Sonographic Evaluation of the Effect of Long-Term Exercise on Achilles Tendon Stiffness using Shear Wave Elastography

Abstract

Objectives: This study aimed to assess the feasibility of using quantitative Shear Wave Elastography (SWE) to assess the stiffness (Young's modulus) of Achilles tendon and to investigate the effect of long-term weight-bearing exercise on the stiffness of human Achilles tendon by comparing the frequent and infrequent exercise groups.

Design: Case-control study.

Methods: A total of 36 healthy subjects aged 19-25 were recruited. Subjects were categorized into frequent and infrequent exercise groups dependent on their level of lower limb weight bearing exercise. B-mode and shear-wave ultrasound examination of Achilles tendon were performed. Measurements of the Achilles tendon stiffness were conducted with the foot position standardized by an ankle fixer. To evaluate inter and intra-operator reliability of Young's modulus measurements, each subject was scanned by three operators and each operator scanned the subject three times.

Results: The intra-operator reliability of Young's modulus measurements ranged between 0.803 and 0.845. The inter-operator measurement reliability was 0.585. Result showed that Achilles tendon on non-dominant ankle in frequent-exercisers (median: 320.1kPa) was significantly stiffer than that in infrequent-exercisers (median: 296kPa) ($p<0.05$), whereas there was no significant difference in Achilles tendon stiffness on dominant ankle between the two groups ($p>0.05$).

Conclusions: Shear Wave Elastography is feasible for assessing the Achilles tendon's stiffness in vivo. The stiffness of Achilles tendon of frequent-exercisers was significantly higher than that of infrequent-exercisers on non-dominant ankle but not on dominant ankle. With the use of an ankle fixer, there was high repeatability and moderate reproducibility in SWE measurement of Achilles tendon stiffness.

Keywords: physical activity, exercise physiology, ultrasonography, elasticity imaging techniques, elastic modulus

Introduction

Achilles tendon is the strongest and largest tendon in the human body, originating from the aponeurosis of Soleus and gastrocnemius muscles and inserts at the mid-portion of the posterior calcaneal tuberosity. Owing to increasing recreational athletics and greater physical demand on sport, the number of Achilles tendon injuries has risen drastically [1,2]. People who perform frequent exercise, especially athletes, have a higher chance of Achilles tendinopathy than those who infrequently perform exercise [3]. The current practice for diagnosis of Achilles tendon diseases is mainly based on the clinical history and imaging examinations.

Measuring the elasticity is one of the methods to assess Achilles tendon, and is useful for assessing Achilles tendinopathy and tendon degeneration [4]. It has been reported that Achilles tendons with tendinopathy are softer than normal Achilles tendons [5]. Measuring the stiffness of Achilles tendon could be a potential diagnostic method for assessing tendinopathy. Since different factors affect the mechanical properties of Achilles tendon including weight-bearing exercise (mechanical loading) and dominance of leg [6,7], it is necessary to understand the normal variation of the stiffness of Achilles tendon so that accurate diagnosis of abnormalities can be made.

Ultrasonography is a common imaging tool in the assessment of musculoskeletal structures including Achilles tendon [8,9]. Sonoelastography is an ultrasound technique which assesses the elasticity of soft tissue by evaluating its Young's modulus or calculating the strain ratio of the target tissue relative to its adjacent soft tissue. Moreover, sonoelastography is fast, inexpensive, and easily available which makes it an ideal imaging technique to assess the stiffness of musculoskeletal structures [10]. Among different sonoelastography techniques, strain sonoelastography (strain EUS) and shear wave elastography (SWE) are common real-time sonoelastography techniques applied in detecting and characterizing a range of lesions in different tissues and organs, including the Achilles tendon [11].

Shear wave elastography is a new development in soft tissues elasticity imaging. With the use of focused ultrasound beam, acoustic radiation force impulses are produced and transmitted to the soft tissues resulting the generation of shear waves within the tissues. Using the ultrafast ultrasound tracking techniques, the velocity of shear wave propagation is measured and the Young's modulus (i.e.

stiffness) of the soft tissue is obtained. SWE can quantify soft tissue stiffness, and provide absolute value of the stiffness of the soft tissue. Therefore, the results of SWE are objective and the quantitative data can be used for clinical references. Although SWE assessment of Achilles tendon elastic property has been reported [12-16], literature has scant information about the changes of normal Achilles tendon stiffness after prolonged physical activities. Therefore, this study was undertaken to investigate the effect of long-term weight bearing exercise on Achilles tendon stiffness of human subjects by comparing frequent and infrequent exercisers.

Methods

Healthy Chinese subjects were recruited from different local universities for the study. Subjects with history of hormone therapy, previous contraceptive pills intake or contraceptive injections were excluded because different levels of estrogen would exert an effect on collagen synthesis which alters the Achilles tendon mechanism [17]. Subjects with history of tendon injury, hypothyroidism, treatment with corticosteroids, metabolic and inflammatory diseases such as gout, ankylosing spondylitis, and rheumatoid arthritis were also excluded because these may affect the normal size, thickness and stiffness of Achilles tendon [9]. This study was approved by the Human Subject Ethics Subcommittee of the Hong Kong Polytechnic University. An information sheet about the study's aims, examination procedures, ultrasound's safety and the volunteers' rights was given to each subject. Informed written consent was obtained from each subject before the examination.

Each subject was requested to fill in the Victorian Institute of Sports Assessment – Achilles questionnaire (VISA-A). It evaluates the effect of tendinopathy on function and quantifies the symptoms and dysfunction of Achilles tendon [18]. According to a previous literature, a recreational person with Achilles tendinopathy will not score higher than 70 on the VISA-A. Moreover, a patient who has VISA-A score reached 70 indicated that the patient was cured [18]. Therefore, in the present study if the subject's score in the questionnaire was below 70, the subject would be excluded from the study. Also, the age, weight (kg), height (m), the exercise's duration, frequency and types of exercise of each subject were recorded.

For convenient sampling, university students were recruited in the campus and thus subjects aged between 18 and 30 years old were recruited. Subjects were recruited and classified into two groups based on the following criteria according to Ying et al. [9]:

1. frequent exercise group (having 6 or more hours of weight-bearing exercise per week)
2. infrequent exercise group (having less than 6 hours of weight-bearing exercise per week)

The weight-bearing exercise is defined as the force-generating activities which generates loading to the skeletal regions with intensity stronger than daily activities [19]. Subjects in the frequent exercise group were recruited from the athletics teams of local universities, whilst subjects in the infrequent exercise group were recruited from acquaintance.

It has been reported that long-term exercise causes different extents of effect on dominant and non-dominant legs [9]. The dominant leg of each subject was recorded. To identify the dominant leg of subject, subjects were asked to electively use either the left or right foot for kicking a ball. The elected side for ball kicking was defined as the dominant side while the other side was the non-dominant side. In the study, basketball, football and high jump were the most common exercises that subjects in the frequent-exercise group performed (Table 1).

All ultrasound examinations were performed with the Aixplorer ultrasound unit (Supersonic Imaging, Aix-en-Provence, France) in conjunction with the Supersonic Super Linear™ SL15-4 transducer (4 – 15 MHz). Before the ultrasound examination, each subject was asked lying prone for 5 minutes to ensure the subject was at resting state during the ultrasound measurement [10]. In the ultrasound examination, each subject lay prone with the feet hanging over the edge of the examination couch. To standardize the position of subject's foot for ultrasound scanning, the foot of the subject was fixed and supported by a customized ankle fixer with the plantar aspect of the foot against the base of the ankle fixer so that the foot was 90° to the lower leg. A previous study on elastography of Achilles tendon reported that the longitudinal scans achieved data with higher reproducibility than transverse scans [20]. Therefore, longitudinal scans were used in the present study to assess the stiffness of Achilles tendon. To increase the coupling efficiency of ultrasound and accurate measurement of tendon stiffness, generous amount of ultrasound gel was applied over the Achilles tendon. During the ultrasound examination, the transducer was placed over the ultrasound gel and effort was made to avoid any tissue compression by the transducer since the tendon stiffness would be affected by the additional load of pressure [10]. The set-up for the ultrasound examination is shown in Fig 1.

In the ultrasound examination of Achilles tendon, grey scale ultrasound was initially used to identify the Achilles tendon. Longitudinal scans were performed medially and laterally across the Achilles tendon until the scan plane showing the Achilles tendon clearly and maximum tendon thickness was obtained. To minimize anisotropic effect, the transducer was adjusted so that the ultrasound beam was perpendicular to the tendon fibers. Once the optimal scan plane of the tendon was identified, the SWE function was then activated. SWE was set at the penetration mode with the measurable range of stiffness standardized at 0kPa to 800kPa. The SWE colour map (height x width:

1.4 x 1.3cm) was placed just above the superior border of calcaneum. Elastogram was obtained and stored when the colour signals became steady for several seconds.

In the measurement of the tendon stiffness, archived elastograms were retrieved and the tendon stiffness was measured with stiffness measurement tool - Q-box™. The circular measurement area (Q-box) was set to 2 to 3mm in diameter dependent on the tendon size and was just covered the Achilles tendon without including other adjacent soft tissues. Three Q-boxes were placed at the superior, middle and inferior parts of the tendon within the SWE colour map (Figs. 2 and 3). For each Q-box, the maximum, minimum and mean (in kPa) of stiffness (i.e. Young's modulus) of the tendon were measured.

To evaluate the inter-operator variability of the measurement, each subject was scanned by three operators and the same scanning protocol was used. The operators were sonographers with more than one year of experience in shear wave elastography of Achilles tendon. The operators were blinded to the measurement result of other operators. To evaluate the intra-operator variability of the measurement, each operator scanned the subject 3 times in the same scanning session. To avoid bias, in measuring the tendon stiffness using Q-box™ on archived elastograms, the area of the monitor of the ultrasound unit displaying the numerical stiffness measurement reading was masked by a small piece of paper so that the operators were blinded to their measurements during the intra-operator variability assessment. Images with the measurements were stored for subsequent data retrieval.

Data analysis was conducted using an average measurement of all the operators. All statistical analyses were performed using the Statistical Package for the Social Science (SPSS 20.0 for Windows, Chicago, IL, USA). The body mass index (BMI) of the subjects was calculated with the formula BMI =weight (kg)/height (m^2). Because of the small sample size of the frequent-exercise group (n=12), two-tailed Mann-Whitney test was used to evaluate the level of significance of the difference in Achilles tendon stiffness between frequent-exercise and infrequent-exercise groups. Wilcoxon matched-pairs signed-ranks test was used to evaluate the significance of the difference in Achilles tendon stiffness between dominant and non-dominant legs. Intraclass correlation coefficient models 2 and 3 [ICC2 (absolute agreement) and ICC3 (consistency) respectively] were used to assess inter-operator reproducibility and intra-operator repeatability respectively. Coefficient of variation

(CV) was also used to evaluate the measurement variability.

Results

A total of 40 subjects were recruited (30 men and 10 women). Four subjects (3 men and 1 woman) had a VISA-A score less than 70 and were excluded from the study. The remaining 36 subjects were included in the study in which 12 were frequent-exercise subjects (33.3%) and 24 were infrequent-exercise subjects (66.7%). None of the 36 subjects had substantial thickening of the Achilles tendon or hypoechoic areas in the tendon. None of the subjects in the infrequent-exercise group involved in high intensity exercise such as volleyball or basketball and majority of them just performed activities of daily living. A total of 72 Achilles tendons were examined. There was no significant difference in the body weight (median: 65.5 kg; interquartile range, IQR: 9.9 kg and median: 61.3 kg; IQR: 9.2 kg respectively), height (median: 176.7 cm; IQR: 11.9 cm and median: 171.8 cm; IQR: 8 cm respectively) and BMI (median: 21.5; IQR: 1.9 and median: 20.6; IQR: 2.9 respectively) between the subjects in frequent-exercise and infrequent-exercise groups ($p > 0.05$) (Table 1).

Regarding with the intra-operator repeatability, the individual ICC (3, k) of the three operators were 0.845, 0.835 and 0.803 respectively and the CV of their measurements were 0.09, 0.1 and 0.11 respectively. For the inter-operator reproducibility, the ICC (2, k) among the three operators was 0.585 and the CV was 0.13.

For non-dominant ankles, result showed that the stiffness of Achilles tendon of the subjects in frequent-exercise group (median: 320.1 kPa; IQR: 39.9 kPa) was significantly higher than that of the subjects in infrequent-exercise group (median: 296 kPa; IQR: 48 kPa) ($p < 0.05$; effect size, $r = -0.352$). However, for dominant ankles, there was no significant difference in the stiffness of Achilles tendon between subjects in the frequent-exercise and infrequent-exercise groups (median: 322.1 kPa; IQR: 64.7 kPa, and median: 294.5 kPa; IQR: 46.3 kPa respectively) ($p > 0.05$; $r = -0.218$).

In both frequent-exercise and infrequent-exercise groups, the Achilles tendon stiffness was not significantly different between dominant and non-dominant legs ($p > 0.05$, $r = -0.115$ to 0.192).

Discussion

Results of the present study showed that the stiffness of Achilles tendon in non-dominant ankles of frequent-exercisers is significantly higher than that of infrequent-exercisers. The result is consistent with previous studies which found that after chronic mechanical loading like exercise Achilles tendon became stiffer [13,21]. A meta-analysis demonstrated that long duration of exercise is more efficient to induce tendon adaptive responses than short duration [22]. It has reported that Achilles tendon stiffness did not significantly increase after two months of exercise training but became statistically significant by the end of the three-month training [23,24]. However, information in the literature about causes of exercise on Achilles tendon stiffness is limited. Some previous studies suggested that the increased stiffness of the tendon may be associated with increased amount of type I collagen in the tendon [25,26], and the synthesis of type I collagen increases in response to prolonged exercise [26,27]. Therefore, the increased synthesis of type I collagen may account for the significantly stiffer Achilles tendon in the non-dominant ankle of frequent-exercisers than infrequent-exercisers. In addition, Vilarta and Vidal [28] evaluated the effect of exercise on the alignment and number of collagen fibrils, and found that the stiffness of Achilles tendon of rats increased after 30 days of exercise. They found that there were more collagen fibrils in the Achilles tendon of the rats after the exercise and the collagen fibrils were more aligned with each other. There are limited information in the literature about the effect of prolonged exercise on human Achilles tendon, and the causes for the change in mechanical properties of Achilles tendon due to exercise are still unclear. Further studies to investigate the association between the mechanical property change of Achilles tendon and its histological variation after prolonged exercise are suggested. The present study applied SWE to quantify the change in the stiffness of Achilles tendon after prolonged weight-bearing exercise. It provides baseline information about the feasibility of using SWE to assess the effect of exercise on Achilles tendon stiffness, and the study result is useful for future ultrasound investigations on human musculoskeletal system.

In the present study, result showed that there was no significant difference in Achilles tendon stiffness on dominant ankles between the frequent-exercise and the infrequent-exercise groups. The insignificant finding may be due to the preferential use of one leg over another. In the present study, basketball, football and high jump were the most common exercises performed by the subjects in frequent-exercise group. For these types of physical activities, subjects tended to use the non-dominant leg for supporting and jumping actions, and it is also the landing leg which exposes the tendon to high loads of tensile force. Therefore, the mechanical loading on the two legs was unequal. A meta-analysis revealed that high magnitude of mechanical loading is more effective to cause tendon adaptation [22]. Moreover, Arampatzis et al. [29] found that the increase in Achilles tendon stiffness occurred only in the leg with exercise at high strain magnitude, whereas low-strain-magnitude exercise did not trigger adaptation effect on the Achilles tendon. Moreover, the strain magnitude applied to Achilles tendon should exceed a threshold in order to trigger adaptation effect on the tendon [29]. As the loading strain magnitude of dominant ankles in present study was lower than that in non-dominant ankles, the mechanical loading on dominant ankles may not be larger enough to induce adaptation effect on the Achilles tendon. This may explain the effect of long-term physical exercise was found on non-dominant ankles but not on dominant ankles. Future studies using SWE need to account for the differences in the non-dominant and dominant legs.

Shear wave elastography measurement of the Achilles tendon stiffness has been reported [12-16]. However, either the studies did not evaluate the measurement reliability [13,15] or they achieved a low reliability with an ICC of 0.42-0.43 [14,16] or a coefficient of variation of 0.49 [12]. In the present study, the measurement reliability (intra-operator repeatability, ICC=0.803-0.845 and inter-operator reproducibility, ICC=0.585) was higher than that of previous studies. The higher measurement reliability in the present study may be due to the use of ankle fixer for the ultrasound examination and the standardized ultrasound scanning protocol. Nevertheless, some measurement errors still exist. In the present study, the longitudinal scan of Achilles tendon for SWE measurement was obtained at the scan plane which shows the maximum tendon thickness. The determination of the scan plane with maximum tendon thickness by the operator was subjective, and this might associate with the measurement errors between ultrasound scans of the same operator (intra-operator) as well as scans of different operators (inter-operator). The consideration for future studies using SWE should be that one operator is used.

The position of the ankle during ultrasound scanning would affect the reliability of the measurement result. Peltz et al. [16] reported that the low measurement reliability in the study may be due to the subtle differences in ankle joint position during the ultrasound scanning. Aubry et al. [14] also stated it was difficult to achieve the desirable ankle position for scanning when the ankle joint position is not stabilized. Therefore, the unstable and unstandardized ankle joint position during scanning in previous studies caused the low reliability in SWE measurement of Achilles tendon. In the present study, the repeatability (ICC=0.803-0.845) and reproducibility (ICC=0.585) of SWE measurement of Achilles tendon were higher than those in previous studies [12,14,16]. The higher measurement reliability of the present study is probably due to the use of the ankle fixer to maintain a stable and standardized ankle joint position so that there was less movement of the ankle joint during ultrasound examination, leading to higher measurement reliability.

Obesity is considered as a risk factor for Achilles tendonitis, and it has been reported obese people had higher incidence of Achilles tendinopathy [17]. In the present study, there was no significant difference in the body weight and BMI of subjects between frequent-exercise and infrequent-exercise groups. Therefore, the effect of the subjects' body weight and BMI on the Achilles tendon's mechanical property between the two study groups is minimal. Central adiposity is a risk factor for Achilles tendon pathology [30]. However, the waist circumference and waist hip ratio of the subjects did not measure in the present study and thus the central adiposity of the subjects may be a possible confounder of the study.

There were limitations in the present study. The sample size of the study was small with only 12 frequent-exercisers and 24 infrequent-exercisers. In the present study, the difference of the median scores of non-dominant leg between frequent and infrequent-exercisers was smaller than that of dominant leg, but significant difference was found in the non-dominant leg. This may be an artifact of using median scores and non-parametric tests that will change with larger sample size and the use of parametric tests. Moreover, we did not evaluate the difference in Achilles tendon stiffness among different weight-bearing exercises. Therefore, further studies with a larger sample size and to investigate the Achilles tendon stiffness of different athletes are suggested. Furthermore, the association of different types and intensities of exercise with Achilles tendon stiffness did not evaluate in the study. Further studies to investigate this association are suggested so that possible reasons for the different Achilles tendon stiffness between study groups, and errors associated with measurement reliability can be determined. In addition, this study is limited due to the cross-sectional design and future prospective studies are needed. Also, the study only looked at current physical activity level of the subjects and did not account for any physical activity in the past.

Conclusion

Shear Wave Elastography is feasible for assessing the Achilles tendon's stiffness in vivo with high measurement reliability. SWE is useful to evaluate the effect of prolonged exercise on Achilles tendon stiffness. The stiffness of Achilles tendon in frequent-exercise group is significantly greater than that in infrequent-exercise group on non-dominant ankles but not on dominant ankles.

Practical Implications

- The new ultrasound elasticity imaging technique (i.e. shear wave elastography) is reliable for measuring Achilles tendon stiffness with CV varies between 0.09-0.13. Note the inter-operator reproducibility was 0.585 (CV=0.13), follow up scans should be performed by the same operator.
- The Achilles tendon in the non-dominant ankle of people who do exercise frequently is stiffer than that of people who do exercise less frequently. However, this variation was not found in the dominant ankle. Note the small sample size of the present study, further study with a larger sample size is suggested to verify the finding.
- Sport medicine scientists and professionals should aware of the Achilles tendon stiffness difference between dominant and non-dominant ankles as well as between frequent-exercise and infrequent-exercise people for better management and prevention of related injuries.

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Figure Legends

Fig 1. The set-up for the shear wave elastographic examination of Achilles tendon. The subject's foot was fixed by the ankle fixer. Generous amount of ultrasound gel was applied over the posterior aspect of the ankle for the scanning. The transducer was placed over the ultrasound gel to avoid any compression on the tendon.

Fig 2. Longitudinal shear wave elastogram in a frequent-exercise subject shows the Achilles tendon in the non-dominant leg. The tendon has relatively higher stiffness values than the tendon in the infrequent-exercise subject as shown in Fig. 3.

Fig 3. Longitudinal shear wave elastogram in an infrequent-exercise subject shows the Achilles tendon in the non-dominant leg. The tendon has relatively lower stiffness values than the tendon in the frequent-exercise subject as shown in Fig. 2.