extensive work through anatomy [1], [15], [24], ultrasound [25]–[27], MRI [28], [29], etc., and some progress has been made. Especially in the field of ultrasound, some empirical criteria for the clinical diagnosis of plantar fasciitis have been formed. According to standards, the thickness of the plantar fascia at the normal calcaneus is less than 4 mm, and when the thickness is greater than 4 mm accompanied by echo reduction, this can lead to plantar fasciitis [26], [27], [30]–[32]. All subjects recruited in this study were healthy. The thickness of the plantar fascia, *d,* at the calcaneus ranged from 0.279 to 0.39, which was consistent with the clinical standard.

The measurement results of this study showed that the thickness, *d,* and Young's modulus, *E,* were largest at the tubercle of the calcaneus, which demonstrated that planar fascia had high stiffness and low elasticity at the calcaneus and that the effective area attached to the calcaneus was small. During normal walking, the plantar fascia alternates between relaxation and tension, bearing the greatest pulling force at the calcaneus. Crary *et al.* [33] found, through experiments, that the plantar fascia was the first to resist deformation when loading on the foot was induced. The tension of the plantar fascia causes the fascia and calcaneus to be pulled, and the plantar fascia is affected by this repeated pulling. Older age and the long-term stress beyond physiological limits also affect the plantar fascia elasticity. The fact that the plantar fascia is most likely to tear at the calcaneus [34] is caused by many factors including repeated pulling, long-term and over-physiological stress, high stiffness and low elasticity of the plantar fascia at the calcaneus.

The measured results of this study showed that the thickness, *d,* and Young's modulus, *E,* of the plantar fascia at the first metatarsal were obviously higher than the *d* and *E* at metatarsals 2-5, and the thickness, *d,* and Young's modulus, *E,* of the plantar fascia at the fifth metatarsal were obviously lower than the *d* and *E* at metatarsals 1-4. The results showed that the medial longitudinal arch was significantly higher than the lateral longitudinal arch in the distribution of force at the front of the longitudinal arch. This also explains why chronic medial longitudinal arch collapse occurs in patients with heel pain after plantar fasciolysis, leading to complications such as low arch and middle-foot varus [35]. We also found that both the thickness, *d,* and Young's modulus, *E,* of the plantar fascia show simple and specific spatial dependence with the characteristics of gradient distribution. The results demonstrated that the thickness, *d,* and Young's modulus, *E,* of five plantar fascia bundles were the largest at the calcaneus. As the plantar fascia extends from the calcaneus to the five toes, both the thickness, *d,* and Young's modulus, *E,* of the five plantar fascia bundles showed a downward trend in negative exponential function and approached the minimum at the five metatarsus ends. This finding provides a better understanding of the natural heterogeneous mechanical properties of the plantar fascia and a basis for further investigation. It avoids the limitation of simplifying the plantar fascia into homogeneous and isotropic materials in the existing finite element models of the foot. Additionally, it provides accurate material parameters for a finite element model of the musculoskeletal system of the foot, which is beneficial for obtaining more accurate simulation results. In the future, it is important to study the associated biomechanical behavior of this spatial-dependent property of the plantar fascia and how it is beneficial to the human body.

In this study, the distribution characteristics of the plantar fascia thickness, *d,* and Young's modulus, *E,* are consistent, and they seemed to show some specific associations, which may be due to the similarity of the tissue morphology and materials for adapting to the same function. Evidently, only healthy people satisfy this rule. In previous studies of plantar fasciitis, researchers conducted a comparative study of patients and healthy people, and it was found that the thickness, *d,* increased [11], [32], [36] and Young's modulus, *E,* decreased [11], while the thickness, *d,* and Young's modulus, *E,* trended in opposite directions. Cardinal *et al.* [36] analyzed the cause of the increase in plantar fascia thickness, *d,* at the calcaneus due to a chronic inflammatory response and tissue edema on the affected side. Wu *et al.* [11] inferred that the decrease in Young's modulus, *E,* of the plantar fascia at the calcaneus was related to the growth of a large number of new blood vessels in the plantar fascia. At present, study of the distribution characteristics of plantar fascia thickness, *d,* and Young's modulus, *E,* in patients with plantar fasciitis is still incomplete. This study only conducted preliminary trials for a specific number of healthy people, and it is essential to explore the difference in these measures compared to patients.

In this paper, using two-dimensional ultrasound and the SWE technique, the overall spatial distribution characteristics of the plantar fascia thickness, *d,* and Young's modulus, *E,* were systematically studied, and the relationship between *d* and *E* was also explored. The study not only provides real morphology and material properties for the finite element model of plantar fascia but also develops a more targeted plan of the plantar fasciocutaneous release according to the abnormal condition of fascia mechanics in patients. However, there are a few limitations to our study. First, the study only explored the mechanical properties of the plantar fascia in healthy people and did not include patients with plantar fasciitis. There are differences in the thickness, *d,* and Young's modulus, *E,* of the plantar fascia at the calcaneus between patients and healthy people. Additionally, it is necessary to explore the spatial distribution characteristics between them. Second, only healthy young males were recruited in the study. Some studies have confirmed that the mechanical properties of the plantar fascia were affected by the age, weight, and other factors [37], [38]. Subjects with similar body conditions are chosen to assure repeatability of the measurements, which demonstrates that ultrasound is reliable to be used in evaluating the morphology and mechanical properties of plantar fascia. In the future, the effect of plantar fasciitis, age, weight, and gender on the thickness, *d,* and Young's modulus, *E,* of the plantar fascia would be studied.

IV. CONCLUSIONS

Ultrasound is a reliable, repeatable, in vivo technique that is used to measure the thickness, *d*, and Young's modulus, E, of the plantar fascia. Both the thickness, d, and Young's modulus, E, of the plantar fascia showed simple and specific spatial dependence with the characteristics of gradient distribution. The results indicated that the thickness, *d,* and Young's modulus, *E,* of five plantar fascia bundles were largest at the calcaneus. As the plantar fascia extends from the calcaneus to the five toes, both the thickness, *d,* and Young's modulus, *E,* of the five plantar fascia bundles showed a downward trend in negative exponential function and approached the minimum at the five metatarsals. This study provides a foundation of research for understanding the mechanical properties and investigating the spatial heterogeneity of plantar fascia in-depth. For healthy individuals, the distributions of the plantar fascia thickness, *d,* and Young's modulus, *E,* were consistent; however, there may be differences in the distribution characteristics of the plantar fascia thickness, *d,* and Young's modulus, *E,* in patients with plantar fasciitis, which warrants further study.

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