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Quantitative ultrasound (QUS) assessment of tissue properties for Achilles tendons

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Abstract
Quantitative ultrasound (QUS) techniques have recently been widely applied for the characterization of tissues. For example, they can be used for the quantification of Achilles tendon properties based on the broadband ultrasound attenuation (BUA) and the speed of sound (SOS) when the ultrasound wave passes through the tissues. This study is to develop an integrated system to investigate the properties of Achilles tendons using QUS images from UBIS 5000 (DMS, Montpellier, France) and B-mode ultrasound images from HDI 5000 (ATL, Ultramark, USA). Subjects including young (32 females and 17 males; mean age: 23.7 ± 2.0) and middle-aged groups (8 female and 8 males; mean age: 47.3 ± 8.5 s) were recruited and tested for this study. Only subjects who did not exercise regularly and had no record of tendon injury were studied. The results show that the BUA is significantly higher for the young group (45.2 ± 1.6 dB MHz^{-1}) than the middle-age group (40.5 ± 1.9 dB MHz^{-1}), while the SOS is significantly lower for the young (1601.9 ± 11.2 ms^{-1}) compared to the middle-aged (1624.1 ± 8.7 m s^{-1}). On the other hand, the thicknesses of Achilles tendons for both groups (young: 4.31 ± 0.23 mm; middle age: 4.24 ± 0.23 mm) are very similar. For one patient who had an Achilles tendon lengthening (ATL) surgery, the thickness of the Achilles tendon increased from 4 mm to 4.33 mm after the surgery. In addition, the BUA increased by about 7.2% while the SOS decreased by about 0.6%. In conclusion, noninvasive ultrasonic assessment of Achilles tendons is useful for assisting clinical diagnosis and for the evaluation of a therapeutic regimen.

Keywords: quantitative ultrasound (QUS), Achilles tendon, BUA, SOS, aging effect

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The Achilles tendon is the strongest tendon in the human body. It connects the gastrocnemius to the calcaneus. The main function of tendons is to assist in concentrating the pull of the muscle on a small area of the bone. When the gastrocnemius contracts, its attached tendon will contract as well and pull the calcaneus to a new position in space. Inflammation of the Achilles tendon usually results from a small stretch injury causing the tendon to become swollen, painful and less flexible. To evaluate the tendon function during the rehabilitation period, a non-invasive *in vivo* technique, such as ultrasound, is generally used.

The chance of Achilles tendon injury increases with exercise frequency and age [1]. Aging is also a significant factor affecting the mechanical properties of the Achilles tendon as the collagen content gradually decreases along with a decrease in proteoglycans and glycoprotein. A decline in water content and an increase in cross-linking of the tropocollagon molecules have also been observed. If the process continues, calcification will be induced and the elasticity and strength of the tendon deteriorates [2, 3].

Ultrasound techniques are non-invasive and efficient tools for the characterization of soft tissues [4] and bone tissue [5]. Recently, they have been applied to characterize calcaneus bone [6, 7] and for osteoporosis assessment [8]. Additionally, the mechanical properties of soft tissues, such as animal muscles and tendons, have also been widely investigated using ultrasound. Wang and Shung [9] used the A-mode ultrasonic technique to measure fresh chicken breast muscles and discovered that the speed of sound (SOS) decreased 3% and the broadband ultrasound attenuation (BUA) decreased up to 60% when the muscles were extended 40% in length. The tendon strain of rabbits [10] and the tendon elasticity of cattle [11] were also investigated *in vitro*. Ying *et al* [12] found that the thickness of Achilles tendons for young people (age: 19 to 25) who exercise frequently is significantly greater than those who exercise less often. In this study, we used QUS parametric images, including SOS and BUA images, to investigate the effect of aging on the mechanical property of the Achilles tendon. The variation of tendon thickness for different age groups was also studied. Noninvasive ultrasonic assessment of Achilles tendons is useful for doctors to assess the severity of tendon injury and monitor the effectiveness of a therapeutic regimen.

2. Material and methods

2.1. Two-dimensional quantitative ultrasound image

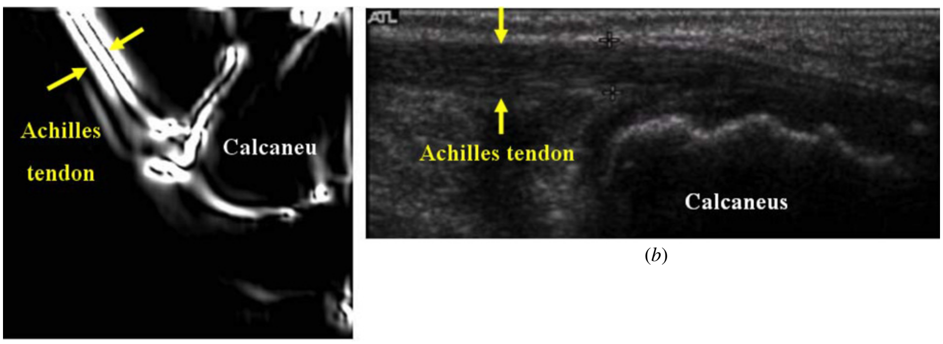
The quantitative ultrasound (QUS) technique was proposed by Laugier *et al* [5] to measure two-dimensional parametric images of tissues. Two transducers, one for transmitting and the other for receiving, are used for measuring the tissue characteristics in this two-dimensional QUS technique. Both transducers have to be aligned coaxially and confocally before each measurement. The image is obtained by scanning through the heel in a raster pattern using a two-axis scanning device so that both transducers can be moved simultaneously.

In this study, ultrasound parametric images were acquired by a QUS scanner, UBIS 5000 (DMS, Montpellier, France), with two 0.5 MHz transducers (diameter: 29 mm; focus: 50 mm). The UBIS 5000 ultrasound bone sonometer is a portable medical device that uses ultrasound to assess the strength of the heel bone. However, it can also provide quantitative ultrasound (QUS) images around the heel. In this study, we used the UBIS 5000 to acquire ultrasonic parametric images of the heel. For each measurement, the subject's foot was immersed in water kept at a temperature of 30 °C. Transverse parametric images with an area of 60 mm × 60 mm were taken for each 1 mm increment along the longitudinal direction.

In this study, we used the BUA image for measuring the thickness of the Achilles tendon. The accuracy of the Achilles tendon thickness obtained using the UBIS 5000 was verified with the results measured manually by an expert using the HDI 5000 (ATL, Ultramark, USA), as shown in figure 1. The parameters can be estimated according to the formula shown in (1) for BUA (dB MHz^{-1}) and (2) for SOS (m s^{-1}), respectively. As shown in equation (1), BUA is generally used to estimate the broadband ultrasonic attenuation (dB MHz^{-1}) by calculating the slope of a linear regression fit to attenuation against frequency plot:

$$\text{BUA} = \text{slope}_{[0.2-0.6\ \text{MHz}]}(\alpha(f)) \qquad (1)$$

where



(*a*) (*b*)

Figure 1. Parametric and B mode ultrasonic images of the Achilles tendon from images obtained by (*a*) UBIS 5000 and (*b*) HDI 5000, respectively.

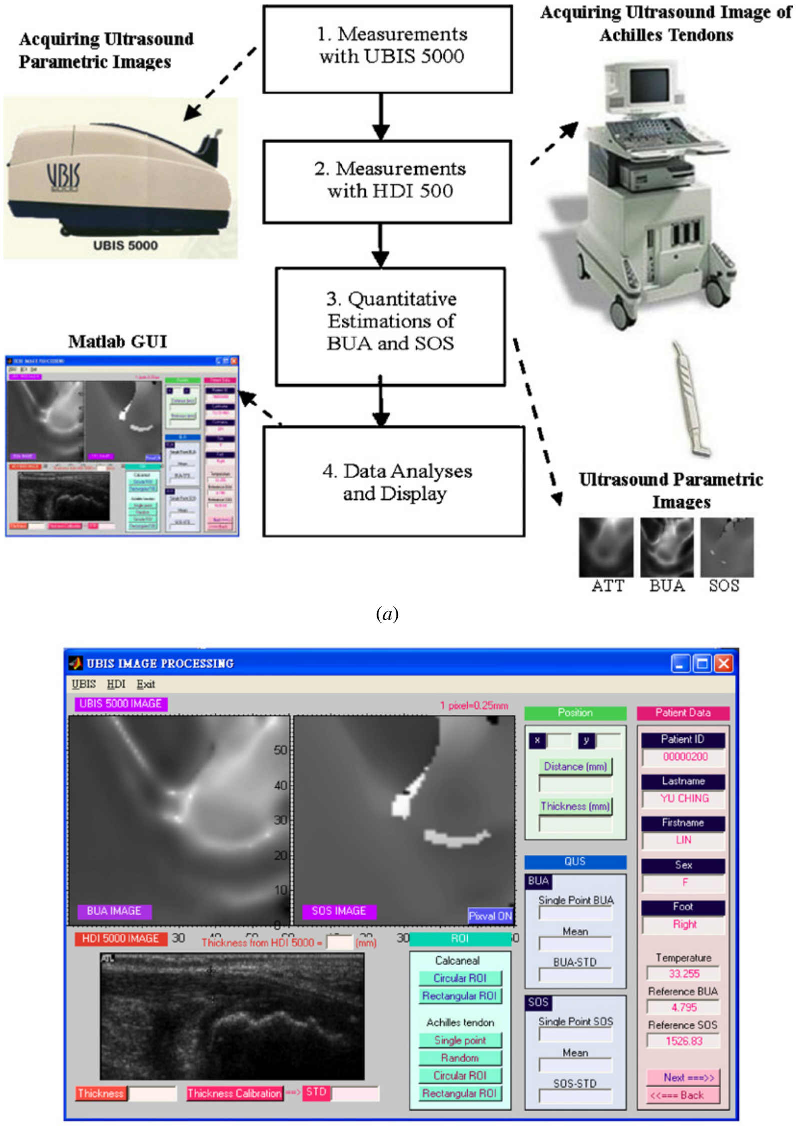


Figure 2. (*a*) The experimental setup and procedure. (*b*) A developed GUI (graphic user interface) on Matlab for the display of patient information, parametric images and evaluated parameters.

$$\alpha(f) = 20\log_{10}\left(\frac{|S_w(f)|}{|S(f)|}\right) \qquad (2)$$

with $S_w(f)$ and $S(f)$ indicating the frequency spectrum of the detected signals after the ultrasound waves have passed through the water and the tendon interface, respectively. SOS, on the other hand, represents the speed of sound (m s^{-1}) derived from the phase difference, as shown in equation (3):

$$\text{SOS} = \text{slope}_{[0.2\text{–}0.6\ \text{MHz}]}(c_p(f)) \qquad (3)$$

where

$$c_p(f) = \frac{c_w}{1 - (c_w\Delta\phi(f))/2\pi d_{\text{bone}}} \qquad (4)$$

and

$$\Delta\phi(f) = \tan^{-1}\left(\frac{S(f)}{S_w(f)}\right). \qquad (5)$$

In equation (4), $\phi(f)$ indicates the phase velocity of the ultrasound, d_{bone} represents the thickness of bone which is fixed at 28 mm in this investigation and C_w denotes the speed of sound in water.

2.2. Experimental setup

As shown in figure 2(*a*), the experimental procedure is divided into four steps. First, an instrument (UBIS 5000) was used to acquire parametric images of Achilles tendons. The size of the parametric image is 60 × 60 pixels. Secondly, an HDI 5000 with a CL15-7 probe (Philips) was used by an expert (Dr Lin) to manually measure the tendon thickness. Transverse and sagittal parametric images of the Achilles tendons were acquired by scanning from the intersection between the Achilles tendon and the calcaneus along the longitudinal direction. Then, the tendon thickness was obtained by marking the tendon boundaries on the images by the expert. In the next step (step 3), the image acquired by the UBIS 5000 was transferred to an IBM PC, where the image enhancement was manipulated and the tendon thickness measured. In addition, the tendon thickness obtained from the HDI 5000 and the UBIS 5000 were compared. Finally, a program designed with MATLAB (The MathWorks, Natick, USA), which combined a

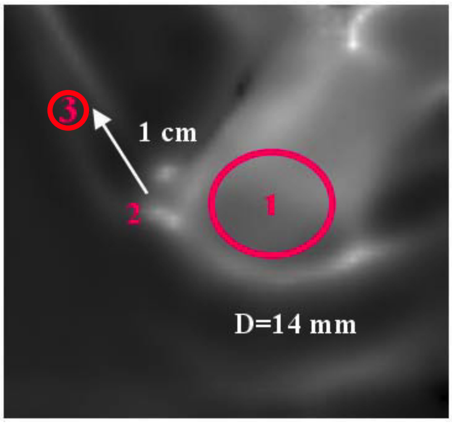


Figure 3. ROIs selection for ultrasound measurements of (1) calcaneus, (2) Achilles tendon–calcaneus insertion and (3) Achilles tendon.

user-friendly graphic interface and several analysis programs, was used to select the regions of interest (ROI) for calculating parameters from the ultrasound parametric images.

In figure 3, three areas, including the circular ROIs selected from (1) the calcaneus, (2) Achilles tendon–calcaneus insertion and (3) Achilles tendon which is located at the position 1 cm above the calcaneus insertion (arrow), are demonstrated. The characteristics of the calcaneus insertion of the Achilles tendon (soft tissue) are significantly different from the calcaneus (hard tissue) on the parametric image. The centre of the Achilles tendon, ROI (3), can be found following the localization of the tendon and calcaneus insertion (2) on the image. The diameter of ROI (3) is set to 4 mm since the thickness of the Achilles tendon has been found to be about 4–6 mm, according to previous investigations [1]. It was also measured by an expert from the parametric image to get a reliable and accurate thickness of the Achilles tendon.

2.3. Subjects

Subjects were divided into two groups including young (32 females and 17 males with mean age of 23.7 ± 2.0) and middle age (8 female and 8 males with mean age of 47.3 ± 8.5). The subjects in the young group are mostly graduate students recruited from our institution, while the subjects of the middle-aged group are parents and relatives of the young subjects. All the participants did not exercise regularly and revealed no history of tendon injury. In addition, the BMI indices of all subjects were between 18 and 27. One patient with muscle dystrophy was measured before and after Achilles tendon lengthening (ATL) corrective surgery. This patient had a history of muscle dystrophy in his left foot, which made him toe-walk because of difficulty in walking. Consent agreement was signed by the patient before the operation and measurement.

2.4. Image enhancement and edge detection

In order to precisely differentiate the anatomic structure of the Achilles tendons from the BUA images, image processing procedures, including bilinear interpolation, local standard

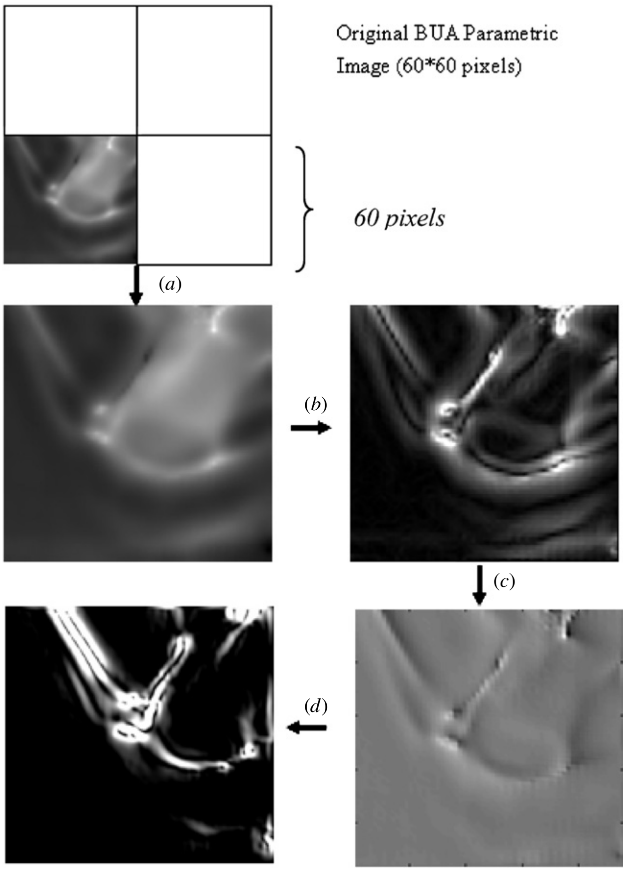


Figure 4. Image processing procedure and the intermediate results for (*A*) bilinear interpolation, (*B*) local standard deviation, (*C*) co-occurrence matrix and (*D*) Canny filter of the BUA parametric image.

deviation, co-occurrence matrix and Canny filter, were used to enhance the images. First, bilinear interpolation was used to increase the apparent resolution of original images from 60 × 60 pixels to 120 × 120 pixels. It was observed that large contrast could be found in a heterogeneous area where the local standard deviation is significantly higher than the homogeneous area. Therefore, the local standard deviation was used to identify and enhance the image boundary of the Achilles tendon. Here we calculated the standard deviation within an $n \times n$ block for mask processing, as shown in equation (6) [13]:

$$I_{SD}(x, y) = \frac{1}{n^2 - 1}\sqrt{\sum_{i=(n-1)/2}^{(n+1)/2}\sum_{j=(n-1)/2}^{(n+1)/2}[I(x+i, y+j) - M(x, y)]^2} \tag{6}$$

where $M(x, y)$ indicates the mean grey level within the $n \times n$ block for mask processing, that is,

$$M(x, y) = \frac{1}{n^2}\sum_{i=(n-1)/2}^{(n+1)/2}\sum_{j=(n-1)/2}^{(n+1)/2}[I(x+i, y+j)]. \tag{7}$$

In equations (6) and (7), $I(x, y)$ denotes pixel intensity at the location (x, y) on the original image and I_{SD} represents

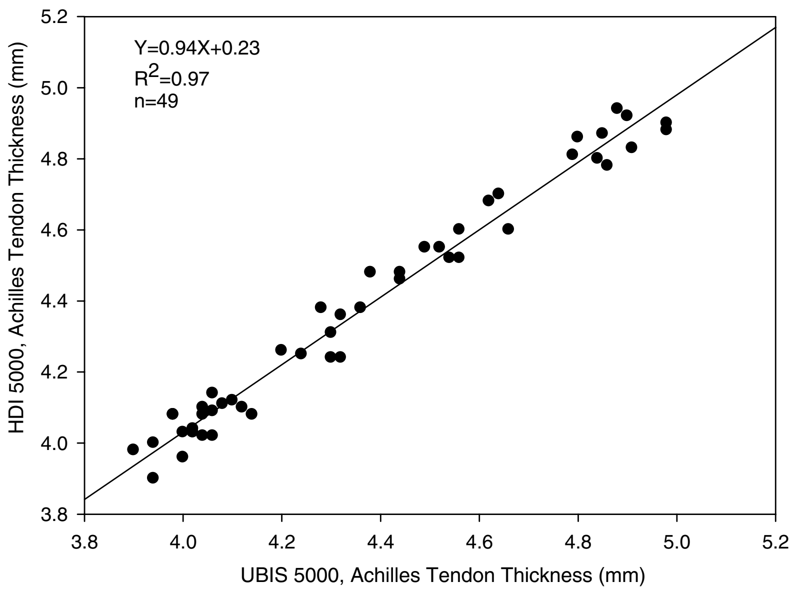


Figure 5. Correlation between the thickness measured with UBIS 5000 and the result obtained manually using HDI 5000 by an expert.

Table 1. Comparisons of BUA, SOS and tendon thickness between the young and middle-aged groups.

Subject	Sex	BUA (dB m^{-1})[a]	SOS (m s^{-1})[a]	Tendon thickness (mm)[b]
Young	Male	44.40 ± 1.64	1609.49 ± 9.70	4.47 ± 0.34
	Female	45.58 ± 1.46	1597.84 ± 9.86	4.14 ± 0.28
	Pooled	45.17 ± 1.61	1601.88 ± 11.20	4.26 ± 0.33
Middle-aged	Male	40.20 ± 1.89	1622.38 ± 10.06	4.32 ± 0.22
	Female	40.70 ± 2.01	1625.54 ± 7.33	4.15 ± 0.23
	Pooled	40.45 ± 1.90	1623.96 ± 8.66	4.24 ± 0.23

[a] With significant difference ($p < 0.001$) by comparing pooled data between the two groups.
[b] Without significant difference ($p > 0.05$) between the two groups.

the image pixels after enhancement. Additionally, local co-occurrence was applied to reinforce the detection of the object boundaries [14, 15]. A co-occurrence matrix, also referred to as a co-occurrence distribution, is defined over an image to be the distribution of co-occurring values at a given offset. I_{cont} can be obtained by summing the co-occurrence matrices corresponding to four directions, 0°, 45°, 90° and 135°, as shown in equation (8):

$$I_{cont}(x, y) = \sum_{x=1}^{n}\sum_{y=1}^{n-1}|I(x, y) - I(x, y+1)| + \sum_{x=2}^{n}\sum_{y=1}^{n-1}|I(x, y) - I(x-1, y+1)| + \sum_{x=2}^{n}\sum_{y=1}^{n}|I(x, y) - I(x-1, y)| + \sum_{x=2}^{n}\sum_{y=2}^{n-1}|I(x, y) - I(x-1, y-1)| \quad (8)$$

where $I(x, y)$ denotes the pixel intensity at location (x, y) on the original image and I_{cont} represents the image after enhancement. Finally, a Canny filter was applied to deal with the problems of thick lines and noise. The optimality criterion used in a Canny filter combines boundary, good localization and single response [16, 17]. In this study, we designed the Canny filter using the Matlab toolbox function. Figure 4 illustrates the above processing steps and the intermediate results for each step.

3. Results

Figure 5 shows the correlation between the thicknesses measured using UBIS 5000 and HDI 5000. The correlation coefficient is 0.97 for a total of 49 test samples, which demonstrates that the UBIS 5000 provides an efficient way of measuring the thickness of Achilles tendons. The results show that UBIS 5000 is efficient in evaluating osteoporosis from the calcaneus and is also useful for measuring the properties of Achilles tendons. With this extended function and the accompanying software developed in our laboratory, physicians are able to evaluate the function of the Achilles tendon and to inspect the recovery status of the Achilles tendon after surgery.

As shown in table 1, since we focus on the age effect in BUA, SOS and thickness of the Achilles tendons, male and female data for the individual young and middle-aged groups were pooled together for further statistical analysis. The aging effect is demonstrated in figure 6 where BUA, SOS and tendon thickness are compared between the two groups. As shown in

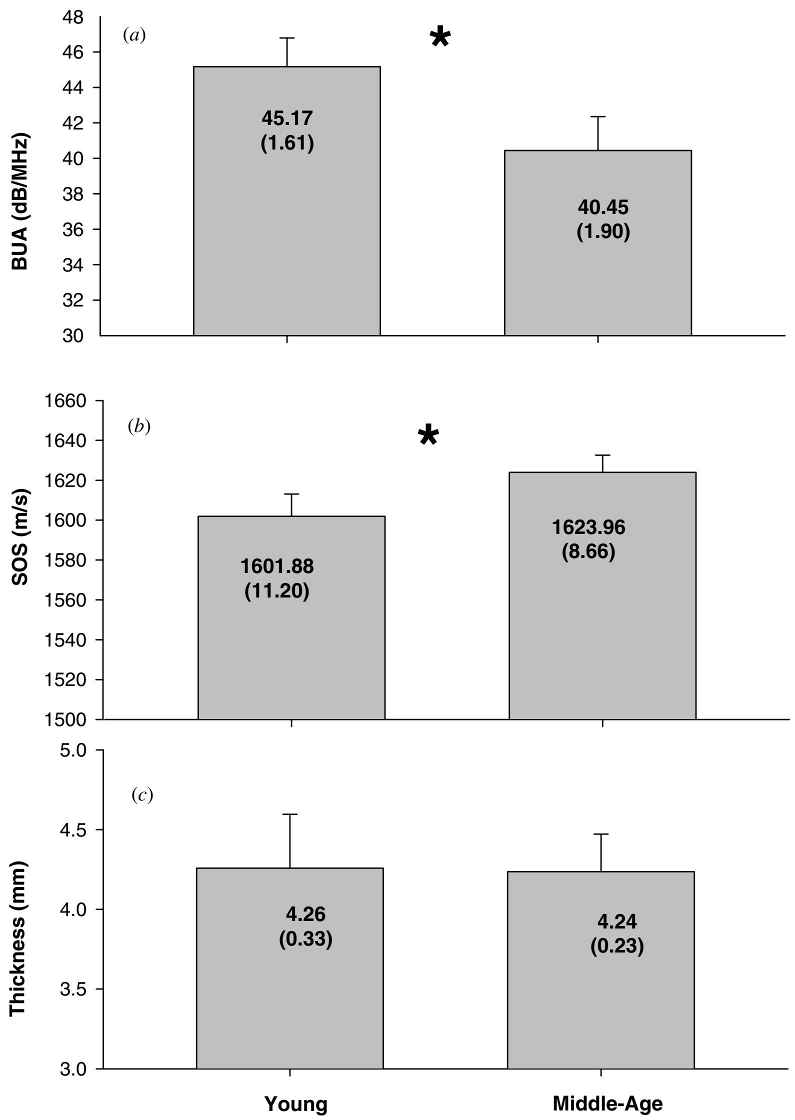


Figure 6. Comparisons of (*a*) BUA, (*b*) SOS and (*c*) thickness of Achilles tendons between the young and middle-aged groups. Note that ∗ indicates significant difference with $p < 0.05$

figure 6(*a*), the BUA measured from the middle-aged group is less than for the young group. Specifically, the BUA is 45.2 ± 1.6 dB MHz^{-1} for the young group, while it is 40.5 ± 1.9 dB MHz^{-1} for the middle-aged group. A significant difference ($p < 0.05$) in BUA was found after *t*-test analysis, which is consistent with previous findings [1].

The mean SOS is 1601.9 ± 11.2 m s^{-1} for the young and 1623.96 ± 8.66 m s^{-1} for the middle-aged group. Although the difference in SOS between these two groups is only 1.22%, it is statistically significant ($p < 0.05$). A previous study reported that the water content of the tendon gradually decreases with age [1], which might be the factor causing the difference in SOS between the young and the middle-age groups (figure 6(*b*)). The averaged ultrasound speed in water is around 1480 m s^{-1}, which is less than the sound speed in soft tissue (1540 m s^{-1}).

As shown in figure 6(*c*) and table 1, the thickness of the Achilles tendons is 4.3 ± 0.2 mm (male: 4.47 ± 0.34 mm; female: 4.14 ± 0.28 mm) for the young and 4.2 ± 0.2 mm (male: 4.32 ± 0.22 mm; female: 4.15 ± 0.23 mm) for the middle-aged. The result shows that there is only a mild decrease in thickness for the middle-aged group without reaching a level with significant difference ($p > 0.05$). According to previous investigations, the area of Achilles tendons increases during the growth period and then recesses in adulthood [1]. When a person grows old, the decreasing tendency becomes more and more obvious.

4. Discussion and conclusion

Achilles tendons degenerate gradually with age, which results in the degradation and change of the internal structure. The effect can be observed by smaller BUA and larger SOS values. A decrease in the water content of the tendons can be observed from an increase in mean ultrasound speed (SOS). Comparing female subjects with male for these three parameters, no significant difference was found. After pooling male and female data for the young and the middle groups, significant

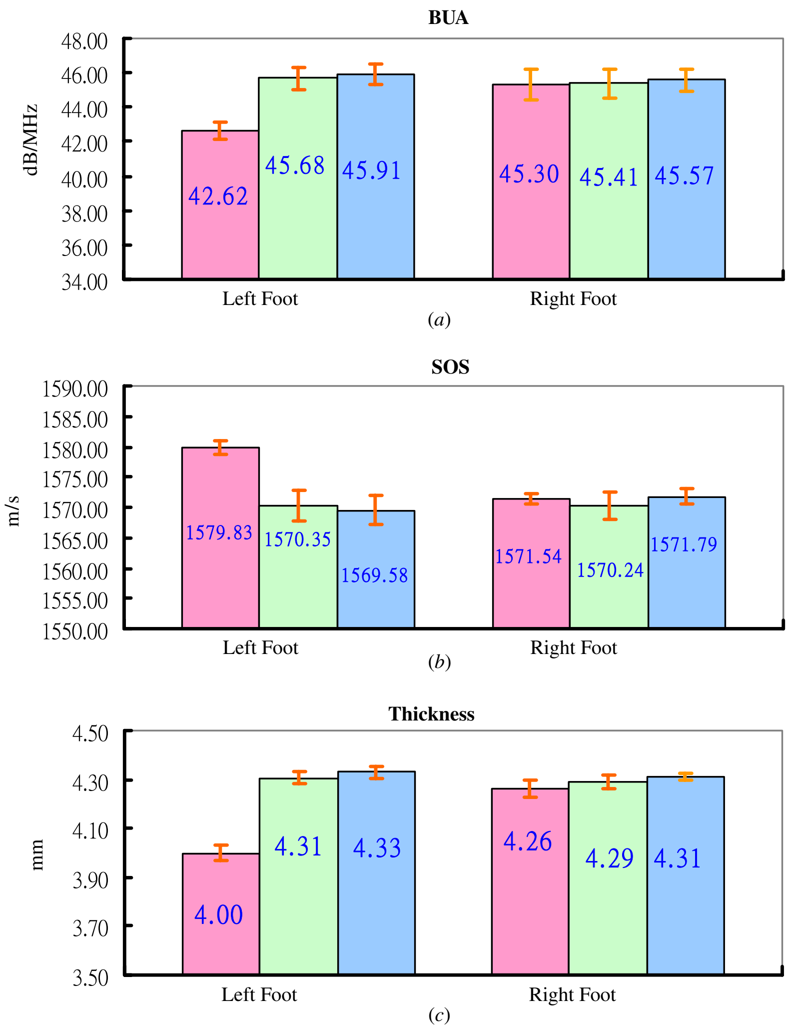


Figure 7. Comparisons of the quantitative parameters before operation, and two and four months after operation for (*a*) BUA, (*b*) SOS and (*c*) tendon thickness

differences between the two groups were observed for both the BUA and the SOS measurements, but no obvious difference regarding tendon thickness.

A clinical application of this investigation demonstrates that it can be applied to evaluate the efficiency of a surgical operation on the Achilles tendon after a certain period of rehabilitation. Figure 7 compares the three parameters (BUA, SOS and tendon thickness) obtained by measuring the Achilles tendon of a patient with cerebral palsy before and after Achilles tendon lengthening (ALT) operation. Because of a long-term spasm of his left foot, the patient had suffered great pain and difficulty in walking [18]. The Achilles tendon of his right foot was also measured for comparison with the left foot. As shown in figure 7, for the right foot, no significant difference was found for all three parameters if compared among pre-operation and two and four months after the operation. Regarding the left foot, on the other hand, significant differences were observed before and after operation for all three parameters. The patient had recovered his walking capability after the operation following a short-term rehabilitation. The recovery of his walking capability can be predicted by observing the values of the quantitative parameters.

In the future, further animal studies should be made by measuring the BUA and SOS invasively to evaluate the accuracy of the parameters measured using QUS parametric images. We expect that this technology will have great potential in clinical application for evaluating tendon strength *in vivo*.

Acknowledgments

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References

[1] Kannus P, Paavola M and Jozsa L 2005 Aging and degeneration of tendons *Tendon Injures: Basic Science and Clinical Medicine* (London: Springer) pp 25–31

[2] Lewis G and Shaw K M 1997 Tensile properties of human tendon Achilles: effect of donor age and strain rate *J. Foot Ankle Surg.* **36** 435–45

[3] Revel G-M, Scalise A and Scalise L 2003 Measurement of stress–strain and vibrational properties of tendons *Meas. Sci. Technol.* **14** 1427–36

[4] Wear K 2000 Measurement of phase velocity and group velocity in human calcaneus *Ultrasound Med. Biol.* **26** 641–6

[5] Laugier P, Fournier B and Berger G 1996 Ultrasound parametric imaging of calcaneus: *in vivo* results with a new device *Calcif. Tissue Int.* **58** 326–31
[6] Chen P J, Chen T, Lu M C and Yao W J 2005 The measurements of ultrasound parameters on calcaneus by two-sided interrogation techniques *Meas. Sci. Technol.* **16** 1349–54
[7] Chen P J and Chen T 2006 Measurements of acoustic dispersion on calcaneus using spilt spectrum processing technique *Med. Eng. Phys.* **28** 187–93
[8] Chen T, Chen P J, Fung C S, Lin C J and Yao W J 2004 Quantitative assessment of osteoporosis from the tibia shaft by ultrasound technique *Med. Eng. Phys.* **26** 141–5
[9] Wang C-Y and Shung K K 1998 Variation in ultrasonic backscattering from skeletal muscle during passive stretching *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **45** 504–10
[10] Li P-C, Kuo P-L and Shun C-T 1999 Ultrasonic strain measurements of tendon *IEEE Ultrason. Symp.* **2** 1661–4
[11] Kuo P O, Li P C and Li M L 2001 Elastic properties of tendon measured by two different approaches *Ultrasound Med. Biol.* **27** 1275–84
[12] Ying M, Yeung E, Li B, Li W, Lui M and Tsoi C W 2003 Sonographic evaluation of the size of Achilles tendon: the effect of exercise and dominance of the ankle *Ultrasound Med. Biol.* **29** 637–42
[13] Ali M and Clausi D 2001 Using the Canny edge detector for feature extraction and enhancement of remote sensing images *IEEE Geosci. Remote Sensing Symp.* vol 5 2298–300
[14] Chang D C and Wu W R 1998 Image contrast enhancement based on a histogram transformation of local standard deviation *Med. Imag.* **17** 518–31
[15] Carr J R and Miranda F P 1998 The semivariogram in comparison to the co-occurrence matrix for classification of image texture *Geosci. Remote Sens.* **36** 1945–52
[16] Canny J 1986 A Computational Approach to Edge Detection *IEEE Trans. Pattern Anal. Mach. Intell.* **8** 679–98
[17] Davignon F, Deprez J-F and Basset O 2005 A parametric imaging approach for the segmentation of ultrasound data *Ultrasonics* **43** 789–801
[18] Mueller M J, Sinacore D R, Hastings M K and Strube M J 2003 Effect of Achilles tendon lengthening on neuropathic plantar ulcers: a randomized clinical trial *J. Bone Joint Surg.* **85** 1436–45