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ORIGINAL ARTICLE

Observational Study

Application of real-time shear wave elastography to Achilles tendon hardness evaluation in older adults

Xuan He, Xin Wei, Jia Hou, Wei Tan, Ping Luo

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Abstract

BACKGROUND

Real-time shear wave elastography (SWE) is a non-invasive imaging technique used to measure tissue stiffness by generating and tracking shear waves in real time. This advanced ultrasound-based method provides quantitative information regarding tissue elasticity, offering valuable insights into the mechanical properties of biological tissues. However, the application of real-time SWE in the musculoskeletal system and sports medicine has not been extensively studied.

AIM

To explore the practical value of real-time SWE for assessing Achilles tendon hardness in older adults.

METHODS

A total of 60 participants were enrolled in the present study, and differences in the elastic moduli of the bilateral Achilles tendons were compared among the following categories: (1) Age: 55-60, 60-65, and 65-70-years-old; (2) Sex: Male and female; (3) Laterality: Left and right sides; (4) Tendon state: Relaxed and tense state; and (5) Tendon segment: Proximal, middle, and distal.

RESULTS

There were no significant differences in the elastic moduli of the bilateral Achilles tendons when comparing by age or sex ($P > 0.05$). There were, however, significant differences when comparing by tendon side, state, or segment ($P < 0.05$).

CONCLUSION

Real-time SWE plays a significant role compared to other examination methods in the evaluation of Achilles tendon hardness in older adults.

Key Words: Aged Achilles tendon; Real-time; Shear wave elastography; Young's modulus; Muscle stiffness

Core Tip: We aimed to quantify Achilles tendon stiffness in older adults using real-time shear wave elastography (SWE) technology, and to analyze the overall change in Achilles tendon elasticity at different ages. Sixty participants were enrolled in the present study, and the differences in the elastic moduli of the bilateral Achilles tendons were compared among participants of different ages and sexes, as well as those with different tendon sides, states, and segments. After the research, we concluded that real-time SWE plays a significant role compared to other examination methods in the evaluation of Achilles tendon hardness in older adults.

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INTRODUCTION

The Achilles tendon is the largest tendon in the human body and is comprised of three component parts: the tendon-muscle junction, tendon, and tendon-heel bone junction. It plays very important roles in human locomotion, including walking, running, jumping, and even climbing stairs, and is also the tendon most prone to rupture during exercise[1]. The unique biomechanical properties of the Achilles tendon mean that it is strong enough to withstand the high tensile stresses of muscle contraction, as well as the compressive and shear forces which occur during angulation[2]. When the Achilles tendon undergoes chronic degeneration, which occurs due to a variety of factors, such as decreased blood supply, aging, repeated trauma, and drug-related effects, the internal collagen fiber structure and arrangement, nuclear morphology, and morphological diversity changes. In turn, the normal function and biomechanical properties of the tendon are affected, making it easy for the tendon to rupture under the action of an external force[3,4]. With the ongoing improvement to people's living standards, increased emphasis regarding health awareness and delayed retirement ages, the proportion of older adults aged 55-70 years who continue to contribute to their jobs and engage in physical exercise has increased significantly. Owing to the degeneration of body functions in older adults, even minor activities may cause soft tissue damage, and the pain may not be obvious, or may be difficult to detect. Due to such delayed detection, therefore, it is likely that the optimal treatment window will be missed[5].

Various tissues in the body have different elastic coefficients, and strains (primarily morphological changes) to these tissues change after the application of external forces or alternating vibrations. Ultrasound elastography collects the signals of each segment of a designated area during a certain period of time, which are then comprehensively analyzed using a combined autocorrelation method. The subsequent results produce gray-scale or color-coded image[6]. Real-time shear wave elastography (SWE) is a new real-time two-dimensional (2D) elastography method for estimating stiffness quantitatively in kilopascals (kPa). Real-time SWE uses focused ultrasonic beams to induce a radiation force in tissues, as well as ultrasonic imaging sequences capable of observing movement in real-time[7]. In real-time SWE, a transducer emits ultrasound waves that induce shear waves within the tissue of interest. These shear waves propagate through the tissue and their velocity is directly related to the tissue's stiffness. By analyzing the propagation speed of these shear waves, the technique can calculate the elastic modulus of the tissue, which reflects its stiffness or hardness[8]. Real-time SWE can provide information surrounding tissue texture, elastic hardness, elastic value, shape and area ratios, and establish another independent dimension regarding tissue information, which has broad prospects for clinical applications involving almost all organs of the human body[9]. Real-time SWE has been widely used to evaluate the liver, gallbladder, spleen, pancreas, kidney, thyroid, breast, cardiovascular, nerve, prostate, uterine tissues, and various lesions in tissues, as well as in radiofrequency ablation and anti-angiogenesis tumor therapies[10].

Real-time SWE is a popular research topic in the field of ultrasound imaging[11]; Using SWE, Caroline Ewertsen and colleagues examined the biceps brachii, gastrocnemius, and quadriceps muscles of healthy volunteers[12]. Wang *et al*[13] used SWE to measure shear wave velocity of supraspinatus tendons and muscles to help predict residual tendon mass and found that this is one of the key factors in successful rotator cuff repair. A recent study using the SWE technique found that ankle joint position and probe frequency are factors that affect the elastic value of the Achilles tendon[14]. Another study evaluated the association of renal elasticity with renal fibrosis in patients with chronic kidney disease using real-time SWE[15]. However, the application of real-time SWE in the musculoskeletal system and sports medicine in older adults of different ages has not been extensively studied.

With the increased clinical promotion and application of real-time SWE, it is also being increasingly applied to study the skeletal muscle system. The purpose of the present study, therefore, was to collect data concerning Achilles tendon stiffness in older adults, aged 55-70 years old, to quantify Achilles tendon stiffness in these older adults using real-time SWE technology, and to analyze the overall change in Achilles tendon elasticity at different ages, and promote further research regarding the use of real-time SWE to evaluate the health status of tendons in different populations and provide information for clinical decision-making.

MATERIALS AND METHODS

General information

A total of 60 subjects without any obvious limitations in terms of ankle motion were randomly selected from inpatients in our hospital and were enrolled in the present study. The subjects were between 55 and 70 (average 62.15 ± 1.25) years old. Of the 60 subjects, 45 were women and 15 were men. The participants were divided into three groups: 55-60 years old (n = 35), 61-65 years old (n = 14), and 66-70 years old (n = 11).

Inclusion criteria: (1) Age between 55 and 70 years; and (2) No activity.

Exclusion criteria: (1) Patients with a history of neuromuscular diseases or musculoskeletal injuries involving the lower extremities; (2) Patients who had recently (within 1 month) taken drugs that affect muscle function; (3) Patients with an obvious unilateral dominant foot (the maximum circumference difference between the calf and thigh on both sides should be < 10%); (4) Heart disease or severe asthma; (5) Abnormal gait (caused by central nervous system or peripheral nerve injury, bone and joint disease, lesions, or vascular skin disease); and (6) Systemic diseases such as fibromyalgia, degenerative joint disease, calcific Achilles tendinitis, chronic Achilles tendon pain, rheumatoid arthritis, and neuropathy.

Instruments and methods

Real-time SWE procedure: The present study utilized a Supersonic Aixplorer (France Acoustics) ultrasound instrument and a linear array probe to perform SWE examinations, with the probe frequency set at 4-15 MHz and probe model L11-3U. Patients were instructed to lay in the prone position with their legs stretched and relaxed, feet hanging off the edge of the examination table, toes pointed down and perpendicular to the horizontal plane, and Achilles tendon fully exposed. SWE examination was performed at least 10 minutes after the tendon is completely relaxed, using the L18-5 linear probe and then using the L20-6 hockey stick probe, which was selected by default musculoskeletal parameters. The Q-box depth was set to 1 cm. After a uniform color diagram was obtained, it was measured three times and the average values were taken for further analysis. Between each collection, the probe was removed from the patient's skin.

First, with the Achilles tendon in a relaxed state, the parameter mode was adjusted so that the Achilles tendon and its surrounding tissues were clearly displayed in 2D ultrasound mode. The Achilles tendon was divided into proximal (muscle-tendon junction), middle (2-6 cm above the attached end of Achilles tendon), and distal segments (attached end of Achilles tendon), and each segment was scanned vertically and continuously along the maximum long-axis section. After obtaining a stable image, SWE was performed using a 1.0 cm × 1.0 cm sampling frame. Once the elasticity map was complete, stable, and without defects, 3 mm regions of interest were used to measure and record the elastic modulus (kPa). Three measurements were obtained from each section of the Achilles tendon, at different locations on the elasticity map, from which average values were obtained. The average elastic modulus of the Achilles tendon on each side was calculated from the mean values of the three sections. The patient was then asked to stretch the dorsum of the foot by 15°, stretching the Achilles tendon to its greatest extent, such that the tendon was in a tense state. The elastic modulus of the three segments of the Achilles tendon was measured again. The average value for each segment and that for each unilateral Achilles tendon were calculated separately. All measurements were obtained by the same sonographer.

Statistical analysis

SPSS v.26.0 software was used for data processing, and measurement data are described by mean ± SD. Analysis of variance was used to compare multiple groups of measured data, and the least significant difference method was used to compare groups. Statistical significance was set as $P < 0.05$.

RESULTS

Comparison of elastic moduli in different age groups, relaxed state

Elastic moduli of the bilateral Achilles tendons in the relaxed state did not significantly differ among the groups categorized by age ($P > 0.05$). Further details are presented in Table 1.

Comparison of elastic moduli between sexes, relaxed state

Elastic moduli of the bilateral Achilles tendons in the relaxed state did not significantly differ between the groups categorized by sex ($P > 0.05$). Further details are presented in Table 2.

Comparison of elastic moduli between left and right sides, relaxed state

Elastic moduli of the Achilles tendon in the relaxed state differed significantly between the left and right sides ($P < 0.05$). Further details are presented in Table 3.

Comparison of elastic moduli of the bilateral Achilles tendon, various states

Elastic moduli of the Achilles tendon differed significantly based on the state of relaxation and tension ($P < 0.05$). Further details are presented in Table 4.

Comparison of elastic moduli among the three segments, relaxed state

Elastic moduli of the Achilles tendon in the relaxed state differed significantly based on the segment involved ($P < 0.05$). Further details are presented in Table 5.

Table 1 Elastic modulus of bilateral Achilles tendon in relaxed state among multiple groups of measurement data, mean ± SD

Variable		55-60 (*n* = 35)	61-65 (*n* = 14)	66-70 (*n* = 11)	*F* value	*P* value
Relaxed modulus of elasticity	Left average	326.39 ± 81.44	315.09 ± 57.09	365.51 ± 63.38	1.609	0.209
	Right average	354.63 ± 90.1	321.42 ± 59.88	406.98 ± 127.42	2.666	0.078

Table 2 Elastic modulus of bilateral Achilles tendon in relaxed state, mean ± SD

variable		Male (*n* = 15)	Female (*n* = 45)	*t* value	*P* value
Relaxed modulus of elasticity	Left average	323.69 ± 61.47	333.33 ± 78.55	-0.433	0.667
	Right average	352.33 ± 78.6	357.86 ± 100.4	-0.194	0.847

Table 3 Elastic modulus of Achilles tendon in relaxed state, mean ± SD

Variable	Left average	Right average	*t* value	*P* value
Relaxed modulus of elasticity	330.92 ± 74.27	356.48 ± 94.81	-2.849	0.006

Table 4 Elastic modulus of bilateral Achilles tendon, mean ± SD

Variable	Relaxed modulus of elasticity	Elastic modulus under tension	*t* value	*P* value
Left average	330.92 ± 74.27	762.92 ± 26.02	-44.262	< 0.001
Right average	356.48 ± 94.81	768.74 ± 24.05	-34.413	< 0.001

Table 5 Elastic modulus of two groups of three segments of bilateral Achilles tendon in relaxed state, mean ± SD

Variable	Relaxed modulus of elasticity	*t* value	*P* value
Far left	288.19 ± 83.67	-4.288	<0.001
Middle left	328.11 ± 81.92		
Far left	288.19 ± 83.67	-6.206	<0.001
Near left	376.46 ± 105.42		
Middle left	328.11 ± 81.92	-4.326	<0.001
Near left	376.46 ± 105.42		
Far right	329.61 ± 118.97	-2.309	0.024
Middle right	353.75 ± 98.01		
Far right	329.61 ± 118.97	-4.424	<0.001
Near right	386.08 ± 103.78		
Middle right	353.75 ± 98.01	-3.144	0.003
Near right	386.08 ± 103.78		

DISCUSSION

The power behind the activity of the lower limb muscle group primarily originates from the muscle action of the lower limbs and trunk. Muscle activity helps to maintain balance, absorb shock, accelerate and decelerate motion, and promote limb movements[16]. The quadriceps are integral in hip flexion and knee extension, and act as a knee extensor in the first 20% of the jogging cycle. After the heel departs the ground, the quadriceps also play a role in hip flexion and knee extension. When the anterior thigh muscles, such as the quadriceps, relax, the posterior thigh muscles, such as the biceps femoris, contract to flex the calf. When quadriceps and other anterior thigh muscles contract, the biceps femoris and other posterior thigh muscles relax, working in tandem to flex and extend the calf. When the gastrocnemius lifts the heel off the ground, its concentric forceful contraction reaches a peak, producing a powerful kicking action that forces the body's center of gravity forward. The tibialis anterior is the dorsiflexor of the ankle, contracting when the heel strikes and the toes leave the ground during jogging to control the plantar flexion of the ankle joint[17]. The Achilles tendon is the largest tendon in the human body, formed by fusion of the calf triceps muscles (soleus, gastrocnemius inner, and outer heads) approximately 15 cm above the heel. It is primarily composed of dense connective tissue with a scarce blood supply and connects the muscle groups at the back of the calf to the calcaneus. The primary function of the Achilles tendon is to flex the calf and plantarflex the foot. Together with the calf muscles, it plays an important role in numerous movements, such as standing upright, jumping, and running. During physiological exercise, the physical characteristics of the muscles change dynamically to adapt to the needs of various physiological and motor functions. Quantification of muscle physical properties helps in understanding their physiological function, of which muscle stiffness is an important parameter[18]. Muscle stiffness can change under a variety of conditions, such as active contraction and passive stretching, and is important for muscles to function efficiently[19]. Moreover, a strong linear relationship exists among muscle stiffness, strength, and tension[20].

The Achilles tendon, as a viscoelastic tendon structure that maintains the stability of ankle joint activities, has unique biomechanical properties, and its elasticity and hardness are a manifestation of these biomechanical properties. Achilles tendon injuries are the most common types of tendon injuries, and their incidence has increased in recent years. Because the Achilles tendon is a poorly vascularized tissue, it is prone to numerous post-injury complications, and is difficult to repair and heal. Stress and injury to the Achilles tendon affect its mechanical properties[21]; therefore, quantification of muscle stiffness aids in understanding the physiological functions of skeletal muscles. Understanding changes in muscle stiffness in older adults who have suffered an Achilles tendon injury is necessary to guide the management of clinical treatment and rehabilitation training. In sports medicine, quantifying the elastic characteristics of skeletal muscle is helpful for understanding the impact of changes in muscle stiffness on pain or injury in older adults with Achilles tendon injury, along with its underlying mechanisms. Numerous methods, such as soft tissue ultrasound palpation and magnetic resonance elastography, are available for measuring muscle stiffness[22,23]. In the diagnosis of Achilles tendon injury, traditional ultrasound technology is inexpensive, noninvasive, reproducible, and can detect morphological changes in muscles; however, biomechanical evaluations and quantitative analyses cannot be performed.

In most skeletal muscle examinations performed using ultrasound, an operator applies manual pressure to the patient's body using an ultrasound probe, causing the tissue to deform, with softer tissues deforming more and experiencing stress. In contrast to harder tissues, the corresponding strain rate can be obtained by comparing the strain rate in the static state. A major problem with semiquantitative analysis is that the operator may find it challenging to maintain a constant pressure each time a force is applied. SWE is a new generation of elasticity imaging technology that obtains information concerning hardness of the examined tissues based on the elastic modulus calculated during an elasticity test performed without compressing the tissue[24]. SWE is used to quantify tissue stiffness using the shear wave method, and those data are used to analyze the results. In the SWE method, 3ρC2 (E = Young's modulus, ρ is tissue density, C is shear wave velocity, and the resulting Young's modulus (in Pascal) can directly characterize mechanical properties of the tissue. SWE allows for the real-time quantitative analysis of the elastic properties of tissues, and the resulting color-coded map can distinguish between various tissues based on their degree of elasticity. The color range reflects the stiffness of the tissue; that is, Young's modulus. When the Young's modulus was elevated, the SWV was higher, indicating greater tissue stiffness[25]. Researchers first used ultrasound elastography to study the musculoskeletal structure of healthy adults, and found that musculoskeletal tissue has a relatively high hardness[26]. Additionally, the experimental results of other studies have shown a good linear relationship between the Young's modulus obtained by SWE and muscle activity reflected by electroencephalogram results. Because muscle mechanical properties are nonlinear, Young's modulus should exhibit a certain relationship with muscle tension; therefore, SWE can accurately reflect and evaluate muscle tension[27]. As SWE is a real-time, full-amplitude, and fully quantitative imaging system for human tissue stiffness evaluation, this technology was used in a previous multicenter study to evaluate the Achilles tendon in normal people. The results showed that there were significant differences in elasticity of the Achilles tendon in different postures, although the parallelism between the probe and Achilles tendon affected the test results. Therefore, when testing elasticity of the Achilles tendon, the foot on the side being tested should be allowed to hang naturally, and the probe should be placed parallel to the tendon. Simultaneously, the examiner should move calmly, gently lower the probe, and obtain the most stable Young's modulus values when the long axis of the Achilles tendon is clearly visible.

The results of the present study showed that among the 60 older adult participants, there was no statistically significant difference in the elastic moduli of the Achilles tendon in a relaxed state based on age or sex (see Tables 1 and 2, respectively, for details). Achilles tendon stiffness does not increase or decrease regularly with age, and the changes between sexes have no definitive significance. Although the change in Achilles tendon stiffness in this age group is not specific, and the correlation with different sexes was not close enough, we obtained a corresponding reference range for estimating the normal Achilles tendon elastic modulus value in older adults. When the Achilles tendon was in the relaxed state, the elastic moduli of the two sides were different (see Table 3 for details), with that of the right side higher than that of the left. This result is most likely related to the fact that the right lower limb plays a key role in controlling various bodily activities. With the Achilles tendon in relaxed and tense states, there was a significant difference in its elastic modulus, as the hardness in the tense state was significantly higher than that in the relaxed state (Table 4). Aubry *et al*[28] and Slane *et al*[29] also demonstrated that the elastic modulus of the Achilles tendon increases with a gradual increase in the degree of dorsiflexion of the ankle joint, and that dorsiflexion of the ankle joint can give traction to the Achilles tendon, which has a greater effect on the medial side of the Achilles tendon. Such an unbalanced distribution is likely the key reason for Achilles tendon injuries. Dorsiflexion is frequently involved in various activities of the ankle joint. Therefore, older adults who walk, run, or jump often are more prone to Achilles tendon injuries than their less active counterparts. Older adults who love sports should be taught how best to prevent Achilles tendon injuries and evaluate its health so that disorders can be prevented before they occur. Here, when the Achilles tendon was in a relaxed state, the difference in elastic modulus was statistically significant among the three segments (Table 5). Moreover, the hardness of the Achilles tendon gradually decreased from near to far. Some foreign scholars compared Achilles tendon elastography with histological diagnosis, which showed that elastography could accurately evaluate the degree of Achilles tendon degeneration[30]. The hardness value of mild degeneration was reduced, while that of severe degeneration increased due to the presence of calcification. Although no pathological changes were detectable by ultrasound in the middle and distal parts of the Achilles tendon, the histology is very likely to show slight degeneration and tendency to injury, inflammation, and other related problems.

The incidences of chronic Achilles tendon disorders and rupture are increasing in older adults. Achilles tendon rupture treatment aims to fully restore the physiological length, integrity, and toughness of the tendon, plantar flexion force of the triceps of the lower limbs, and function of the ankle joint. Ultrasound SWE is a new imaging technology and a research hotspot which has emerged in recent years. It provides hardness information by detecting the Young's modulus value of a given tissue, and gradually demonstrates its unique application value in clinical practice. The change in Young's modulus of elasticity is an important indicator for determining health of the Achilles tendon, and can help clinically evaluate the condition of the tendon, formulate treatment plans based on that condition, and help patients recover better.

The findings of this study have the potential to provide clinicians with a non-invasive and quantitative method for assessing Achilles tendon stiffness in older adults. This information is crucial for early detection of tendon degeneration, monitoring disease progression, and evaluating the effectiveness of treatment interventions. Real-time SWE offers a direct measurement of tissue elasticity, which can complement traditional imaging modalities and subjective clinical assessments, leading to more accurate and objective evaluations of tendon health. Moreover, by focusing on older adults, this study addresses a population that is particularly susceptible to tendon injuries and degenerative changes. Understanding age-related alterations in Achilles tendon hardness can help in identifying individuals at higher risk of tendon pathologies and implementing preventive strategies to maintain tendon health in the aging population. In the broader context of musculoskeletal imaging research, this study contributes to the growing body of knowledge surrounding the utility of real-time SWE in assessing tendon properties. By demonstrating the feasibility and potential clinical value of this imaging technique in older adults with Achilles tendon concerns, our findings expand the application of elastography in musculoskeletal imaging and pave the way for further research in this area.

Overall, the implications of this study lie in its potential to advance the field of musculoskeletal imaging by providing a novel approach for evaluating Achilles tendon hardness in older adults. The insights gained from this research can inform clinical decision-making, improve patient care, and stimulate further investigations into the use of real-time SWE for assessing tendon health in diverse populations.

CONCLUSION

In summary, the application of real-time SWE to assess Achilles tendon stiffness in older adults can provide quantitative clinical indicators of Achilles tendon health and guide rehabilitation treatment.

FOOTNOTES

Author contributions: He X was the guarantor and designed the study; He X, Wei X, Hou J participated in the acquisition, analysis, and interpretation of the data, and drafted the initial manuscript; He X, Wei X, Hou J, Tan W, Luo P revised the article critically for important intellectual content.

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