Ultrasonic Evaluations of Achilles Tendon Mechanical Properties Post Stroke

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ABSTRACT

Spasticity, contracture, and muscle weakness are commonly observed post stroke in muscles crossing the ankle. However, it is not clear how biomechanical properties of the Achilles tendon change post stroke, which may affect functions of the impaired muscles directly. Biomechanical properties of the Achilles tendon including the length and cross-sectional area in the impaired and unimpaired sides of 10 hemiparetic stroke survivors were evaluated using ultrasonography. Elongation of the Achilles tendon during controlled isometric ramp-and-hold and ramping up then down contractions was determined using a block-matching method. Biomechanical changes in stiffness, Young’s modulus, and hysteresis of the Achilles tendon post stroke were investigated by comparing the impaired and unimpaired sides of the 10 patients. The impaired side showed increased tendon length (6%, \( P=0.04 \)), decreased stiffness (43%, \( P<0.001 \)), decreased Young’s modulus (38%, \( P=0.005 \)), and increased mechanical hysteresis (1.9 times higher, \( P<0.001 \)) compared to the unimpaired side, suggesting Achilles tendon adaptations to muscle spasticity, contracture, and/or disuse post stroke. In vivo quantitative characterizations of the tendon biomechanical properties may help us better understand changes of the calf muscle-tendon unit as a whole and facilitate development of more effective treatments.

KEYWORDS: Stroke; Achilles tendon; Mechanical property; Ultrasound
INTRODUCTION

Achilles tendon plays an important role in force transmission, energy storage and return during functional activities such as walking and running, (26) and interacts with the calf muscle directly (32). Recent studies show that the metabolic activity in human tendon is remarkably high which affords the tendon the ability to adapt to changing demands (3, 4, 15, 16). Stroke survivors often develop spasticity, contracture, and/or muscle weakness at the ankle, which contribute considerably to their disabilities post-stroke (5, 12, 14, 34). About 34% of stroke survivors develop ankle contracture (27, 28, 34). The impaired/spastic plantar flexors and associated foot-drop post stroke makes it hard for the foot to clear the ground during locomotion and the lack of ankle plantar flexion power results in reduced forward propulsion (34, 35). Although a number of studies have been done on the changes of muscle fascicle mechanical properties post stroke (5, 8-10), e.g., shortened muscle fascicles have been found in the gastrocnemius muscle post stroke, it is not clear about the associated changes of Achilles tendon mechanical properties and how the tendon interacts with the architectural/functional changes of the calf muscles in stroke survivors.

One study proposed that the increase of passive ankle stiffness was due to the increase of Achilles tendon stiffness, based on the assumption that Achilles tendon was more compliant than muscle (31). In another study, Achilles tendon stiffness post stroke was evaluated indirectly during eccentric-concentric muscle actions based on a muscle-tendon complex model (30). With the B-mode ultrasonography, the mechanical properties of human tendon can be evaluated in vivo and noninvasively
A number of ultrasonic studies have been carried out to investigate tendon properties and their changes associated with aging, disuse, exercise, and paralysis (1, 11, 13, 17, 23, 37). Tendon mechanical properties were commonly evaluated with the subject performing maximum voluntary contractions (MVC). The ultrasound images of the muscle-tendon junction (MTJ) before and after contraction were recorded and manually compared to measure the tendon elongation. However, due to muscle weakness and lack of control, the impaired ankle of stroke survivors can only generate a fraction of a healthy subject’s MVC. The MTJ displacement in the impaired ankle is therefore considerably smaller and requires accurate and objective measurement.

The purpose of the present study was to investigate changes of the Achilles tendon biomechanical properties post stroke. An automatic block-matching method based on minimum sum of absolute differences (MSAD) algorithm (19) was used to continuously track the displacement of the soleus-Achilles MTJ. The hypotheses were that the impaired side had longer, thinner, and more compliant Achilles tendon with lower energy efficiency than the unimpaired side.

**METHODS**

**Subjects**

Ten stroke survivors participated in the study (5 right side impaired and 5 left side impaired, both the left and right-side impaired groups contained one female and 4 male subjects). The inclusion criteria for the patients were: having hemiparesis following a stroke at least one year earlier, able to walk with a cane or without any
mechanical aid, able to generate plantar flexion torque using the calf muscles. Exclusion criteria were: having other severe disease, leg musculoskeletal injuries, and/or orthopaedic surgeries on the leg. The patients had a mean age of 60.3 ± 8.4 (mean ± SD, range 52.8-78.8) years, stroke duration of 12.0 ± 5.8 (range 4.5-20.8) years, a mean height of 170.8 ± 10.2 (range 147.3-181.6) cm, body mass 80.6 ± 15.3 (range 59.9-99.9) kg. Their modified Ashworth scale was 1.6 ± 1.3 (range 0-3). Their passive range of motion (ROM) was 11.0 ± 4.8 (range 5-19) degrees in dorsiflexion, and 42.6 ± 4.5 (range 37-51) degrees in plantar flexion, respectively. Three subjects wore AFOs and one subject was using anti-spasticity medication. Three subjects used the straight cane and one subject used the quad cane. All participants gave informed consent which was approved by the Institution Review Board.

**Experimental setup**

The experimental setup was comprised of four major parts: a custom knee-ankle joint-driving device, an ultrasound imaging system, an electromyography (EMG) system, and a personal computer.

A custom knee-ankle joint-driving device was used to position the leg and the ankle, and measure the joint torque. The motor at the knee was fixed rigidly to a frame anchored to the ground and a leg linkage was mounted to the knee motor through a torque sensor. The ankle motor was mounted at the distal end of the leg linkage and a footplate was mounted to the ankle motor through another torque sensor. The ankle motor and footplate could be adjusted along the leg linkage so that the
ankle and knee motors were aligned with the ankle and knee flexion axes, respectively (Fig. 1).

The ankle plantar flexion torque was measured and displayed on the screen in real-time as a visual feedback. Bagnoli™ EMG system (Delsys Inc., Boston, MA) was used to monitor the EMG signal from the tibialis anterior muscle. A trigger signal was sent to the ultrasound imaging system to initiate the ultrasound image recording. The sampling rate for both torque and EMG data acquisition was 1000 samples/sec.

A commercial ultrasound imaging system, GE LOGIQ-9 with a 12 MHz high-resolution matrix probe M12L (GE Healthcare, Waukesha, WI), was used to obtain images of the Achilles tendon and monitor the movement of the soleus-Achilles MTJ.

Experimental design

The experiment for every subject was composed of two visits. Each of the legs was tested in one of the two visits, following the same protocol. The sequence of the side being tested was selected randomly. Time between the two visits for each subject was within one week. For the patients who were taking anti-spastic medications, the experiment was done at least 4 hours after the medicine was taken.

The subject was seated upright with the thigh and trunk secured using Velcro® straps. The leg and foot were securely attached to the leg linkage and footplate, respectively (Fig. 1), with the knee and ankle at full extension and 0° dorsi-flexion, respectively. After several warm-up isometric contractions in plantar flexion, the
subject gradually increased the plantar flexion torque until reaching a specified level and then held for a period of time (ramp-and-hold), following the target and actual torques displayed in real-time on the monitor. The ramping speed was set so that the subjects could carry out the task properly and the MTJ displacement could be tracked in the ultrasound images. The task was repeated three times with a one-minute rest in between. The subject then performed a ramp up and down (gradually increased the torque to a specified level then gradually decreased it) isometric plantar flexion following the target torque for three times separated by a one-minute rest. The torque levels for both tasks were set (about 15 Nm) so that the subject could finish the task properly without losing control or inducing much fatigue during the isometric contractions. The ultrasound video data, ankle joint torque, and EMG signals were recorded throughout both tasks.

Measurement of Achilles tendon length

The Achilles tendon insertion into the calcaneus notch and the soleus-Achilles MTJ were located with LOGIQ-9 and marked at the corresponding positions on the skin surface. The soleus-Achilles MTJ was defined as the location where Achilles tendon (or so called “free tendon”) (25) divides into soleus aponeurosis and gastrocnemius tendon. In an ultrasound image (Fig. 2(b)), the MTJ was the intersection between the most distal muscle fascicles of the soleus muscle and the Achilles tendon. A line (defined as “line A”) was drawn along the Achilles tendon on the skin surface to connect these two points (Fig. 2(a)). The probe was placed
perpendicular to the skin and moved smoothly along line A, scanning in the sagittal plane with the subject relaxed. A special function of LOGIQ-9 called LOGIQView\textsuperscript{TM}, was used to extend the field of view and register the images covering the full tendon length (Fig. 2(b)). The scan was repeated 10 times to minimize the measurement error. ImageJ (National Institutes of Health, Bethesda, MD) was used to measure the distance from the soleus-Achilles MTJ to the calcaneus notch insertion along the tendon line of action (LOA) in the LOGIQView images.

**Measurement of moment arm**

A simple method was developed to measure *in vivo* the Achilles tendon moment arm, defined as the perpendicular distance from the center of rotation (inferior tip of the malleolus) (33) to the tendon LOA. Another line (defined as “line B”) from the center of rotation along the direction perpendicular to the tendon LOA was drawn on the skin surface (Fig. 2(a)). The intersection of line A and line B was marked (Fig. 2(a)) and the total distance from the center of rotation to the intersection projected in the sagittal plane $m_g$ was measured. The corresponding position of the intersection can be found in the LOGIQView image shown in Fig. 2(b), by using a marker to produce shadow in the ultrasound image. Then the distance from the intersection to the tendon LOA $m_i$ was measured in the LOGIQView image (Fig. 2 (b)) and Achilles tendon moment arm $m_A$ was obtained by subtracting $m_i$ from $m_g$ (Equation (1)):

$$m_A = m_g - m_i$$

(1)
**Measurement of the cross-sectional area (CSA)**

Three points dividing line A equally into five sections were marked on the skin surface. The transverse plane at each point was scanned three times using standard ultrasonography. Great care was taken to make the probe and the scanning plane perpendicular to the Achilles tendon. The direction of the transducer was adjusted gradually to get the minimum area which corresponded to the CSA. A representative image of the Achilles tendon cross-section is shown in Fig. 3. ImageJ was used to measure the CSA. The average value from the 9 measurements was calculated as the Achilles tendon CSA.

**Displacement**

The ultrasound probe was securely attached to the lower leg with a customized probe holder with the soleus-Achilles MTJ in sagittal plane clearly visualized at rest. The probe holder was made of thermoplastic material and custom fit to the shape of the probe at one end and the shape of the posterior lower leg at the other end so that the probe can be mounted to the leg securely using Velcro® straps. The properly strapped holder helped keep the probe perpendicular to the skin. When fixed properly, the probe would not move relative to the leg during the plantar flexion effort. The ultrasound video data were continuously recorded at 50 frames/sec during the entire plantar flexion effort once LOGIQ-9 received the trigger signal from the PC.

The ultrasound video data were analyzed frame-by-frame to determine the soleus-Achilles MTJ displacement using the MSAD block-matching method, which
was proposed to quantify two dimensional velocities in human (2) and regional myocardial dysfunction in mice (19), and has been validated using simulation and experimental data. Briefly, this method specifies a tracking pixel block from a previous image frame, and moves the block around in the following frame to find the best match by comparing the sum of absolute differences. In the present study, a tracking pixel block size of approximately 2 mm × 2 mm was used to search best match in a 6 mm × 6 mm surrounding region in the next frame. Parabolic interpolation was used to estimate sub-pixel displacements and a 3-tap median filter was used to smooth the estimated displacements between successive image frames. Four regions near soleus-Achilles MTJ were tracked in consecutive frames and two representative ultrasound images without and with contraction were displayed together with the tracking result of one region in Fig. 4. The arrow points from the original position towards the displaced position based on MSAD block-matching. Therefore the average displacement of the four regions was regarded as the estimated displacement of the soleus-Achilles MTJ. The estimated MTJ displacement during a ramping up then down task was shown in Fig. 5, together with the corresponding ankle joint torque recorded.

*Monitoring co-contraction and heel motion*

EMG signal from the tibialis anterior muscle was used to monitor the activities of dorsiflexors. The EMG signals recorded at rest were saved as the baseline. The trials with the EMG amplitude higher than the baseline mean amplitude plus 3 times of
baseline standard deviation (6) were rejected. A marker was placed on the heel and the motion of the marker was captured by a high resolution (1920×1080 pixels) digital camcorder (Sony HDR-SR11). The camcorder was mounted on a tripod placed close to the marker on the heel. A ruler was placed at the same distance as the marker to show the scale of the picture. After each trial, the video was played back and trials with the heel motion greater than 0.3 mm were discarded.

*Calculation of tendon Young’s modulus, stiffness and mechanical hysteresis*

The MTJ displacement was determined as the Achilles tendon elongation. Achilles tendon strain was obtained by dividing the tendon elongation with the initial tendon length. Tendon force was calculated by dividing the ankle joint torque with the tendon moment arm. Tendon stress was acquired by dividing the tendon force with the average tendon CSA. With the stress-strain curve for the ramp-and-hold task determined, the slope of the curve at 3% strain was defined as the tendon Young’s modulus. Similarly, the slope of the force-elongation curve at the displacement corresponding to 3% strain was defined as tendon stiffness. Force-displacement curves from the ramping up then down task were used to calculate the tendon mechanical hysteresis during loading and unloading, which was defined as the ratio of the area within the loop to the area below the loading curve (22). Representative force-displacement curves from both sides of the same subject are shown in Fig. 6.

*Statistics*

The various measurements were presented as means ± standard deviations. Paired
Student’s T-test was used to test differences in the tendon dimension and biomechanical measures between the impaired and unimpaired sides. Statistical difference was set at a level of $P < 0.05$.

**RESULTS**

*Achilles tendon length and CSA*

The Achilles tendon length measured in the impaired side ($68.5 \pm 13.3$ mm) was significantly longer ($P=0.04$) than in the unimpaired side ($64.4 \pm 11.4$ mm) (Fig. 7(a)). No significant difference ($P=0.19$) was found between the Achilles tendon CSA measured in the impaired side ($53.5 \pm 11.2$ mm$^2$) and in the unimpaired side ($56.1 \pm 11.2$ mm$^2$) (Fig. 7(b)).

*Tendon Young’s modulus and stiffness*

The estimated Achilles tendon Young’s modulus in the impaired side ($136.4 \pm 38.1$ MPa) was significantly lower ($P=0.005$) than that in the unimpaired side ($220.2 \pm 83.3$ MPa) (Fig. 7(c)). Similarly, the estimated Achilles tendon stiffness in the impaired side ($105.0 \pm 14.6$ N/mm) was significantly lower ($P<0.001$) than that of the unimpaired side ($184.8 \pm 48.4$ N/mm) (Fig. 7(d)).

*Tendon mechanical hysteresis*

Three subjects were excluded in this test due to obvious co-contraction during the unloading (ramping down) task. From the remaining 7 subjects, the tendon mechanical hysteresis calculated in the impaired side ($19.6 \pm 3.4$ %) was significantly
Changes of tendon mechanical properties post stroke higher (P<0.001) than in the unimpaired side (6.8 ± 3.0 %), as shown in Fig. 7(e), indicating the impaired limbs had lower energy efficiency than the unimpaired limbs.

DISCUSSION

In the present study, changes of Achilles tendon mechanical properties post stroke were evaluated in vivo and noninvasively using ultrasonography combined with biomechanical measurements. Results showed significant changes in the tendon dimension and biomechanical properties, including increased tendon length, lower tendon stiffness and Young’s modulus, and higher mechanical hysteresis in the impaired side compared to the matched unimpaired side of the stroke survivors.

It was important to monitor agonist-antagonist co-contraction and heel motion in order to achieve accurate evaluations in the present study. With potential dorsiflexors co-contraction, the estimated Achilles tendon force could be lower than the actual force. The subjects in this study were selected from those who still could control their plantar flexors and generate certain levels of plantar flexion torque (about 15 Nm) in their impaired lower limbs and the subjects learned to minimize co-contraction after practicing the task multiple times with EMG signals from dorsiflexors displayed as visual feedback. As a result, the subjects managed to avoid co-contraction during the ramp-and-hold task, and there was not obvious co-contraction during the loading or holding phase, especially when the task was set at comfortable levels for the subjects. However, considerable co-contraction still occurred during the unloading phase of the ramp then down task in some subjects and 3 subjects were excluded for the
mechanical hysteresis evaluation due to the reason. In addition, some subjects also tended to lift their heels during plantar flexion effort, which could cause overestimation of tendon displacement. Therefore the calcaneus motion was monitored using a digital camcorder and the subject’s foot was tightly secured to the footplate. The subjects were also asked to perform the plantar effort tasks without lifting the heel. Moreover, some subjects tended to flex or extend their knees during the tasks. So the knee and the leg were mounted to the leg linkage tightly to minimize knee movement.

Results showed that tendon length was slightly longer (6%) in the impaired side compared to the unimpaired side. This was probably due to the fact that all the subjects were chronic stroke patients (average 12 years after stroke) who had developed spasticity/contracture in the plantar flexor muscles for a long time. In related studies, shortening of muscle fascicles was found in the plantar flexors of chronic stroke patients (8, 9, 18). Roughly, calf muscles and Achilles tendon act like two springs in series, with the total length of the two springs determined by the leg length. With the calf muscles become stiffer and shorter post stroke, the middle point between the two springs (the soleus muscle tendon junction) may shift proximally towards the calf muscles and the Achilles tendon gets elongated post stroke (Fig. 8). In the process of muscle stiffening and shortening post stroke, it may apply stress onto the Achilles tendon and creep may also be a mechanism involved in the potential Achilles tendon elongation process. Of note is that such a possible adaptation post stroke involves relatively low level of loading, which is much lower than the failure
loads in previous failure testing of Achilles tendon (36). Although no significant
difference was found in the tendon CSA between the impaired and unimpaired sides
in the present study, the average CSA in impaired side was slightly smaller (5%) than
that of the unimpaired side. The difference might have become significant over a
larger sample.

Decreased tendon Young’s modulus (38%) and stiffness (43%) were found in the
impaired side of the stroke survivors in this study. Reductions of patella tendon
Young’s modulus and stiffness were reported in spinal cord injured subjects compared
to able-bodied controls (23). Although the amount of reductions were greater than
what were found in our study, our comparisons were done between the closely
matched impaired and unimpaired sides of the same patients post stroke. In addition,
the tendon Young’s moduli calculated in the present study were lower than values
reported in some other studies with muscles under maximal voluntary contraction (21,
22, 24), which may be related to the sub-maximal contractions within the comfortable
torque-generation range of the stroke survivors in this study, considering the
stress-strain relation has an overall non-linear curve with lower slope in the
lower-stress/“toe region” of the tendon stress-strain curve. In the present study,
Young’s moduli and stiffness were calculated at 3% strain for fair comparison, which
were consistent with those in the corresponding region of the stress-strain curve
reported in previous studies (23, 25, 29).

Increased mechanical hysteresis was found in the impaired side (19.6%)
compared to the unimpaired side (6.8%). Both values are within the range (3% to 38%)
that has been reported based on tensile testing of isolated specimens, and also comparable to the value of gastrocnemius tendon (18%) reported in (22). The difference between different studies might be due to the different tendon segments and measurement approaches. Higher hysteresis values showed more energy was dissipated during the loading-unloading cycle, indicating lower energy efficiency in the impaired limbs.

The method in this study could only be used to evaluate patients with the ability of repeatedly performing controlled sub-maximal isometric plantar flexion tasks, with the subjects trained to perform the tasks following the torque target while avoiding co-contraction. For patients who can not generate sufficient plantar flexion torque, electric stimulation may be an alternative method for tendon property evaluation (20).

CONCLUSION

In the present study, Achilles tendon dimension and mechanical properties of impaired and unimpaired sides of 10 hemiparetic stroke survivors were evaluated. Increased tendon length, decreased stiffness and Young’s modulus, and increased mechanical hysteresis were found in the impaired side. These changes may reflect adaptations to the changes of calf muscle fascicles post stroke. A better understanding of the adaptations and changes of the tendon biomechanical properties may help us gain insight into spasticity/contracture and motor impairment post stroke, and facilitate development of rehabilitation procedures.

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REFERENCES


FIGURE CAPTIONS

Fig. 1 A custom knee-ankle joint-driving device used for the study. This knee-ankle evaluation device consisted of two motors and a linkage in between. The torque sensors were mounted on the motor shaft at both joints to measure the ankle and knee joint torques. With the knee flexion axis aligned with the knee motor, the ankle motor can be adjusted along the leg linkage to align it with the ankle flexion axis.

Fig. 2 Achilles tendon length and moment arm measurements. (a) A picture of a human foot and ankle. Line A was drawn along the Achilles tendon from the calcaneus to soleus-Achilles MTJ. Line B was drawn from the inferior tip of malleolus perpendicular to the tendon LOA. The intersection of line A and line B is also shown. (b) A LOGIQView image of Achilles tendon in sagittal plane. The image was acquired by scanning the probe along line A. The tendon length was defined as the distance from the MTJ to the calcaneus notch along the tendon LOA. The tendon moment arm was calculated by subtracting the perpendicular distance between the intersection and the tendon LOA $m_t$ in (b), from the distance between the center of rotation and the intersection $m_g$ in sagittal plane.

Fig. 3 An ultrasound image of Achilles tendon on transverse plane. The region inside the brighter boundary shows the cross-section of Achilles tendon.

Fig. 4 (a) An ultrasound image of soleus-Achilles MTJ at rest. The zoomed block shows the region to be tracked during ramp-and-hold task. (b) An ultrasound image during the holding phase from the same task. The arrow was pointing from the original position to the tracked position after the tendon elongation took place.

Fig. 5 The Achilles tendon force and MTJ displacement estimated during a ramping up then down task. The force and displacement data displayed were decimated to 5 samples/sec. From the trend of the curves we can see how tendon force and MTJ
displacement correlated.

**Fig. 6** Force-displacement curves collected from both sides of a subject in ramping up then down task. From the figure we can conclude: (1) the tendon in the impaired side was more compliant than the unimpaired side; (2) the impaired side had higher mechanical hysteresis compared to the unimpaired side.

**Fig. 7** Mean and standard deviation of (a) Achilles tendon length; (b) Achilles tendon CSA; (c) Achilles tendon stiffness; (d) Achilles tendon Young’s modulus; and (e) Achilles tendon mechanical hysteresis in the impaired (G1) and unimpaired (G2) sides, respectively.

**Fig. 8** Illustration of the changes of the calf muscles and Achilles tendon (simplified and modeled as two springs in series, with the spring width representing its stiffness value) post stroke. As the calf muscles become stiffer and shorter post stroke, the middle point between the two springs (the soleus-Achilles MTJ) may shift towards the calf muscles with the Achilles tendon elongated.
(a) Achilles tendon length [mm]
(b) Achilles tendon CSA [mm²]
(c) Achilles tendon stiffness [N/mm]
(d) Tendon Young's modulus [MPa]
(e) Tendon mechanical hysteresis [%]
Achilles tendon

Calf muscles

Leg

MTJ

Unimpaired

Heel

Impaired

Shorter Stiffer

More compliant