Effects of tendon viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in athletes

H.-K. Wang¹, K.-H. Lin¹, S.-C. Su², T. T.-F. Shih³, Y.-C. Huang⁵

¹School and Graduate Institute of Physical Therapy, College of Medicine, National Taiwan University, Taipei, Taiwan, ²Department of Business Administration, Hwa Hsia Institute of Technology, Taipei, Taiwan, ³Department of Medical Image, National Taiwan University Hospital, Taipei, Taiwan, ⁴Department of Surgery, College of Medicine, National Taiwan University, Taipei, Taiwan, ⁵Department of Physical Medicine and Rehabilitation, Chen Hsin Rehabilitation Medical Center, Taipei, Taiwan

Corresponding author: Hsing-Kuo Wang, PhD, Sports Physiotherapy Laboratory, School and Graduate Institute of Physical Therapy, College of Medicine, National Taiwan University, Floor 3, No.17, Xuzhou Rd., Zhongzheng District, Taipei City 100, Taiwan. Tel: +886 2 33668134, Fax: +886 2 33668160, E-mail: hkwang@ntu.edu.tw

Accepted for publication 26 June 2012

The aim was to compare viscoelastic properties of Achilles tendons between legs in elite athletes with unilateral tendinosis, and to investigate relationships between the properties and explosive performance and clinical severity. Seventeen male athletes (mean ± standard deviation age, 27.3 ± 2.0 years) who had unilateral, chronic middle-portion tendinopathy of the Achilles tendon were assessed by the Victorian Institute of Sport Assessment questionaire, measurements of tendon viscoelastic properties, voluntary electromechanical delay (EMD), normalized rate of force development (RFD), and one-leg hopping distance. Compared with the non-injured leg, the tendinopathic leg showed reduced tendon stiffness (−19.2%, \( P < 0.001 \)), greater mechanical hysteresis (21.2%, \( P = 0.004 \)), lower elastic energy storage and release (−14.2%, \( P = 0.002 \) and −19.1%, \( P < 0.001 \)), lower normalized RFD at one-fourth (−16.3%, \( P = 0.02 \)), 2/4 (−17.3%, \( P = 0.006 \)), and three-fourths maximal voluntary contraction (−13.7%, \( P = 0.02 \)), longer soleus and medial gastrocnemius voluntary EMD (+26.9%, \( P = 0.009 \) and +24.0%, \( P = 0.004 \)), and shorter hopping distances (−34.1%, \( P < 0.001 \)). Tendon stiffness was correlated with normalized RFD, voluntary EMD in the medial gastrocnemius, and hopping distances (\( r \) ranged from −0.35 to 0.64, \( P < 0.05 \)). Hysteresis was correlated to the soleus voluntary EMD and hopping distances (\( r = 0.42 \) and −0.39, \( P < 0.05 \)). We concluded that altered tendon viscoelastic properties in Achilles tendinosis affect explosive performance in athletes.

Tendons are noncontractile viscoelastic structures that connect the contractile muscles to the skeleton. Through a curvilinear relationship between force and elongation, the tendons transfer forces generated by the muscle to produce joint moments and utilize elastic energy to minimize energetic costs during locomotion (Reeves et al., 2003; Magnusson et al., 2008). In vivo viscoelastic properties of the tendon-aponeurosis complex, including stiffness and mechanical hysteresis, are often measured with a real-time ultrasonography technique during ramp isometric contractions and relaxation (Magnusson et al., 2008). Tendon stiffness is determined by the tendon elongation under a given force range, and hysteresis refers to the ratio between dissipated and stored elastic energy under a stretch–recoil condition (Magnusson et al., 2008). Tendon stiffness is important to explosive performance such as voluntary electromechanical delay (EMD) and rate of force development (RFD) (Reeves et al., 2003). Mechanical hysteresis of tendons indicates the percentage of stored elastic energy dissipated as heat during recoil from the stretch. Tendon hysteresis is relevant to the efficiency of movement, power output in the stretch-shortening cycles, and thermal stress within the tendon (Maganaris & Paul, 2000). However, these properties in tendinopathy have not been fully investigated.

Middle-portion tendinopathy, also known as tendinosis, is a degenerative injury involving adaptation failures in the cell matrix to excessive load changes (Paavola et al., 2002). Decreased tendon stiffness and increased tendon–aponeurosis strain (compliance) have been observed in middle-portion Achilles tendinopathy (tendinosis) in the middle-aged general population and middle-aged runners, respectively (Arya & Kulig, 2010; Child et al., 2010). In addition, tensile strain has been found to increase intratendinous levels of nociceptive neurotransmitters, such as substance P, in a rat tendinopathic model (Fedorczyk et al., 2010). These findings indicate that (a) decreased stiffness in Achilles tendinosis may adversely affect ankle explosive performance, such as voluntary EMD and normalized RFD; and (b) the clinical severity of Achilles tendinosis may be related to the decreased tendon stiffness owing to increased tendon.
strain and levels of intratendinous nociceptive mediators. Nevertheless, none of these hypotheses has been proven. Other faults in previous tendinopathic studies included lack of analysis of tendon mechanical hysteresis. Whether it affects athletic performance relying on explosive work output, such as one-leg hopping, remain unclear. Understanding the relationships between altered viscoelastic properties in tendinosis and explosive performance and clinical severity is important to achieve a better understanding of this injury and a comprehensive program design of physical therapy. The clinical severity of Achilles tendinopathy is commonly assessed using the Victorian Institute of Sport Assessment–Achilles (VISA-A) questionnaire (Robinson et al., 2001). The VISA-A questionnaire, with a total score of 100, was specifically designed for patients to report their pain, function, and sports activities based on conditions of the Achilles tendon. The aims of this study involving high-competition–level athletes with unilateral Achilles tendinosis were (a) to compare tendon viscoelastic properties (including stiffness, hysteresis, and energy utilization) and explosive neuromuscular performance between legs with and without Achilles tendinosis; and (b) to investigate relationships between the viscoelastic properties and explosive performance tests or VISA-A scores.

Materials and methods

Subjects
This was a cross-sectional study that was approved by our institutional review board. All subjects provided written informed consent, and the rights of the subjects were protected. To recruit eligible subjects, advertisements with information sheets, recruitment inclusion criteria, and consent forms were posted in five colleges and universities with departments of physical education and one national training center during the 2010 training season (September 2010 to May 2011). Male athletes were recruited, because a previous study indicated that female hormones can influence tendon–aponeurosis strain (Bryant et al., 2008). In addition, to minimize the effects of the diversity of subjects and tendinopathies on measurements, factors such as age, activity level, history of injury or treatment, and tendon injury, other than the area of interest, were controlled for. The incidence of Achilles tendinopathy is related to age, especially in subjects older than 30–35 years (Renström & Woo, 2007). Those older than 35 years tend to develop age-related diseases rather than load-related degenerative tendinopathies (tendinosis), and are not representative of an athletic group undergoing intensive training. The inclusion criteria for eligible subjects were as follows: athletes who (a) were less than 35 years old and currently playing or training for international competition levels; (b) had no prior injection into or surgery on their Achilles tendons; (c) had no traumatic or chronic history of hip, knee, or ankle injury that caused them to seek medical help within 1 year prior to the year of recruitment; (d) had unilateral chronic pain and tenderness of the middle portion of the Achilles tendon, with chronic pain defined as pain occurring at the beginning of or a short time after the end of their regular training sessions for at least 3 months, and the middle portion of the Achilles tendon defined as 2–6 cm proximal to the insertion (Alfredson, 2003); and (e) met the criteria during physical examination and ultrasonographic screening. The subjects who met the inclusion criteria contacted the researchers (using instructions on the posted sheets) and were then assessed within 3 days, using physical examinations, ultrasonographic screenings, and measurements, successively. All subjects were asked not to perform any strenuous exercise for at least 24 h prior to the measurements. Before the measurements were taken, the subjects were surveyed by collecting histories, filling out a questionnaire, and performing a bilateral physical examination to ensure that they met the first four inclusion criteria. History-taking included physical characteristics (body height and weight), pain or injury history, and training experiences (years playing a particular sport). The subjects indicated the clinical severity of their condition by filling out the VISA-A questionnaire (Robinson et al., 2001). Help with translating the English content of the questionnaire was provided if needed. All recruited subjects were examined by at least two qualified physiotherapists using the techniques of the Royal London Hospital test to ensure the coherence between Achilles tendon tenderness and pain location (Maffulli et al., 2003). During ultrasonographic screening, the subjects were bilaterally evaluated using ultrasound (EnVisor, Philips Medical Systems, Inc, Bothell, WA, USA) with a 3- to 12-MHz broadband linear array transducer to search for the following image criteria in both longitudinal and transverse scanning: any evidence of intratendinous local hypoechoic swelling (thickness difference greater than 2 mm) in grayscale images or neovascularization (Fig. 1) seen in or close to the area of the tendon with hypoechoic changes in color Doppler images correlated with subjects’ tendon pain (tendinosis) (Alfredson, 2003).

During the processes of collecting histories, performing physical examinations, and conducting ultrasonographic screenings, several factors – including Achilles tendon injuries other than middle-portion degeneration, physically inherent factors that cause multiple tendinopathies (Riley, 2004), and treatment programs – that may have had negative effects on our outcome measurements were identified as exclusion criteria. Therefore, subjects were excluded if they (a) exhibited any ultrasonographic evidence of partial tearing or calcification within their afflicted tendons (nondegenerative changes) in either leg (Maffulli et al., 2003); (b) exhibited any ultrasonographic evidence of fluid accumulation, increased blood flow around the tendon, crepitation during palpation (paratendinopathy) (Maffulli et al., 2003), Haglund deformity (exostosis), or retrocalcaneal bursitis at the insertional zone (insertional tendinopathy) in either leg (Sofka et al., 2006); (c) exhibited positive signs in the Royal London Hospital test and abnormal ultrasonographic images in both legs indicating bilateral tendinosis; or (d) were currently undergoing an intensive treatment program (frequency of more than once per week) for their tendon pain.

Recordings of ankle angle, torque, and electromyography (EMG)
All measurements were performed in an institutional sports laboratory. The measurements – including viscoelastic properties, normalized RFD, and voluntary EMD – were conducted separately on both legs in the following setting and in an order of block randomization regardless of chronic Achilles tendinopathy. Each subject lay prone on an examination table with both ankles hanging over the edge; the lower back and knees were tightly secured by straps. The foot was positioned at 90° relative to the tibia and fixed on a footplate to minimize ankle movements. The effectiveness of the ankle fixation method was assessed using an electrogoniometer (Sharp Sensor S700, Measurand Inc, Fredericton, Canada). To place this electrogoniometer (or potentiometer) over the center of rotation of the ankle joint, the ends of the electrogoniometer were fixed to the medial side of the lower leg parallel to the tibia and to the medial side of the foot parallel to the first metatarsal bone. Electrical outputs from the electrogoniometer provided a continuous record of the angle of dorsiflexion or plantarflexion (in degrees) present at the ankle joint during the
measurements. The electrogoniometer was fed into the MP100 (same for the load cell). A load cell (model S6001; Celtron Techniques Inc, Taipei, Taiwan) connected to the footplate was used to record voluntary isometric plantarflexion/dorsiflexion torque (Nm).

Data on voluntary muscular activities of the triceps surae and tibialis anterior muscles were collected using surface EMG (MP100; BIOPAC Systems Inc, Santa Barbara, CA, USA) and four pairs of active recording electrode pads (TSD150B). These active recording electrodes were connected to an interface (HLT-100C) of the MP100 system, and the MP100 system was connected to a computer (D672; ASUS, Taipei, Taiwan) on which AcqKnowledge 3.8 acquisition software (BIOPAC) was installed. Signals were amplified from these surface electrodes (stainless steel disk diameter 11.4 mm, disc spacing 20 mm, impedance = 100 MΩ; gain = 350), band-pass filtered from 20 Hz to 500 Hz, and sampled at 1200 Hz with a common mode rejection ratio of 95 dB. A 60-Hz notch filter was used to eliminate background noise from electrical power sources and the research equipment. Electrode orientations were approximately parallel to the muscle fibers of the triceps surae and tibialis anterior muscles. Electrodes were placed (a) at a site corresponding to the proximal third (distance between the lateral malleolus of the ankle and the lateral condyle of the knee) of the gastrocnemius medialis and lateralis muscles; (b) slightly lateral to the middorsal line of the lower leg, about 5 cm distal from where the two heads of the gastrocnemius muscle join the Achilles tendon; and (c) parallel to the tibia at approximately one-third the distance between the knee and ankle to record EMG signal amplitudes from the surface of the gastrocnemius medialis and lateralis, soleus, and tibialis anterior. Surface electrodes were positioned with an inter-electrode distance of 20 mm with the reference electrode placed on the lateral malleolus of the left ankle, as described by Gondin et al. (2006) and in our previous study (Wu et al., 2011). The skin was prepared prior to application of the surface electrodes, and a portable EMG instrument (Sierra II; Cadwell, Kennewick, WA, USA) was used to ensure that the interelectrode resistance was below 5 kΩ. To ensure continuous conduction between these electrode pads and the skin, a small amount of electrode gel was applied on the skin, and the electrode pads were held tightly in place with adhesive tape. When collecting data on muscle voluntary activity (described in the next paragraph), concomitant signals of the electrogoniometer, surface EMG, and load cell were stored on the computer at 1200 Hz. Real-time development or changes in torque, amplitudes of surface EMG, and angle of the ankle joint were displayed to subjects on computer monitors using a software window (AcqKnowledge software, BIOPAC Systems Inc, Santa Barbara, CA, USA) for visual feedback to encourage maximal contraction and to determine the muscle status of relaxation or maximal isometric contraction. This online visual feedback facilitated the reproducibility of results. Subjects were evaluated using the same sequences in subsequent measurements.

During the offline analyses, the load cell signal was filtered by a digital fourth-order, zero-lag recursive Butterworth low-pass filter with an upper cutoff frequency of 50 Hz (Guissard & Duchateau, 2006). Subsequently, the load cell force signal was converted to newtons and multiplied by the individual lever arm length (the horizontal distance between the lateral malleolus and the ball of the foot) to calculate the torque (Lévénez et al., 2008). The plateau phase of maximal isometric plantarflexion torque was defined as the peak value. To ascertain negative forces from the antagonist muscle (tibialis anterior co-contraction) during plantarflexion, each subject also performed a ramp 5-s isometric contractions and relaxation of dorsiflexion. Negative forces of the tibialis anterior during plantarflexion were estimated by the co-contraction of EMG signal amplitudes and the relationship between the dorsiflexion force and the root mean square (RMS) EMG. These negative forces were then added (adjusted) to the corresponding plantarflexion forces to avoid force underestimation. During the offline analysis, the EMG signals were digitally high-pass filtered using a fourth-order, zero-lag Butterworth filter (the cutoff frequency was set at 20 Hz), followed by a moving RMS filter with a time constant of 50 ms by using custom-made software developed in MATLAB 7.1 (MathWorks, Natick, MA, USA) (Aagaard et al., 2002).

Tendon elongations and viscoelastic properties

In this measurement, each subject was instructed to gradually increase plantarflexion force in their right foot from a relaxed status to maximal voluntary isometric contraction (MVIC) within 5 s, to maintain MVIC for 1 s, and then to completely relax within
5 s (Kubo et al., 2007). The subjects were familiarized with the protocol using a 5-min series of submaximal contractions. Verbal instructions, beats from a metronome, and visual feedback from the monitor were provided to facilitate rhythmic contraction and relaxation. A 5- to 10-MHz linear array transducer (L38; SonoSite Inc, Seattle, WA, USA) with near-field resolution (axial resolution 0.7 mm) was aligned on the mid-longitudinal axis of the gastrocnemius at the level of the distal myotendinous junction (Maganaris & Paul, 2000). The transducer was fixed on the skin with a custom-made frame and secured with double-sided adhesive plasters. Tendon elongation measurements were taken during the ramping contraction, MVIC, and relaxation by ultrasonography, using B-mode ultrasound (SonoSite 180plus; SonoSite Inc.). The real-time images were stored on a disc at 30 Hz. For synchronization, software containing simulating switching circuits written using Labview 7.1 (National Instruments, Austin, TX, USA) was used to add audio-electrical signals to the camera and Biopac system at the beginning and end of each measurement. Therefore, images were recorded with simultaneous data regarding EMG, ankle joint angle, and plantarflexion force. Images corresponding to each 5% level of maximal isometric torque between 0% and 100% were chosen to measure the displacement of the myotendinous junction. Displacement digitalization of the junction was performed by the same examiner with software from AutoCAD (AutoCAD; Autodesk Inc., Los Angeles, CA, USA). Previous work from our laboratory demonstrated that the interday reproducibility of calculating the displacement on the basis of a coefficient of variation was 9.1%. To ensure the myotendinous junction displacements of the gastrocnemius obtained during the isometric contractions were not overestimated by additional displacement from ankle plantarflexion, the additional displacements caused by passive ankle plantarflexion from 90° to 80° were continuously recorded by the synchronized ultrasonography and electrogoniometer. Tendon displacements calculated in each sequential ultrasonographic image of plantarflexion were initially corrected by the rotation-attributed displacement according to the corresponding ankle joint of plantarflexion (Magnusson et al., 2001).

The measured plantarflexion torques (TQ) were converted to tendon force (Ft) by the following equation: \[ Ft = \frac{TQ}{MA} \] where the moment arm (MA) was determined using the methodology of Maganaris and Paul (2000). Corrected displacements of the myotendinous junction of the gastrocnemius in the ultrasonographic images with adjusted corresponding tendon force values during ascending (contraction) and descending (relaxation) phases were fitted with second-order polynomial functions forced through zero used to plot a stress–strain loop (Fig. 2). Tendon stiffness was defined as the slope of the ascending phase of muscle contraction between 50 and 100% of maximum force (Kubo et al., 2007). The areas under the ascending and descending phases represented the elastic energy of storage and release, respectively. The ratio of the area within the stress–strain loop to the area beneath the curve during the ascending phase was calculated as hysteresis (Maganaris & Paul, 2000). Area calculations were made with MATLAB 7.1 software. Each measurement consisted of three trials spaced 3 min apart. Previous work from our laboratory demonstrated that the interday reproducibility of calculating stiffness and hysteresis on the basis of coefficients of variation were 8.7 and 10.7%, respectively.

Voluntary EMD and normalized RFD
In this measurement, subjects were told to relax their leg muscles for a period of 1 min and then to plantarflex their ankle as quickly as possible. The voluntary EMD was quantified as the time interval between the onset of EMG signals of the triceps surae muscles (including gastrocnemius medialis, gastrocnemius lateralis, and soleus) and the onset of plantarflexion torque measured by MATLAB 7.1 software. The onset of EMG was displaced on a computer screen and identified as the EMG signals deviated by more than five times standard deviations for a minimum of 25 ms, above the baseline level (averaged over 200 ms before the instruction of the trial). The onset of voluntary contractions were determined when the moment curve exceeded baseline moment by 7.5 Nm (Aagaard et al., 2002). If the automatic EMG or force-onset identification differed from the researchers’ experiences by more than 5 ms, visual combined with manual onset identification was used. The normalized RFD was the slope of the torque–time curve normalized to (divided by) peak torque of MVIC and determined at normalized force intervals from the onset of contraction (the time point when the moment curve exceeded 2.5% of the difference between baseline and MVIC moments) to one-fourth MVIC, one-half MVIC, three-fourths MVIC, and four-fourths MVIC (Aagaard et al., 2002; Blazevich et al., 2008).

One-leg hopping test
During this test, the subjects stood behind a take-off line marked on the floor. Tests started from an erect standing position, and subjects were instructed to perform a triple jump on one leg as far as possible without losing balance or stepping onto the other leg. The subjects were allowed to maximize their forward drive by performing a countermovement of quick knee bending and backward arm swing prior to the jump. The hopping distance was determined as the farthest point of landing (tip of foot) from the take-off line with one scale of centimeters. The subject performed at least three maximal trials for each leg, and the longest hopping distance for each leg was recorded for analysis. The approved trials were defined as three trials with no successive increases.

Statistical analyses
All variables except the hopping distance were averaged over at least three trials. All data are presented as mean (standard deviation). Wilcoxon’s signed rank tests were used to analyze differences of the means of the variables between legs with and without Achilles tendinosis. Spearman’s tests were used to analyze the correlations between the viscoelastic properties and performance tests. Correlations between differences of the viscoelastic properties within the subjects and questionnaire score (VISA-A) were also analyzed. All analyses were performed in the null form and
conducted using the Statistical Package for the Social Sciences (SPSS) 17.0 for Windows (SPSS Inc., Chicago, IL, USA), with the α level set at 0.05.

Results

Twenty eligible male subjects were recruited for the study, and 17 were enrolled; three were excluded because of paratendinopathy (1), insertional tendinopathy (1), or receipt of an intensive treatment program for their tendon pain (1). Athletes were participating in sports including 100- or 200-m sprinting (4), 110-m hurdles (3), badminton (4), tennis (2), middle- and long-distance running (3), and basketball (1). The characteristics and VISA-A questionnaire scores of these 17 subjects are summarized in Table 1.

Compared with the noninjured leg, the viscoelastic properties of the injured leg showed reduced tendon stiffness (−19.2 ± 11.3%), greater mechanical hysteresis (+21.2 ± 26.3%), and lower stored (−14.2 ± 19.0%)弹性 energy (all P-values < 0.05) (Table 2). In addition, results of explosive performance tests in the tendinopathic leg demonstrated lower normalized RFD at one-fourth MVIC (−16.3 ± 28.5%), one-half MVIC (−17.3 ± 25.7%), and three-fourths MVIC (−13.7 ± 18.7%), longer voluntary EMD in the soleus (+26.9 ± 31.6%) and medial gastrocnemius (+24.1 ± 34.1%) muscles, and shorter one-leg hopping distances (−34.1 ± 24.6%) (all P-values < 0.05) (Table 3). Because the correlations between the tendon stiffness and voluntary EMD are negative, the magnitude of the association for these measures between tendon stiffness and explosive performance, including EMD, RFD, and hopping distance, were ranged between −0.35 and 0.64 (P < 0.05). Hysteresis showed significant correlations with the soleus voluntary EMD (positive) and one-leg hopping distance (negative) (r = 0.42 and -0.39, P < 0.05) (Table 4). However, the differences in values in viscoelastic properties between the injured leg and noninjured (control) leg were not correlated with the clinical severity of symptoms as represented by the questionnaire scores (all P-values > 0.05).

Discussion

In this study, subjects with unilateral Achilles tendinosis showed changes in the tendon viscoelastic properties of stiffness and elastic energy utilization in their tendinopathic legs compared with the noninjured legs. Furthermore, these changes were correlated to decreased explosive neuromuscular performance, either isometric or dynamic. Nevertheless, no significant correlations

Table 1. Characteristics of the subjects involved in this study (N = 17)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean (standard deviation) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>27.3 (2.0)</td>
</tr>
<tr>
<td>Body height (cm)/weight (kg)</td>
<td>183.2 (7.1)/75.9 (10.8)</td>
</tr>
<tr>
<td>Training experience (years)</td>
<td>13.1 (4.2)</td>
</tr>
<tr>
<td>Duration of pain before recruitment (months)</td>
<td>5.9 (1.3)</td>
</tr>
<tr>
<td>Questionnaire (VISA-A) score</td>
<td>70.7 (7.8)</td>
</tr>
</tbody>
</table>


Table 2. Comparison of viscoelastic properties of the Achilles tendon between legs with and without tendinosis

<table>
<thead>
<tr>
<th>Viscoelastic properties (unit)</th>
<th>Injured leg</th>
<th>Noninjured leg</th>
<th>P value</th>
<th>Mean difference</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness (N/mm)</td>
<td>105.9 (19.8)</td>
<td>132.7 (26.3)</td>
<td>&lt;0.001</td>
<td>-26.8</td>
<td>-35.0 to -18.5</td>
</tr>
<tr>
<td>Mechanical hysteresis (%)</td>
<td>28.0 (6.7)</td>
<td>23.6 (5.3)</td>
<td>0.004</td>
<td>4.4</td>
<td>1.4 to 7.3</td>
</tr>
<tr>
<td>Elastic energy stored (J)</td>
<td>6.1 (1.3)</td>
<td>7.3 (1.2)</td>
<td>0.002</td>
<td>-1.2</td>
<td>-1.9 to -0.4</td>
</tr>
<tr>
<td>Elastic energy released (J)</td>
<td>4.5 (1.0)</td>
<td>5.6 (0.8)</td>
<td>&lt;0.001</td>
<td>-1.1</td>
<td>-1.7 to -0.5</td>
</tr>
</tbody>
</table>

Note: Values are given as mean (standard deviation).

Table 3. Comparison of results of explosive performance tests between legs with and without Achilles tendinosis

<table>
<thead>
<tr>
<th>Explosive test (unit)</th>
<th>Injured leg</th>
<th>Non-injured leg</th>
<th>P value</th>
<th>Mean difference</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized 1/4 RFD (%MVIC/s)</td>
<td>1188.0 (523.8)</td>
<td>1414.7 (509.2)</td>
<td>0.02</td>
<td>-226.8</td>
<td>-415.8 to -37.7</td>
</tr>
<tr>
<td>Normalized 1/2 RFD (%MVIC/s)</td>
<td>1511.3 (525.1)</td>
<td>1844.2 (479.2)</td>
<td>0.006</td>
<td>-332.8</td>
<td>-547.0 to -118.7</td>
</tr>
<tr>
<td>Normalized 3/4 RFD (%MVIC/s)</td>
<td>1127.3 (394.1)</td>
<td>1330.8 (490.3)</td>
<td>0.02</td>
<td>-203.5</td>
<td>-342.3 to -64.7</td>
</tr>
<tr>
<td>Normalized 4/4 RFD (%MVIC/s)</td>
<td>404.2 (179.1)</td>
<td>507.6 (253.0)</td>
<td>0.09</td>
<td>-103.4</td>
<td>-213.3 to 6.5</td>
</tr>
<tr>
<td>MG voluntary EMD (ms)</td>
<td>32.6 (7.6)</td>
<td>26.6 (6.0)</td>
<td>0.004</td>
<td>6.9</td>
<td>2.0 to 9.9</td>
</tr>
<tr>
<td>LG voluntary EMD (ms)</td>
<td>31.0 (7.5)</td>
<td>26.5 (6.1)</td>
<td>0.09</td>
<td>6.0</td>
<td>-1.0 to 9.9</td>
</tr>
<tr>
<td>Sol voluntary EMD (ms)</td>
<td>25.0 (6.5)</td>
<td>19.3 (4.5)</td>
<td>0.009</td>
<td>4.5</td>
<td>3.1 to 10.6</td>
</tr>
<tr>
<td>One-leg hopping distance (cm)</td>
<td>285.3 (59.4)</td>
<td>436.3 (46.1)</td>
<td>&lt;0.001</td>
<td>-150.6</td>
<td>-184.3 to -116.8</td>
</tr>
</tbody>
</table>

Note: Values are given as mean (standard deviation).

RFD, rate of force development; MVIC, maximal voluntary isometric contraction; MG, gastrocnemius medialis; LG, gastrocnemius lateralis; Sol, soleus; EMD, electromechanical delay.
Table 4. Correlations between tendon viscoelastic properties and explosive performance and clinical severity.

<table>
<thead>
<tr>
<th>Clinical severity*</th>
<th>VISA score</th>
<th>One-leg hopping distance</th>
<th>Voluntary EMD</th>
<th>RFD 1/4 MVIC</th>
<th>RFD 1/2 MVIC</th>
<th>RFD 3/4 MVIC</th>
<th>RFD 4/4 MVIC</th>
<th>Elastic energy stored (J)</th>
<th>Elastic energy released (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tendon stiffness (N/mm)</td>
<td>$r = 0.40, \ P = 0.021$</td>
<td>$r = 0.40, \ P &lt; 0.001$</td>
<td>$r = 0.31, \ P = 0.074$</td>
<td>$r = 0.60, \ P &lt; 0.001$</td>
<td>$r = 0.60, \ P &lt; 0.001$</td>
<td>$r = 0.67, \ P = 0.067$</td>
<td>$r = 0.01, \ P = 0.946$</td>
<td>$r = 0.13, \ P = 0.467$</td>
<td>$r = 0.14, \ P = 0.438$</td>
</tr>
<tr>
<td>Mechanical hysteresis (%)</td>
<td>$r = -0.04, \ P = 0.334$</td>
<td>$r = 0.16, \ P = 0.016$</td>
<td>$r = 0.08, \ P = 0.641$</td>
<td>$r = 0.14, \ P = 0.123$</td>
<td>$r = 0.27, \ P = 0.123$</td>
<td>$r = 0.03, \ P = 0.723$</td>
<td>$r = 0.21, \ P = 0.067$</td>
<td>$r = 0.28, \ P = 0.073$</td>
<td>$r = 0.28, \ P = 0.104$</td>
</tr>
<tr>
<td>Elastic energy stored (J)</td>
<td>$r = -0.04, \ P = 0.316$</td>
<td>$r = 0.16, \ P = 0.016$</td>
<td>$r = 0.08, \ P = 0.641$</td>
<td>$r = 0.14, \ P = 0.123$</td>
<td>$r = 0.27, \ P = 0.123$</td>
<td>$r = 0.03, \ P = 0.723$</td>
<td>$r = 0.21, \ P = 0.067$</td>
<td>$r = 0.28, \ P = 0.073$</td>
<td>$r = 0.28, \ P = 0.104$</td>
</tr>
</tbody>
</table>

The results of this study indicate that viscoelastic properties of legs with Achilles tendinosis are different from those in healthy legs and may have adverse effects on explosive performance. These findings not only show that tendinopathy affects explosive neuromuscular functions, but also provide information regarding clinical practice and the treatment of tendinopathy in athletes. The results regarding stiffness in a group of professional athletes are consistent with previous findings in the middle-aged general population and middle-aged runners (Arya & Kulig, 2010; Child et al., 2010). The lower stiffness in the tendinopathy may be caused by tendon structural and compositional changes including loss of the characteristic hierarchical structure, waviness and separation of tendon fibers, random blood vessel formation (hyper-vascularization), and degeneration and disorganization of collagen fibers coupled with increased extracellular matrix, such as glycosaminoglycan (Maffulli et al., 2004). These structural and compositional changes, especially the imbalance between collagen content and extracellular matrix, have been suggested to have strong influences on viscoelastic properties in tendinopathy (Robinson et al., 2004). Tendons are one of the noncontractile mechanisms in human locomotion and play an integral role in mechanotransduction and muscle activation optimization. In an aspect of clinical implications, reduced tendon stiffness in tendinopathy may impede quick movement production by requiring additional time to stretch the series elastic component (SEC) in the myotendinous complex, leading to a lower RFD and longer EMD as found in this study. This low stiffness also indicates excessive tendon elongations and concurrent muscle shortening during contractions, and may constrain neuromuscular ability to (a) achieve accurate positioning of a limb segment; (b) achieve a given position after a perturbation (Biewener & Roberts, 2000); or (c) maintain optimal muscle activation. Moreover, because of poor muscle-length control, coordination between tendinopathic muscles and other muscles, such as in synergistic or antagonistic activities, may have to change in terms of activation levels or time interval to compensate for the altered tendon stiffness. Previous studies supporting these four clinical implications of low tendon stiffness include (a) one study found a relationship between compromised postural stability and Achilles tendon compliance in elderly people (Onambele et al., 2006); (b) subjects with Achilles tendinopathy showed altered neuromuscular activities in timing of running, including delayed onset of tibialis anterior muscle and increased duration of the soleus and lateral gastrocnemius muscles (Munteanu & Barton, 2011); (c) increased antagonist coactivation of the tibialis anterior during fast force development or reduced neuromuscular activities of the medial gastrocnemius were found in the weight-bearing phase of gait cycles in studies of midportion Achilles tendinopathy (Baur et al., 2011; Wang...
et al., 2011). Nevertheless, more evidence is required to confirm that the magnitude of the stiffness changes in tendinopathy is of clinical significance. In addition, although significant differences of maximal torque of MVIC between the healthy control legs and legs with Achilles tendinopathy were not found in this study (data not shown), researchers should be aware that normalization to the MVIC may be a confounding factor in comparisons of normalized RFD because injuries are possibly associated with a decline in torque of MVIC. Our results also indicate that the reduced stiffness of the noncontractile tendon in tendinopathy have adverse effects on the medial gastrocnemius in terms of explosive contractions (the EMD). However, altered contractile mechanisms in the medial gastrocnemius are also possible causes of this increased EMD, because edema and fatty degeneration are commonly found in the soleus and gastrocnemius muscles in patients with Achilles tendon abnormalities (Hoffmann et al., 2011). Future studies are recommended to investigate clinical applications of Achilles tendon viscoelastic properties and to investigate progress in stiffness resulting from physical therapy in patients with Achilles tendinosis.

This study found increased mechanical hysteresis and reduced elastic energy storage and release in the tendinopathic leg in athletes with unilateral Achilles tendinosis. These phenomena indicate a reduced energy-conserving capacity and increased energy dissipated as heat in Achilles tendinopathy. Tendons are the main structures in the myotendinous complex that store energy by active stretching because of inertial, gravitational, and muscle forces (Alexander, 2002). The mechanics and energy of human locomotion involve either repetitive or explosive movements and are affected by tendon mechanical hysteresis. In an experiment with running turkeys, the gastrocnemius tendon was found to recover 5 J/kg muscle, and the muscle would have to do more than double the work without this energy recovery (Roberts et al., 1997). Storage and release of elastic energy by the tendon was found to reduce the actual requirements of metabolic energy costs in repetitive cycles, such as running (Minetti et al., 1994). Increased mechanical hysteresis in the tendon indicates increased metabolic demands and intratendinous hyperthermia. The former may create an oxidative stress that could mediate changes to the tendon structure, and the latter may lead to tendon degeneration (Farris et al., 2011). Our findings imply that tendons with tendinosis show reduced hopping distances and prolonged soleus EMD because of the storage of less elastic energy compared with healthy tendons, which is exacerbated by a lower rate of energy recovery (a high hysteresis). Negative correlations between the hysteresis and hopping distances or soleus voluntary EMD may because the elastic energy utilization in the SEC affects the work output contributing the jump performance (Bobbert, 2001). In addition, the degenerative changes in the soleus muscle found in Achilles abnormalities may reduce energy efficiency or utilization in the Achilles tendon (Hoffmann et al., 2011). Future studies are required to clarify the effects of myoelectrical activities of the muscle on the tendon viscoelasticity in tendinopathy.

The one-leg hopping test involving stretch-shortening cycles is often used to reveal lower-extremity functions in tendinopathic and noninjured legs (Heijke et al., 2009). Our study showed that triple one-leg hopping distances were correlated to both tendon stiffness and hysteresis. Thus, this test reflects tendon viscoelastic properties regarding stiffness and elastic utilization and is therefore recommended as a means to record patients’ improvement during physical therapy.

This study did not demonstrate a correlation between viscoelastic properties and clinical severity using the VISA-A questionnaire. This may be due to the fact that clinical severity is a measure of pain, function, and ability to perform sport activities. In addition, the causes of pain may include biomechanical loading, pain threshold, and biochemical changes, including neurogenic inflammation (the ‘iceberg’ theory) in chronic tendinopathy with intratendinous degeneration and little or no inflammation (Abate et al., 2009). Tendon degeneration with mechanical breakdown of collagen or excessive deformity alone may not be able to explain the clinical severity of tendinopathy. Nevertheless, it would be interesting to know whether there is a parallel relationship between tendon strain changes and neurogenic inflammation by repetitive forces in subjects with compliant tendons. It has been suggested that tendon compliance or poor recoil in repetitive locomotion may result in collagen micro-tears, hyperthermia, and tendon degeneration (Wilson & Goodship, 1994). However, in the current cross-sectional study, it could not be determined whether there is a cause–effect relationship between the viscoelastic properties and tendinopathy.

Eccentric training is an effective therapeutic program for patients with initial tendinopathy. It was found to have neurological and myotendinous effects on tendinopathy, including reduction of Achilles tendon volume, hypervascularization, and pain (Allison & Purdam, 2009; Grigg et al., 2009). Nevertheless, effects of eccentric training on tendon stiffness were insignificant in tendinopathy (Morrissey et al., 2011). Research has found that long-term training such as resistance or plyometric training induces changes in viscoelastic properties in the Achilles tendon, including increased stiffness or reduced mechanical hysteresis (Kubo et al., 2002; Fouré et al., 2011; Wu et al., 2011). These resistance or plyometric training methods are recommended to athletes with Achilles tendinosis once the pain subsides. We concluded that altered tendon viscoelastic properties in Achilles tendinosis, including tendon stiffness and elastic energy utilization, affect explosive performance in elite athletes. These alterations may also influence movement accuracy and energy efficiency in the ankle joint.
With more comprehensive approaches, this study has compared tendon viscoelastic properties between legs with and without Achilles tendinosis and investigated the correlations between the properties and explosive performance or clinical severity. Results of this study provide important information to sports medicine personnel and physiotherapists in anticipating treatment to Achilles tendinopathy. Although it could not be determined whether there is a cause–effect relationship between the viscoelastic properties and tendinopathy, these altered tendon viscoelasticity affect explosive performance and may affect movement control during different levels of force exertion. The chemomechanical change, such as changes of tendon stiffness, is observed concurrently and correlate with performance deficits in Achilles tendinopathy.

Key words: Achilles tendinopathy, tendon stiffness, mechanical hysteresis, one-leg hopping.

Acknowledgements
This study was financially supported by National Science Council in Taiwan, ROC (NSC98-2314-B-002-013-MY3).

References


Magnusson SP, Narici MV, Maganaris CN, Kjaer M. Human tendon behaviour
Tendon elasticity and clinical assessments


