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Short communication

Dynamic creep and pre-conditioning of the Achilles tendon in-vivo

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ABSTRACT

Warm-up exercises are often advocated prior to strenuous exercise, but the warm-up duration and effect on muscle–tendon behavior are not well defined. The gastrocnemius–Achilles tendon complexes of 18 subjects were studied to quantify the dynamic creep response of the Achilles tendon in-vivo and the warm-up dose required for the Achilles tendon to achieve steady-state behavior. A custom testing chamber was used to determine each subject's maximum voluntary contraction (MVC) during an isometric ankle plantar flexion effort. The subject's right knee and ankle were immobilized for one hour. Subjects then performed over seven minutes of cyclic isometric ankle plantar flexion efforts equal to 25–35% of their MVC at a frequency of 0.75 Hz. Ankle plantar flexion effort and images from dual ultrasound probes located over the gastrocnemius muscle–Achilles tendon and the calcaneus–Achilles tendon junction were acquired for eight seconds at the start of each sequential minute of the activity. Ultrasound images were analyzed to quantify the average relative Achilles tendon strain at 25% MVC force ($\varepsilon_{25\%MVC}$) for each minute. The $\varepsilon_{25\%MVC}$ increased from 0.3% at the start of activity to 3.3% after seven minutes, giving a total dynamic creep of ~3.0%. The $\varepsilon_{25\%MVC}$ increased by more than 0.56% per minute for the first five minutes and increased by less than 0.13% per minute thereafter. Therefore, following a period of inactivity, a low intensity warm-up lasting at least six minutes or producing 270 loading cycles is required for an Achilles tendon to reach a relatively steady-state behavior.

1. Introduction

Musculoskeletal structures are viscoelastic materials, meaning their mechanical properties are time and history dependent. Thus, the mechanical properties of musculoskeletal structures can change considerably (Kubo et al., 2001, Maganaris, 2003, Magnusson et al., 2008) during the initiation of physical activity. Dynamic creep is one viscoelastic property of musculoskeletal structures in which during the onset of cyclic loading to a specific force, as might happen during the start of a walk or resistance exercise program, the deformation/strain of the structures increases with each successive loading cycle, eventually approaching an asymptote or "steady-state" response. Warm-up exercises and pre-conditioning protocols are often performed by athletes and research subjects prior to competition or testing to ensure that musculoskeletal structures behave in a repeatable way. However, the number of loading cycles required for musculoskeletal structures to reach a "steady-state" is not well defined and thus varied warm-up and pre-conditioning protocols are advocated both in athletic and research communities. The purpose of this study was to quantify the dynamic creep response of non-pre-conditioned Achilles tendons experiencing submaximum cyclic loading in-vivo, and based on these responses determine the number of loading cycles required for an Achilles tendon to reach a relatively steady-state behavior.

2. Methods

The gastrocnemius-Achilles tendon complexes of 18 subjects were tested to quantify the magnitude of Achilles tendon dynamic creep during more than 300 loading cycles following a period of inactivity. The subjects consisted of an equal distribution of males and females, and equal numbers of children, young adults and seniors: children aged 7–10 years old (mean ± std dev, 9.5 ± 0.8 years), young adults aged 18–25 years old (21.7 ± 1.2 years), and seniors aged 60+ years old (71.2 ± 8.8 years). All procedures were approved by the University of California—Davis Medical Center Human Subjects Institutional Review Board.

Subjects were introduced to the testing procedures and their maximum voluntary contraction (MVC) for isometric ankle plantar flexion determined. The subject's lower leg length, foot length and ankle height were measured and a custom testing chamber adjusted to fit these dimensions. Subjects placed their right leg in the custom testing chamber (Fig. 1). The ankle and knee were held fixed at approximately 90° included angles. Subjects performed a maximum isometric ankle plantar flexion effort by pushing their foot against a thin bar directed medial-laterally at the 5th metatarsal. The bar was connected to a force transducer (Omega Engineering Model LCCA 500 or 1000). LabView 7 Express (National Instruments, Inc.) software was used to collect force data. Subjects then viewed a

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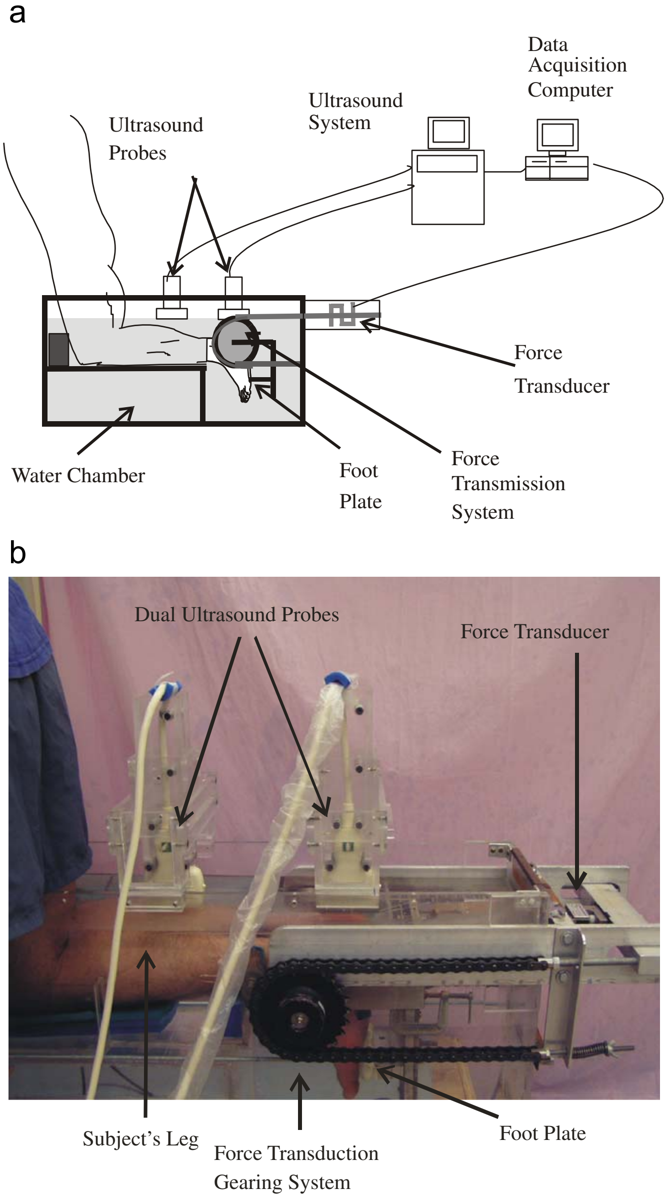

Fig. 1. Illustrated is the basic setup, schematically and physically, used to quantify the ankle plantar flexion effort and Achilles tendon strain during maximum isometric and cyclic submaximum isometric plantar flexion efforts.

computer screen that displayed the force and they practiced performing cyclic (0.75 Hz frequency set via a metronome) ankle plantar flexion efforts equivalent to 25–35% of their MVC until they could consistently generate the desired effort (usually requiring less than one minute of practice time). Subjects were then removed from the testing chamber and sat with their right leg immobilized for one hour to simulate a period of inactivity.

After 1 h, testing resumed. Subjects returned to the testing chamber, without using their right leg, and were positioned as before. Warm water, the temperature adjusted to the comfort of the subject, was added to the chamber to a level just covering the lower leg. The water provided a conducting media to facilitate the acquisition of ultrasound images. A Hitachi 6500 ultrasound system with dual EUP-L53 linear probes operated at 10 MHz was used to obtain images of the Achilles tendon, defined as the region between the gastrocnemius muscle–Achilles tendon junction and the calcaneus–Achilles tendon junction. The probes were located on the surface of the water with one probe positioned directly over the gastrocnemius muscle–Achilles tendon junction and the other over the calcaneus (Fig. 1). Ultrasound images were collected with muscles relaxed to determine the initial length of the Achilles tendon. Subjects were then instructed to perform cyclic submaximum voluntary contractions to just greater than 25% of their MVC at 0.75 Hz for over 7 min (> 315 cycles). Force and ultrasound data were synchronized and collected for 8 s at the start of every minute of testing. After completing the cyclic testing, subjects performed a MVC effort while force and ultrasound image data were collected.

Force and ultrasound images were used to quantify dynamic creep. The gastrocnemius–Achilles muscle–tendon junction (MTJ) and the Achilles–calcaneus osteo-tendinous junction (OTJ) were digitized in the ultrasound images using ImageJ (National Institutes of Health). The MTJ was represented by the distal junction of the superficial and deep aponeuroses of the gastrocnemius (left images in Fig. 2). The OTJ was represented by the clear notch visible in the calcaneus (right images in Fig. 2). Achilles tendon length was defined as the distance between the OTJ and the MTJ and was determined from the digitized points in each ultrasound image and accounting for the distance between probes, hence distance between images (Fig. 2). Tendon initial length (Lo) was determined from ultrasound images obtained prior to the cyclic loading with the muscles relaxed. The force data were used to identify those repetitions that satisfied the effort criterion (i.e. within 25–35% of their MVC value) within each 8 s data epoch (Fig. 3). The anatomical landmarks within the ultrasound images associated with the selected repetitions were digitized. Achilles tendon length (L) at the instant the effort first exceeded 25% of MVC for each trial was calculated from the location of the digitized anatomical landmarks and the distance between probes. The relative Achilles tendon strain present at this instant ($\varepsilon_{25\%MVC}$) was calculated as (L–Lo)/Lo. The average $\varepsilon_{25\%MVC}$ at the start of each minute was determined by averaging the $\varepsilon_{25\%MVC}$ values for those cycles at the start of each minute (usually 3–4 cycles) that satisfied the inclusion criterion. The magnitude of dynamic creep (ε_{DC}) experienced over the 7 min exercise period was defined as the change in average $\varepsilon_{25\%MVC}$ over this time period.

3. Results

Individual characteristics and responses are summarized in Table 1. Achilles tendon rest lengths varied between 12.44 cm (male child) and 21.98 cm (male senior). Relative Achilles tendon strain during MVC varied from 3.10% (female senior) to 10.05% (male young adult).

The average $\varepsilon_{25\%MVC}$ induced in the Achilles tendon increased throughout the duration of loading, but the increase in magnitude per minute or loading cycle decreased after 5 min. The average $\varepsilon_{25\%MVC}$ at the start of cyclic loading was 0.3%, increased fairly linearly (0.56%/min) during the first 5 min of cyclic loading ($\sim$225 cycles), and changed by less than 0.13%/min thereafter (Fig. 4). This response was consistent across all subjects.

The magnitude of dynamic creep during 7 min of cyclic loading to 25–35% of MVC, measured as the change in the average $\varepsilon_{25\%MVC}$ from 0 min to 7 min, was on average 3.04 $\pm$ 0.98% (mean $\pm$ std dev) (Fig. 4). The dynamic creep varied from 1.64% (female senior) to 5.94% (male young adult).

4. Discussion

The objectives of this study were to quantify the magnitude of Achilles tendon dynamic creep under submaximum loading conditions and based on these responses determine the number of submaximum loading cycles required for a tendon to reach steady-state behavior. Ultrasonography and joint testing procedures were combined to achieve these objectives. Specifically, Achilles tendon deformation and strain were quantified during more than 7 min of 0.75 Hz cyclic 25–35% of MVC isometric plantar flexion activity.

The magnitudes of Achilles tendon strain during isometric MVC quantified in this study compare well with previous studies. Rosager et al. (2002) found the strain induced in the Achilles tendon/aponeurosis during maximum isometric plantar flexion efforts of adult male runners and non-runners to be on average 4.1 $\pm$ 0.8% and 4.9 $\pm$ 0.8% respectively. Kubo et al. (2003) found the strain induced in the Achilles tendon/aponeurosis during maximum isometric plantar flexion efforts in sedentary young adult males and females to be on average 8.1 $\pm$ 1.5% and 9.5 $\pm$ 1.1% respectively. Muramatsu et al. (2001) found the maximum strain induced in the Achilles tendon of young adult males was 5.1%. The