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Effect of Ankle Motion and Tensile Stress at the Achilles Tendon on the Contact Pressure Between the Achilles Tendon and the Calcaneus

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A R T I C L E I N F O

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A B S T R A C T

Impingement between the Achilles tendon and the posterosuperior prominence of the calcaneus is considered to be a cause of insertional Achilles tendinopathy. The corresponding treatment intends to reduce tensile stress from calf muscles and avoid hyper-dorsiflexion of the ankle joint for decreasing the contact pressure; however, no study has reported on whether these treatments can decrease impingement. Thus, this study investigated the hypothesis that the tensile stress of the Achilles tendon and ankle motion affect the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus. Six fresh-frozen cadaveric lower leg specimens were procured. Each specimen was set to a custom foot-loading frame and loaded with a ground reaction force of 40 N and a tensile load of 70 N along the Achilles tendon. The contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus was measured using a miniature pressure sensor under different tensile loadings of the Achilles tendon at the neutral ankle position. Similarly, the contact pressures during the ankle motion from a neutral position to maximum dorsiflexion were measured. The tensile load of the Achilles tendon and ankle motion affected the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus. The contact pressure increased with tensile load or ankle dorsiflexion. Conditions with increasing the tensile load of the Achilles tendon or under ankle dorsiflexion increase the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus.

Approximately 6% of the general population suffer from Achilles tendinopathy during their lifetime, and approximately 30%-70% of the cases correspond to the insertional region (1-3). Clinically and histologically, it is known that there are 2 different pathologies around the insertional area of the Achilles tendon. One occurs at the bone and tendon junction, where pathological changes, such as bone spur formation at insertion and degeneration of the insertion area of the Achilles tendon, can be seen (3-5). The other pathology occurs around the retrocalcaneal bursa, which is thought to be caused by repetitive impingement between the Achilles tendon and the posterosuperior prominence of the calcaneus (1,3,6). These 2 pathologies sometimes occur separately and sometimes coincide.

Some treatments for this impingement pathology around the retrocalcaneal bursa are intended to prevent hyper-dorsiflexion of the ankle joint (eg, heel lifting insole) and gain flexibility of calf muscles (eg, exercising of calf muscles, night splint).

However, none of the previous studies could prove that these treatments can decrease the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus. We hypothesize that the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus increases with an increase in the tensile load of the Achilles tendon and with ankle dorsiflexion. To verify this hypothesis, the contact pressures under

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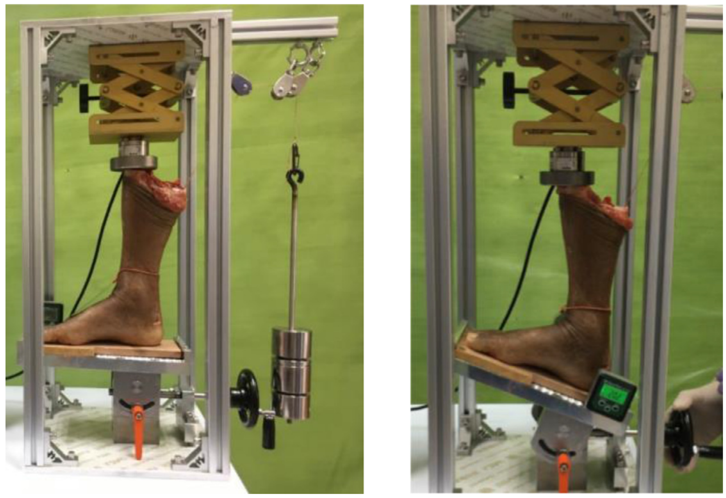

Fig. 1. Loading frame and setting of the cadaveric foot. The foot was set on the frame, and an axial load was applied to the tibia. The loading frame could control the sagittal kinematics of the ankle joint.

different tensile loadings of the Achilles tendon and during ankle dorsiflexion were measured.

Materials and Methods

Specimen Preparation

Six fresh-frozen cadaveric lower leg specimens (mean age, 79.0 years; range, 72-95; 3 males, 3 females) were obtained from the Department of Anatomy at our University. All the specimens were confirmed to have intact Achilles tendons and were observed to be free of any other pathology around the foot and ankle. All the specimens were cut approximately 30 cm from the foot at a temperature of 20° before testing. The Achilles tendon was sutured using the Bunnell technique, and the proximally free end was passed through the triceps surae. For each specimen, longitudinal incisions were made along both sides of the Achilles tendon. The insertion of the Achilles tendon was carefully exposed to ensure that the pressure sensor (PS-20KCM2, Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan) could be placed between the Achilles tendon and posterosuperior prominence of the calcaneus.

Loading Experiment

To simulate scaled physiologic loading, axial compression was applied to the tibia, and a tensile load was applied to the Achilles tendon of each specimen using a custom foot-loading frame (Fig. 1). The foot was placed on a wooden board and fixed with 2 steel wires.

The load cell (Aikoh Engineering, Osaka, Japan) was set between the cadaveric tibia and the frame to enable the axial load adjustment. The Achilles tendon strap was routed over a pulley and fastened to a heavy bob. The loading was performed based on a previously described loading regime (5,7). Specifically, a ground reaction force of 40 N caused by the axial load applied along the tibia axis was maintained, and a tensile load of 70 N was applied along the Achilles tendon through the heavy bob. This frame controlled the sagittal kinematics (dorsiflexion/plantarflexion) of the ankle joint.

Measurement of Contact Pressure

The cadaver feet were preconditioned under an axial loading of 40 N and tensile loading of 70 N of the Achilles tendon for approximately 5 minutes.

The measurements were recorded using a miniature pressure sensor (PS-20KCM2, Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan; the device has a diaphragm-type strain gauge with a sampling rate of 0.02 s (50 Hz); the maximum sensitivity is 100 kPa and 2 MPa, respectively, for the phase 1 and phase 2 studies; the rated output is 0.910 mV/V±1%), whose reliability was assessed previously (8). A sensor was placed on the lateral surface of the posterosuperior prominence of the calcaneus, at which the symptoms of insertional Achilles tendinopathy often appear (Fig. 2) and was fixed to the calcaneus using double-sided tape.

The measurements were recorded in 2 phases: In phase 1, which was a dynamic loading test pertaining to the Achilles tendon, the contact pressure was recorded with varying tensile loading of 0, 10, 20, 30, 40, 50, 60, and 70 N at the neutral ankle position and constant axial loading of 40 N. Data were plotted on a graph, including the tensile force of the Achilles tendon (N; horizontal axis) and pressure force between the Achilles tendon and the posterosuperior prominence of the calcaneus (MPa; vertical axis).

In phase 2, which was an extended range of motion tests, the contact pressure was recorded every 2 degrees from the neutral ankle position to maximum dorsiflexion (axial loading of 40 N, tensile loading of 70 N). Data were plotted on a graph for every 2 degrees

Fig. 2. Setting of the pressure sensor. A miniature sensor (arrow) was placed on the lateral side of the posterosuperior prominence of the calcaneus.

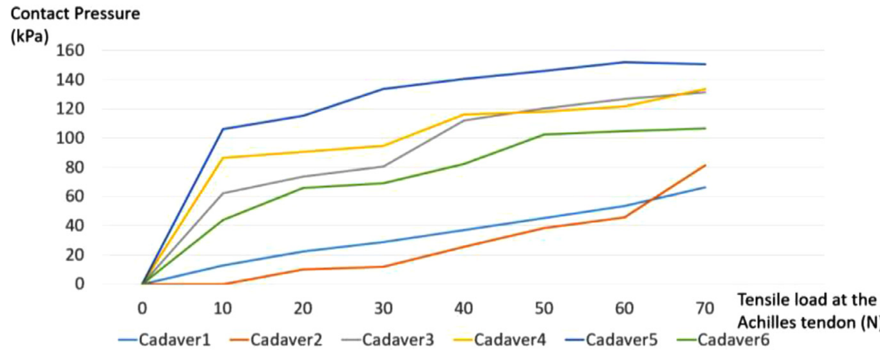

Fig. 3. Results of phase-1 study.

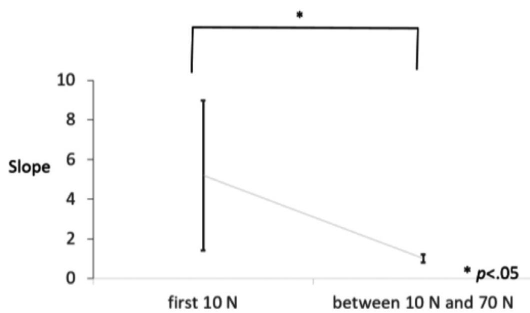

Fig. 4. Significant difference is observed between the mean slope of the first 10 N and between 10 N and 70 N.

of ankle dorsiflexion. Specifically, the angle of ankle flexion (degrees; horizontal axis) and pressure force between the Achilles tendon and the posterosuperior prominence of the calcaneus (MPa; vertical axis) were plotted. The test was performed 3 times for 1 leg.

Statistical Analyses

The JMP 15® software was used for statistical analyses. Spearman's rank correlation coefficient was used to analyze the relationship between the contact pressure and the tension of the Achilles tendon and that between the contact pressure and the ankle angle. The correlation coefficient was denoted with ρ, and $\rho \geqq 0.6$ was considered a strong correlation and $\geqq 0.8$ a very strong correlation. In the phase 1 study, the slope of the graph was approximated, and the relationship was analyzed using the dependent *t*-test. Additionally, *p* values of <.05 were considered to be significant.

Results

Phase 1

The results for the phase 1 study are presented in Fig. 3. All graphs show that the pressure force increases with an increase in the tensile force of the Achilles tendon, and a strong positive correlation exists between the contact pressure and the tension force of the Achilles tendon ($\rho = 0.643$, $p < .01$). The mean slopes for the first 10 N and between 10 N and 70 N were 5.19 ± 3.77 and 1.00 ± 0.195, respectively, and were significantly higher for the first 10 N ($p < .05$; Fig. 4).

Phase 2

The results for the phase 2 study are presented in Fig. 5. All graphs show that the pressure force increases with ankle dorsiflexion, and a very strong positive correlation exists between the contact pressure and the angle of ankle flexion ($\rho = 0.840$, $p < .01$). In addition, the degree of maximum dorsiflexion is different for different cadaver specimens: Specimen nos. 1 and 5; nos. 2, 3, and 4; and no. 6 have maximum dorsiflexion of 18°, 20°, and 16°, respectively.

Discussion

To the best of our knowledge, this is the first study to report on the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus. Among existing work, although Chimenti et al. reported that the contact strain at the insertion of the Achilles tendon, as measured using ultrasound elastography, increased during ankle dorsiflexion (9,10), none of the existing studies have examined the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus. We believe that the measurement of the contact pressure might be more suitable to evaluate the impingement between the Achilles tendon and the posterosuperior prominence of the calcaneus compared to the strain measurement because the pathology of the insertional Achilles tendinopathy was observed not only inside the Achilles tendon, but also degenerative changes were found at the fibrocartilage, which involved a superficial layer of the

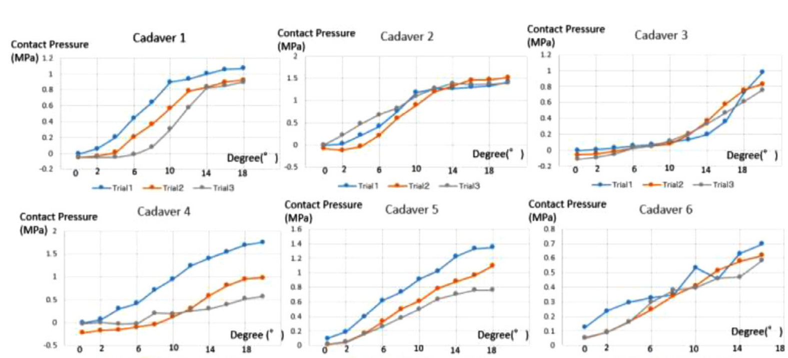

Fig. 5. Results of phase-2 study.

Achilles tendon and posterosuperior prominence of the calcaneus (6,11-13).

This cadaveric study provides further evidence that the tensile loading of the Achilles tendon and ankle dorsiflexion lead to an increase in the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus.

From the results of the phase 1 study, the tensile load of the Achilles tendon is imitated as tightness of the calf muscles, leading to an increase in the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus and developing the risk of insertional Achilles tendinopathy even if the ankle joint is not dorsiflexed. Simultaneously, reducing the tensile stress of the calf muscles may result in the prevention or treatment of the insertional Achilles tendinopathy; therefore, we recommend calf stretching to reduce the tensile stress of the Achilles tendon.

The contact pressure between the Achilles tendon and the calcaneus increases with an increase in the tensile load of the Achilles tendon; however, the increase showed a steep slope in the first 10 N and a shallow slope between 20 N and 70 N. This indicates that although tightness of the calf muscles is related to the contact pressure between the Achilles tendon and the calcaneus, the decrease ratio in the contact pressure via stretching is slow in the early phase. Further studies are required to identify the degree of tension of the Achilles tendon related to the symptoms of insertional Achilles tendinopathy.

In the phase 2 study, we suggest that repetitive ankle motion of hyper-dorsiflexion increases the contact stress between the Achilles tendon and the posterosuperior prominence of the calcaneus and subsequently increases the risk of insertional Achilles tendinopathy. Simultaneously, it may be effective for treatment and prevention to avoid hyper-dorsiflexion and repetitive dorsiflexion of the ankle joint. These results suggest that the heel lift insole is a reasonable treatment to restrict ankle hyper-dorsiflexion. Although some clinical studies pertaining to eccentric exercises for the Achilles tendon have been published, such exercises are less effective in patients with insertional Achilles tendinopathy than in patients with mid-portion Achilles tendinopathy (4,14-17). We have to consider 2 different pathologies in insertional Achilles tendinopathy; one is caused by the tensile stress at the insertion, and the other is caused by impingement between the Achilles tendon and calcaneus. Our study suggests that dorsiflexion of the ankle joint is not favorable for the pathology where impingement of the Achilles tendon and posterosuperior prominence of the calcaneus occurs. In most protocols pertaining to the eccentric exercise of the Achilles tendon, the patients performed eccentric exercise beyond plantargrade. Although these protocols may be critical for the pathology caused by the tensile stress at the insertion, the adversity occurs for the pathology caused by impingement because it increases the contact stress between the Achilles tendon and the posterosuperior prominence of the calcaneus. Jonsson reported favorable results of the new regimen for eccentric exercise, wherein the patients performed a heel raise and then slowly lowered the heel to the floor level (there was no load with the ankle in dorsiflexion) (4). Our result confirmed that the eccentric exercise protocol reported by Jonsson is favorable, especially for the impingement pathology pertaining to insertional Achilles tendinopathy. However, we acknowledge that a cadaver study can only suggest that certain treatment protocols could potentially be beneficial to patients; thus, clinical studies are required to determine if such treatment protocols would benefit patients.

Certain limitations of this study must be acknowledged. First, although insertional Achilles tendinopathy often occurs for middle-aged individuals and young athletes (2,18), only elderly cadavers were used. As the condition of the Achilles tendon and other tissues, in this case, are different from those of younger patients, the results may be different than those of actual patients. Second, the magnitudes of the applied loads were less from those in the physiological condition; however, the ratios of the ground reaction force and tensile loads to the Achilles tendon were consistent with the load distributions documented in previous studies (5,19). Furthermore, the present cadaveric study yielded a certain tendency, making it possible to estimate the pressure changes in the physiological condition.

In conclusion, the contact pressure between the Achilles tendon and the posterosuperior prominence of the calcaneus increases with an increase in the tensile load of the Achilles tendon and during ankle dorsiflexion. These data can help in the treatment and prevention of insertional Achilles tendinopathy.

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