Influence of Stretching and Warm-Up on Achilles Tendon Material Properties

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ABSTRACT

Background: Controversy exists on stretching and warm-up in injury prevention. We hypothesized that warm up has a greater effect on Achilles tendon biomechanics than static stretching. This study investigated static stretching and warm-up on Achilles tendon biomechanics in recreational athletes, in vivo.

Materials and Methods: Ten active, healthy subjects, 5 males, 5 females, With a mean age of 22.9 years with no previous Achilles tendon injuries were recruited. Typical stretching and warm-up routines were created. Testing was performed in a randomized cross-over design. A custom-built dynamometer was utilized to perform controlled isometric plantarflexion. A low profile ultrasound probe was utilized to visualize the musculotendinous junction of the medial gastrocnemius. An eight-camera motion capture system was used to capture ankle motion. Custom software calculated Achilles tendon biomechanics.

Results: Achilles tendon force production was consistent. No statistically significant differences were detected in stretch, stiffness, and strain between pre-, post-stretching, and post-warm-up interventions.

Conclusion: Stretching or warm-up alone, and combined did not demonstrate statistically significant differences. Stretching and warm-up may have an equivalent effect on Achilles tendon biomechanics. Prolonged and more intense protocols may be required for changes to occur. Clinical Relevance: Stretching and warm-up of the Achilles before exercise are commonly practiced. Investigating the effect of stretching and warm-up may shed light on potential injury prevention.

INTRODUCTION

Achilles tendon injuries are common in athletic individuals. The Achilles tendon experiences significant mechanical loads due to its function in storing and returning elastic energy and enabling explosive movements such as running and jumping. It is also one of the few muscle-tendon units that crosses two joints and is the distal attachment of the gastrocnemius-soleus complex. In comparison to other tendons, the Achilles exhibits similar material properties despite experiencing greater mechanical loads, creating a functional dilemma that increases the risk for injury and ultimate failure. Furthermore, the Achilles tendon has an area of hypovascularity, 2 to 6 centimeters from the tendon’s insertion into the calcaneus, which correlates to the area prone to Achilles tendon injury. These physiological and biomechanical factors, coupled with repetitive loading and aging makes the Achilles tendon prone to injury.

Acute static stretching and warm-up prior to exercise are both commonly practiced in recreational and professional sports to prevent muscle-tendon injuries. However, there is no consensus in the scientific literature regarding the efficacy of stretching and warm-up in the prevention of muscle-tendon injuries. In contrast, a review by Small et al. described multiple randomized and controlled clinical trials demonstrating the ineffectiveness of static stretching in preventing injury. Similarly, Pope et al. conducted two large randomized, controlled clinical trials involving army recruits and found that stretching did not prevent lower extremity or leg injuries. These discrepancies exist due to differences in the definitions of stretching and warm-up and differences in methodological designs used to measure changes in muscle-tendon parameters.
The mechanism by which acute static stretching may influence the mechanics of the muscle-tendon unit is still debated. Static stretching has been thought to elongate muscle and tendinous tissues, reducing the strain throughout the tissue during dynamic activities and resulting in increased joint flexibility and range of motion.\textsuperscript{20,30,31,34} This elongation is hypothesized to be due to changes in the viscoelastic properties of muscle-tendon units.\textsuperscript{11,12,13,14} Static stretching is thought to reduce tendon viscosity and increase tendon compliance, leading to greater stored elastic energy.\textsuperscript{22}

Warm-up is commonly utilized by athletes to prepare themselves for physical activity and typically involves jogging or cycling to produce mild sweating without fatigue.\textsuperscript{25,34} Preconditioning the muscle-tendon unit prior to maximal effort exercise is thought to protect against injury by increasing the force and strain required to produce muscle-tendon injury.\textsuperscript{25} Warm-up may change the connective tissue architecture within the muscle-tendon unit and increase muscle metabolism and temperature. These changes may facilitate blood flow and oxygenation and produce more effective interactions of contractile muscle fibers.\textsuperscript{25} \textit{In vitro} animal studies evaluating warm up demonstrated that isometrically pre-conditioned muscles require more force and stretch to fail, compared to contralateral controls and passive warming of muscles to 39°C led to increased muscle length prior to failure.\textsuperscript{25,28} These \textit{in vitro} experiments also found that failure typically occurs at the muscle-tendon junction, not in the free tendon.

The purpose of this study was to investigate the effect of acute static stretching and a low-intensity jogging warm-up on the mechanical stiffness of the Achilles tendon in recreational athletes, a population at risk for Achilles tendon injuries. These two activities were selected to replicate what most recreational athletes would perform prior to an exercise bout. For the purpose of this study, stretching was a static and constant loading of the Achilles tendon over a set time duration, whereas warm-up was considered a dynamic and functional pre-conditioning and loading of the Achilles tendon. We hypothesized that a low-intensity jogging warm-up would have a greater influence on the stiffness of the Achilles tendon compared to an acute bout of static stretching.

**MATERIALS AND METHODS**

**Experimental design**

We implemented interventions that sought to recreate the typical static stretching and warm-up routines utilized by recreational athletes. Testing was performed in the Human Performance Laboratory at Stanford University on two separate sessions on different days. All testing was performed under similar test conditions, including using the same side extremity between subjects and testing sessions, time of day and prior to any exercise other than walking to the test location. A standardized plantarflexion task was performed using a custom dynamometer before and after static stretching and jogging warm-up interventions.

Data were collected on two different days in a randomized cross-over design. A familiarization trial was performed prior to testing on day one, in which subjects performed five maximal isometric plantarflexion tasks with 1-minute rest intervals in between. Using the average of these maximal plantarflexion trials, an 80% submaximal target force was calculated for all further dynamometer trials. After the familiarization trial was complete, warm-up testing was performed. The warm-up testing session required subjects to perform five plantarflexion tasks prior to warming up, followed by a 6-minute jog on a treadmill at a speed of 3 m/s. The five plantarflexion tasks were then repeated to the 80% submaximal target immediately following the warm-up jog.

On the second day of testing, static stretching testing was performed. The static stretching testing session involved the same procedure as that described above except subjects performed the dynamometer test before and after an Achilles tendon static stretching protocol. The stretching protocol involved five 30-second repetitions of continuous static stretching on an inclined platform set at 30 degrees (Figure 1). To determine the combined influence of stretching and warm-up, subjects then performed a 6-minute jog at 3 m/s immediately after the post-stretch flexion tasks and five further plantarflexion measurements were obtained.

**Subjects**

Ten active, healthy individuals volunteered to participate in this study (five males and five females). The volunteers had no previous history of Achilles tendon, calf, lower leg, or...
ankle injuries or disorders. The mean age of the subjects was 22.9 years (SD, 3.40), height 1.70 m (SD, 0.11), and mass 69.4 kg (SD, 15.0). Prior to participation, subjects were asked to document the type and frequency of activity that they typically performed, as well as the frequency of stretching performed with each activity. Eight subjects listed soccer and jogging as their primary activity. One subject listed cycling and another listed raquetball. Two subjects performed their activity daily, four subjects 2 to 4 times per week, and four subjects 1 to 2 times per week. Two subjects never stretched prior to their activity, two subjects stretched 25 to 50% of the time, two subjects stretched 50 to 75% of the time, and four subjects stretched 75 to 100% of the time. All subjects were fully informed of the purpose of the study and the procedures utilized. Written, informed consent was obtained prior to any testing in accordance with the Institutional Review Board at Stanford University.

**Experimental setup**

A custom-built dynamometer was used to perform controlled isometric plantarflexion tasks in a repeated fashion (Figure 2). Subjects lay supine on a bench, with their shoulders secured by adjustable straps. A low profile B-mode ultrasound probe (60 Hz) was used to visualize the muscle-tendon junction of the medial gastrocnemius and secured to the calf with a strap. A 5-mm strip of sports tape was placed across the skin above the muscle-tendon junction. This echogenic marker was clearly visible within the ultrasound image and enabled the quantification of the ultrasound probe relative to the skin. The distance between the echogenic marker and the insertion of the Achilles tendon was calculated during a static standing trial to facilitate the calculation of Achilles tendon length. The left foot and ankle was placed into a modified brace, which was connected to a calibrated load cell (Omega Instruments) via a cable and pulley system. The knee was placed in approximately 15 degrees of flexion. In this configuration subjects could perform isometric plantarflexion at a consistent ankle angle of 10 degrees of dorsiflexion. This combination of ankle angles was chosen as it approaches a triceps surae muscle length that facilitates peak active force output, but does not elicit high passive forces occurring at end range of motion.9,16 A volt-meter provided visual feedback from the force-calibrated load cell to ensure a repeatable target force of 80% of maximum isometric contraction was achieved. Subjects were asked to steadily increase the plantarflexion force up to the target voltage output and relax over two seconds. Characteristic plantarflexion moment, Achilles tendon force, and tendon strain curves during the plantarflexion task were observed with each trial (Figure 3). In addition to the volt-meter feedback, the subject received feedback from in-sole pressure sensors (Zephyr Inc. Auckland, NZ) placed within the modified brace. This allowed the subject to apply equal pressure throughout the foot and keep the heel from lifting off the base of the boot.

**Data collection**

A static trial was collected prior to testing, which enabled the position of the ankle joint to be recorded relative to the shank markers. Retroreflective markers were placed on
the medial and lateral malleoli, calcaneus, and an echogenic marker (sports tape) was placed superior to the muscle-tendon junction. These data enabled the ankle joint center to be determined within the boot to facilitate the calculation of the ankle joint moment and Achilles tendon force.

Retroreflective markers were placed on the ankle rig, knee, shank, and proximal and distal ends of the cable to capture the three-dimensional orientation and position of the ankle rig, knee, shank, foot, and cable. An 8-camera Vicon motion capture system (VICON, Oxford UK) was used to synchronously capture the marker positions and analog force signal from the load cell at 120 Hz. A manual trigger producing a square-wave analog signal was also captured by the motion capture data acquisition system and simultaneously input to the ultrasound ECG recording device where it was clearly visible within the field of view of the ultrasound image. This trigger pulse enabled an accurate synchronization between the ultrasound images, captured at 30Hz, and the marker and force data.

Data analysis

The muscle-tendon junction within the ultrasound image was digitized using a semi-automated tracking algorithm implemented in MATLAB (Mathworks, Natick MA). Digitized data were low pass filtered using a 4th order Butterworth filter with a cut-off frequency of 1 Hz and then resampled to 120Hz using a cubic spline to match the motion capture data. Achilles tendon length (Ltendon) was then determined as follows:

\[ \text{Ltendon} = \text{Lcalc-tape} - \text{Ltape-mtj}, \]

Where Lcalc-tape was the distance between the calcaneus and the echogenic tape placed superior to the muscle-tendon junction (from the motion capture data) and Ltape-mtj was the distance between the echogenic tape and the muscle-tendon junction (from the ultrasound image). The tendon length measurement was made at an ankle angle of approximately 10 degrees plantarflexion and a knee angle of approximately 15 degrees flexion, where passive moments at the ankle were negligible. The maximum Achilles tendon ‘stretch’ was then calculated as the maximum change in Achilles tendon length. Tendon strains were also calculated by normalizing tendon stretch to the resting Achilles tendon length, calculated during a resting supine trial.

Marker trajectories and cable force data were filtered prior to further processing using a fourth order low-pass Butterworth filter with a cut-off frequency of 1Hz. The knee and ankle joint centers and ankle joint angle were calculated using Bodybuilder modeling software (Vicon, OMG plc, Oxford UK). The ankle plantarflexion moment was calculated as the cross-product of the cable force vector and the ankle joint center. Subject-specific moment arm estimates of the Achilles tendon were determined by scaling a musculoskeletal model to match the anthropometry of each subject. Ankle joint angles were used as input to the scaled musculoskeletal model to determine Achilles tendon moment arms for each trial. Achilles tendon force was then estimated as the net ankle joint plantarflexion moment divided by the Achilles tendon moment arm. It was assumed that the contribution of ankle dorsiflexors was minimal during this static plantarflexion task. Achilles tendon stiffness was calculated as the peak force divided by peak tendon stretch.

Statistical methods

Mean Achilles tendon force, stretch, stiffness, and strain were calculated from five trials for each subject in each condition. The conditions included baseline and post-warm-up for session 1 and baseline, post-stretch, and post-warm-up for session 2. Mean Achilles tendon parameters were subject to repeated measures ANOVA testing to determine significant differences between each condition with an alpha level of 0.05.

RESULTS

Achilles tendon forces were similar across conditions, pre- and post-warm-up and post-stretching. There were no differences between Achilles tendon forces across the baseline tests between session 1 and session 2, indicating that subjects were able to consistently obtain the 80% maximum isometric force target (Figure 4A). No statistically significant differences were detected in any of the Achilles tendon parameters (stretch \[ p = 0.27 \], stiffness \[ p = 0.94 \], or strain \[ p = 0.89 \]) between the baseline and warm-up tests in session 1 (Figures 4, B to D). Similarly, there were no statistically significant differences between Achilles tendon parameters measured during session 2, which compared baseline measures following stretching and a jogging warm-up (Figure 4, A to D). Tables 1 and 2 summarize the results and \( p \) values for both sessions.

DISCUSSION

In this study, we recreated characteristic stretching and warm-up protocols that recreational athletes typically utilize in their exercise regimens. We then evaluated the differences between acute static stretching and warm-up in Achilles tendon stiffness, in vivo. Our results demonstrate that a moderate stretching or warm-up intervention, or a combination of both together do not have any effect on the Achilles tendon stiffness. Our results do not support our hypothesis that warm-up would impact the Achilles tendon’s biomechanical profile to a greater degree than static stretching. These data suggest that an acute bout of static stretching and warm-up similar to that performed by recreational athletes in their exercise routines have no effect on Achilles tendon stiffness.
Lichtwark et al. investigated the biomechanical properties of the Achilles tendon during one-legged hopping to simulate high strain conditions in the tendon.\textsuperscript{15} Dynamometry, ultrasound, force plate and motion analysis were utilized to examine force-length and stress-strain relationships with one-legged hopping. Their results demonstrated high tendon strains with relatively linear force-length relationships, and confirmed the ability to store high amounts of elastic energy for activities such as walking, running, and jumping. They found that the majority of the strain occurs at the tendon itself rather than the muscular component of the musculotendinous unit, which may provide a rationale of the mechanism for Achilles tendon injuries with certain explosive activities.

There are multiple studies evaluating the effects of stretching on the Achilles tendon mechanical properties. Kubo et al. found that static ankle stretching held for 10 minutes led to decreases in stiffness and hysteresis of the Achilles tendon, which reflect changes in both the elasticity and viscosity of the tendon.\textsuperscript{11} A likely explanation for the discrepancy in the tendon response to stretching in the study of Kubo et al. and the present study is the stretch duration.\textsuperscript{11} However, their 10-minute stretching protocol is an unrealistic regimen for most recreational as well as competitive athletes.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{Parameter} & \textbf{Session 1} & \textbf{} & \textbf{Warm-up} & & \textbf{Session 2} & \textbf{} & \textbf{Stretch} & \textbf{Warm-up} \\
\hline
\textbf{Force} & Mean & 1127.16 & 295.12 & 1096.81 & 268.7 & 1039.37 & 210.78 & 1033.29 & 193.26 & 1050.67 & 187.1 \\
\textbf{Stretch} & Mean & 12.3 & 8.84 & 13.35 & 7.25 & 15.65 & 7.62 & 15.41 & 7.04 & 15.57 & 6.77 \\
\textbf{Stiffness} & Mean & 163.07 & 127.8 & 159.49 & 195.71 & 86.59 & 45.13 & 85.48 & 47.33 & 78.21 & 25.08 \\
\textbf{Strain} & Mean & 0.071 & 0.055 & 0.077 & 0.046 & 0.087 & 0.047 & 0.085 & 0.044 & 0.086 & 0.045 \\
\hline
\end{tabular}
\caption{Table Summarizing the Study Results, Listing the Means and Standard Deviations for Force, Stretch, Stiffness, and Strain of the Achilles Tendon for Both Sessions}
\end{table}
in their exercise routines. As such, the protocol of Kubo et al. does not reflect the potential changes that may occur in everyday pre-exercise routines conducted by the majority of athletes.11

In another study by Kubo et al., the effect of stretching the Achilles tendon over a 3-week stretching program was evaluated.12 Their protocol consisted of five stretches held for 45 seconds twice a day. The results showed that hysteresis of the Achilles tendon decreased, reflecting a change in the tendon’s viscosity over time. However, no changes in stiffness occurred. This provides further evidence that changes in Achilles tendon stiffness may require a large, and possibly acute stimulus, whereas longer-term static stretching may affect only viscous properties rather than stiffness per se. Importantly, this protocol by Kubo et al. approximates the typical stretching programs utilized by athletes, corroborating our finding that typical stretching routines may have little bearing on tendon stiffness.12

Mahieu et al. compared the effects of static and ballistic stretching on the Achilles tendon utilizing ultrasound in a controlled and randomized 6-week trial.13 Static stretching was defined as slow, controlled lengthening of a relaxed muscle whereas ballistic stretching was a bouncing rhythmic motion used to lengthen the muscle. The study demonstrated no change in Achilles tendon stiffness with static stretching, as compared to the ballistic group who showed a significant decrease in stiffness. The study corroborates with the findings that longer term static stretching does not affect tendon stiffness, whereas a more dynamic, cyclic activity may be necessary to change the stiffness of the Achilles tendon.5,12 These differences in adaptation might be explained by differences in the mechanical loads experienced by the tendon (both magnitude and rate of loading).

Other studies have found that stretching the Achilles tendon leads to decreased plantarflexion force production.7,23 Rosenbaum and Hennig found that with stretching, there is a reduction in force production.23 This change in force production has been postulated to reflect a reduction in musculotendinous stiffness and may decrease the peak stress experienced by the musculotendinous unit. Biomechanical studies performed by Kubo et al. support these postulations as decreases in the viscoelastic properties of the Achilles tendon were seen with certain stretching protocols.11–14 These changes in the biomechanics of the Achilles tendon may impact the risk for injury.

A prospective controlled study of army recruits undergoing basic military training by Mahieu et al. found that plantarflexor strength less than 50 Nm predisposed individuals for Achilles tendon overuse injuries.17 Decreased plantarflexor strength was found to be a statistically significant risk factor for Achilles tendon overuse injuries. The clinical study by Mahieu et al. in army recruits and another in recreational and competitive runners found that stretching the Achilles tendon may actually increase the risk for overuse injuries due to decreased plantarflexion strength.17,19 It is possible that activities such as prolonged 10 minute stretches as performed by Kubo et al. may decrease the stiffness in the Achilles tendon leading to decreased plantarflexion strength, which ultimately may increase the risk for Achilles overuse injuries.11

The biomechanical effects of warm-up type activities have also been previous evaluated. In another study by Kubo et al., repetitive eccentric plantarflexion contractions and their effect on Achilles tendon properties were studied.14 This cyclic exercise may be a component of typical warm up exercises and was shown to decrease both the stiffness and hysteresis of the Achilles tendon. The study demonstrated that this type of cyclic and dynamic exercise may change the viscoelastic properties of the Achilles tendon.

However, no studies to date have simulated typical warm-up exercises to investigate the effect on the biomechanical properties of the Achilles tendon. Noteworthy also is that the previously published studies have not examined the combined effect of stretching and warm up on the biomechanical properties of the Achilles tendon as this study sought to investigate. The effects of static stretching and dynamic warm-up, both as stand-alone interventions and combined, were examined in this study to understand their interactions and delineate their influence on the biomechanical properties of the Achilles tendon.

In summary, the results of this study showed that stretching, warm-up, or both interventions combined did not provide statistically significant differences in the biomechanical profile of the Achilles tendon. In addition, these modalities did not yield any changes in the plantarflexion force production, which has been previously associated with increased risk of Achilles tendon injuries.17 Our findings suggest that typical utilization of stretching and warm-up by recreational athletes may have an equivalent effect on musculo-tendinous structures biomechanically. These pre-exercise activities may not decrease the risk of Achilles tendon injury. For any change of biomechanical properties to occur, prolonged and more intense stretching and warm-up routines may be required, as seen in the 10-minute stretching protocol utilized in by Kubo et al.11 However,

| Table 2: Table Summarizing the p Values for Stretch, Stiffness, and Strain of the Achilles Tendon for Both Sessions |
|----------------|----------------|----------------|
| **Parameter** | **Session 1** | **Session 2** |
|                | Baseline-Warmup | Baseline-Stratch | Stretch-Warmup |
| Stretch        | 0.27            | 0.99            | 0.93            |
| Stiffness      | 0.94            | 0.52            | 0.89            |
| Strain         | 0.89            | 0.96            | 0.95            |

No significant differences were detected between the tested interventions.
these stretching and warm-up routines may be unrealistic and possibly detrimental for the recreational athlete.

REFERENCES