Force in the Achilles Tendon During Walking With Ankle Foot Orthosis

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Background: Ankle foot orthoses are used for postoperative treatment of Achilles tendon ruptures and decrease calf muscle electromyography activity during walking.

Hypothesis: Achilles tendon load decreases with increased restriction of dorsiflexion and is associated with decreased triceps surae activity.

Study Design: Controlled laboratory study.

Methods: In 8 subjects, the maximum force and rate of force development in the Achilles tendon were measured with an optic fiber technique, and the activity of the gastrocnemius, soleus, and tibialis anterior muscles was recorded using electromyography. Trial conditions were walking barefoot and wearing an ankle-foot orthoses set in 3 different positions: (1) locked at 20° of plantar flexion and with free plantar flexion but restricted dorsiflexion to (2) 10° plantar flexion and (3) 10° dorsiflexion, respectively. The design of the ankle foot orthoses did not provide heel support when fixed in a plantarflexed position.

Results: Maximum Achilles tendon force was highest at the ankle-foot orthoses setting of 20° plantar flexion (3.1 times body weight) and decreased to 2.1 times body weight during barefoot walking ($P < .01$). The rate of Achilles tendon force showed an increasing trend with less-restricted dorsiflexion. Soleus activity was 52% of mean barefoot walking activity at 3 20° plantar flexion ($P < .001$) and then increased as dorsiflexion was less restricted.

Conclusion: Weightbearing in ankle-foot orthoses when dorsiflexion is restricted beyond neutral may result in increased forces in the Achilles tendon compared with barefoot walking, despite reduced electromyography activity in the triceps surae and decreased rate of force development.

Clinical Relevance: If patients bear full weight in an ankle-foot orthoses locked at 20° plantar flexion without heel support, the maximum force in the tendon may exceed that encountered during barefoot walking.

Keywords: Achilles tendon loading; ankle foot orthosis (AFO); electromyography (EMG); locomotion

A number of studies have shown that early weightbearing and range of motion exercise after surgically treated rupture of the Achilles tendon shorten the time to return to normal walking, work, and preinjury sports activity without increasing the frequency of reruptures.[2,6,14,20,23] After the initial inflammatory phase of tendon healing (5-7 days), controlled stretching is likely to be beneficial to collagen synthesis and tendon structure.[12] The postoperative use of ankle-foot orthoses (AFOs) permitting gradually increased motion instead of rigid casts has therefore increased. Studies in which patients wore casts during the initial 2 weeks and then changed to AFOs and were allowed to bear weight and perform passive motion exercises reported good results but still muscle hypotrophy.[19,20] In one study, 20 subjects used AFOs and were allowed to bear full weight and perform motion exercises on the first day after surgery.[23] After 6 months, no differences in strength were found between the injured and uninjured legs and no reruptures were reported, suggesting that more intensive rehabilitation may improve long-term prognosis. Little is known concerning the magnitude of Achilles tendon loads during walking in an AFO or how these vary with different ankle angle settings. Empirical knowledge of these loads could assist in designing

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rehabilitation programs and choosing the most appropriate progression of ankle position and range of motion.

Achilles tendon loading is the result of passive stretch or the degree of dorsiflexion of the ankle and activation of the triceps surae muscle group to counteract external load. The EMG activity of the plantar flexors has been shown to decrease compared with normal walking when walking with the ankle immobilized in an AFO at 90°.[1,11] The EMG activity gradually decreases when plantar flexion is increased with heel lifts, and at approximately 10° of plantar flexion, EMG activity relative to normal walking is reduced by 43%.[1] In another study, gastrocnemius activity was found to be significantly lower when walking in shoes with heel lifts (1.9–5.7 cm) compared with that when walking in stockings.[17] Akizuki et al[1] found a high correlation between isometric plantarflexion torque and plantarflexor EMG. In the above mentioned studies, no direct measurements of tendon load were made, and tendon load was instead assumed to be equivalent to muscle activity.

A number of studies have used percutaneously inserted optic fibers to measure the tensile force in tendons.[3,9,10,16] Tensile force in the tendon causes compression of the fiber, which results in a decrease in the transmitted light intensity. This reduction in light intensity varies linearly with the tensile force.[16]

To our knowledge, no studies using tendon force transducers have been performed for the determination of tendon loading differences between different AFO settings. An optic fiber technique was applied in this study to measure the load on the Achilles tendon during walking in an AFO set in 3 different positions used in standard rehabilitation protocols.

The aim of this study was to determine whether Achilles tendon load would decrease with increased restriction of dorsiflexion and if such restrictions would also decrease triceps surae activity.

METHODS

Subjects

Eight healthy subjects—5 female and 3 male; mean age, 24.4 years (SD, 2.6); mean weight, 65.1 kg (SD, 8.1); and mean height, 169.8 cm (SD, 5.6)—participated in the study.

The human ethical committee of the Karolinska Institute, Sweden, and the ethics committee of the University of Jyväskylä, Finland, approved the study. All subjects gave their informed consent.

Electromyography

Muscle activity was recorded for the medial gastrocnemius, soleus, and tibialis anterior muscles. Bipolar surface electrodes were attached to the skin over the middle of the muscle bellies of the medial gastrocnemius and tibialis anterior. The electrode position for the soleus was a position halfway between its distal insertion in the Achilles tendon and the distal aspect of the gastrocnemius muscle bellies. Before electrode attachment, the skin was shaved, abraded, and prepared with 90% alcohol to minimize signal impedance.

Ground-Reaction Force

The subjects walked along a custom-built, strain gauge–based, 10-m force platform separated along the middle for left and right footfalls (Raute Inc, Finland).

Fiber Insertion

The skin over the Achilles tendon, at the site for fiber insertion, was prepared with EMLA cream (eutectic mixture of local anesthetics, Astra Zeneca, Sweden) for 20 minutes before the insertion procedure. After this, subjects lay supine on a specially designed table with 1 leg in a legrest and the Achilles tendon exposed.[3] A 1.1-mm cannula was inserted through the tendon under sterile conditions from lateral to medial approximately midway between the muscle-tendon junction and the tendon's calcaneal insertion. A polymethyl methacrylate optic fiber with 0.5-mm thickness and 1 m in length (PRG series, Toray Inc, Chiba, Japan) was threaded through the cannula, after which the cannula was withdrawn leaving the optic fiber in the tendon. The ends of the fiber were then cleaned and attached to a light-emitting diode (GaAIAs semiconductor, HFBR-1414, Hewlett Packard, Palo Alto, California) and a pin-type photodiode receiver (HFBR-2414, Hewlett Packard). Tendon deformation during measurements modulates the intensity of the light going through the fiber. The light signal detected by the receiver unit was converted into an analog signal and registered by computer. During the experiment, the insertion site was cleaned with disinfectant at regular intervals to prevent coagulation around the fiber and to reduce the risk of infection. The orthopaedic surgeon responsible for fiber insertion stipulated that the fiber should be removed after a maximum of 2 hours.

Calibration

The signal through the optic fiber was calibrated against a strain gauge force transducer during plantar flexion.[3,9] External force was calculated to represent Achilles tendon force (ATF) by using balance of moments about the ankle joint, where the center of the lateral malleolus was chosen as an approximation of the joint's center of rotation. Subjects were lying supine with 1 leg strapped to a leg rest with the knee flexed to 80° and with a 90° angle in the ankle. Before the fiber was inserted, subjects had been instructed to push with the foot against the strain gauge as hard as possible (100% maximal voluntary contraction [MVC]). Instructions were to perform a plantar flexion with the foot and avoid pushing with the whole leg. Three attempts were made to obtain reproducible curves for maximum plantarflexion force. The fiber was then inserted as described above, after which subjects were instructed to push 10% MVC while looking at an oscilloscope for visual feedback. Simultaneously, the signal through the optic

Figure 1. Right lower leg from behind showing opening in ankle foot orthosis (AFO) and the optic fiber in place (arrow).

fiber was recorded. This was repeated with the subjects pushing 20% and 30% of MVC. Higher calibration force levels were avoided to minimize the contribution of plantar flexors other than the triceps surae. The signal from the fiber was then plotted against the signal from the force transducer and a linear regression fitted through these points. This permitted a correlation of the fiber signal (V) to plantarflexion force (N) and the derivation of a calibration coefficient for each subject for calculating the ATF.

Preparation of the AFO

Ankle-foot orthoses with adjustable ankle angles that allow controlled range of motion (short leg walker with articulating hinge, DeRoyal Europe Inc, Ireland) were used in this experiment. Before the experiment, the AFOs were adjusted so as not to interfere with the optic fiber in the Achilles tendon. A longitudinal cut was made through the soft supporting material along the back of the AFO so that the lower leg and foot could be inserted from behind. An approximately 8 × 8-cm hole was cut in the soft material over the Achilles tendon to leave room for the fiber. The most distal of 3 Velcro® straps for fixing the AFO was removed, as this would have interfered with the fiber position. Adjoining metal supports were padded with foam to protect the fiber from chafing (Figure 1).

Experiment

After calibration, the subjects walked barefoot along a 10-m force plate at self-selected speed. Two trials were recorded for each subject and each setting: the walking trial in 1 direction with the right footfalls on 1 of the force platform sections and in the other direction with the right foot landing on the other section. The left foot was not analyzed. Subjects were instructed to walk as relaxed as possible at a comfortable speed. They were then fitted with an AFO. First, the AFO was set to allow active free plantar flexion but restricted dorsiflexion to 10° of plantar flexion (10° pf). Subjects were given the opportunity to practice a few steps until comfortable with the AFO setting and then walked at a self-selected speed. This was repeated with the orthosis set to allow active free plantar flexion but restricted dorsiflexion to 10° of dorsiflexion (10° df) and finally with the orthosis fixed with no range of motion at 20° of plantar flexion (20° pf). No crutches were used for any of the walking conditions. Treatments were not randomized as the above sequence took least time with regards to AFO adjustment, which was necessary to remain within the stipulated time limit. The AFO and the different settings used corresponded to the treatment protocol currently used for postoperative treatment of Achilles tendon ruptures at Karolinska University Hospital, Huddinge, Sweden (Table 1), which has been previously published.[19] The only exception was that 20° pf was used in the study instead of the 30° used in the hospital protocol because 30° of ankle plantar flexion introduced the risk of interference between the optic fiber and the orthosis. Data from the optic fiber, the force plate, and EMG were transferred simultaneously through an A-D converter (sampling rate, 1013.1 Hz) to a Victor Sirius microcomputer (Victor Technologies Inc, Addison, Illinois) for storage and further analysis.

After conclusion of the measurements, the fiber and electrodes were carefully removed and the insertion area was cleaned with disinfectant and bandaged with sterile pads.

Analysis

All raw data were analyzed using Origin 6.1 software (Microcal Software Inc, Northampton, Massachusetts). The EMG raw data were rectified, and overshooting values were removed. The curve was smoothed with a 200-point adjacent averaging filter, and peak values were identified on the resulting curve. First and last steps in each trial were not included in the analysis to avoid acceleration and deceleration effects. The tibialis anterior in general has 2 peaks in a gait cycle, and the peak preceding heel strike and subsequent contraction of the gastrocnemius were chosen for the analysis process. The individual EMG peaks were normalized to the mean activity found for each subject during the 2 barefoot walking trials. A mean value was then calculated for all normalized peaks per subject and walking condition.

Optic fiber data were converted into ATF (N) using the calibration factors calculated for each subject. The ATF

TABLE 1
Treatment Protocol Used for Postoperative Treatment of Achilles Tendon Ruptures at Karolinska University Hospital, Huddinge, Sweden[a]

Time	Treatment	Crutches	Corresponding AFO Setting in Study, No Crutches
Day 1	Tendon suture		
Week 1-2	Plaster cast in pf	Yes	
Week 3-4	AFO locked at 30° pf, no ROM	Yes	20° pf[b]
Week 5-6	AFO set at 10° pf, with ROM between full pf and 10° pf	Yes	10° pf
Week 7-8	AFO set at 10° df, with ROM between full pf and 10° df	Optional	10° df
Week 9-16	Shoes with heel lifts of 1.5–2 cm	No	

[a]See Möller et al (2001).[19] AFO, ankle-foot orthosis; df, dorsiflexion; pf, plantar flexion; ROM, range of motion.
[b]The choice of 20° pf in this study as opposed to the 30° pf in the rehabilitation protocol is explained in the text.

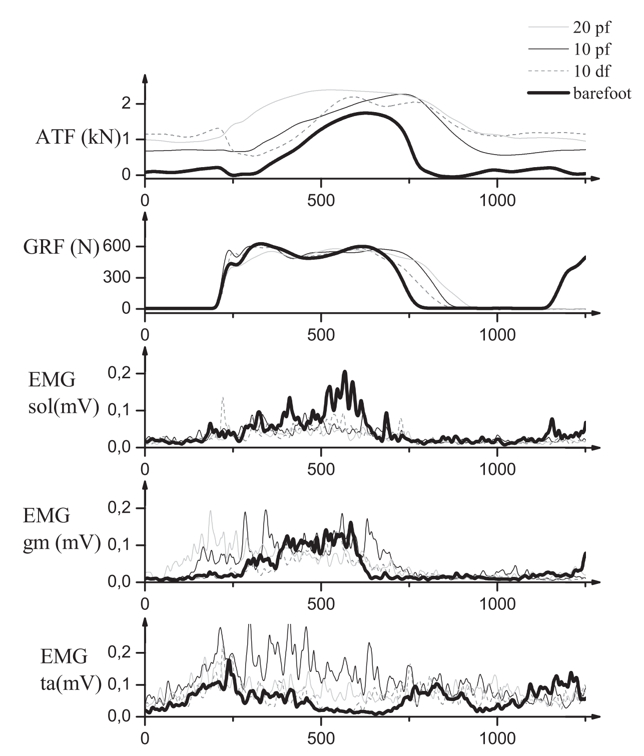

Figure 2. Mean curves for Achilles tendon force (ATF), ground-reaction force (GRF), and EMG for 1 subject. pf, plantar flexion; df, dorsiflexion; sol, soleus; gm, gastrocnemius; ta, tibialis anterior.

was plotted against time as shown in Figure 2. Maximum ATF (ATFpeak) and the rate of ATF development (ATFrate) were calculated. To find peak forces, maximum values of ATF during each stance phase were identified, again ignoring the first and last steps. The ATFpeak values were normalized to body weight. A mean ATFpeak was then found for each subject and walking condition. To identify rate of force development, the slope of the curve between the minimum and ATFpeak before toe-off was determined for each step in a trial. The mean ATFrate was then calculated for each subject and walking condition.

Data for all parameters from both trials at AFO setting 20° pf for 1 subject are missing owing to technical problems with the fiber for this final setting. For gastrocnemius muscle, 1 subject is omitted because all data during barefoot walking had overshooting so no normalization could be made, and for another subject, data were missing for the AFO 10° pf setting for the same reason. So for gastrocnemius activity, there were data available from 6 subjects for 20° pf and 10° pf and from 7 subjects for barefoot and AFO setting 10° df. For the remaining parameters, there were data available from 8 subjects for barefoot and AFO setting 10° df and 10° pf as well as from 7 subjects for 20° pf. All available data were used for analysis, so a missing value for 1 AFO setting did not exclude the subject from analysis of remaining AFO settings.

A repeated-measures analysis of variance using Procedure Mixed in SAS System 9.1 (SAS Institute Inc, Cary, North Carolina) was performed to establish whether there was any difference in ATFpeak, ATFrate, EMG activity, or walking speed between any of the walking conditions. The compound symmetric covariance structure was accepted for all ATFpeak, ATFrate, and EMG variables. For walking speed, the heterogeneous compound symmetric covariance structure was used. The Tukey post hoc test was used to make all pairwise comparisons among condition means. The mean muscle activity during barefoot walking was used for normalization and set to 100%. The 95% confidence intervals (CIs) were calculated for the mean percentage value for the EMG activity variables at the 3 conditions 10° df, 10° pf, and 20° pf. If the CI of a given condition did not include 100%, the difference compared with barefoot walking was considered statistically significant.

RESULTS

Walking speeds are shown in Table 2. There was no statistical difference in walking speed between any of the walking conditions.

Representative mean ATF, ground-reaction force, and EMG curves for 1 subject are shown in Figure 2. Because

TABLE 2
Walking Speeds With 95% Confidence Intervals for Mean Difference From Barefoot[a]

Walking Condition	Speed, m/s	Mean Difference From bf	95% CI for Mean Difference From bf
bf	1.18		
10° df	1.20	–0.026	–0.174 to 0.121
10° pf	1.09	0.089	–0.008 to 0.186
20° pf	1.07	0.105	–0.100 to 0.310

[a]The confidence intervals (CIs) are adjusted according to Tukey's method. bf, barefoot; df, dorsiflexion; pf, plantar flexion.

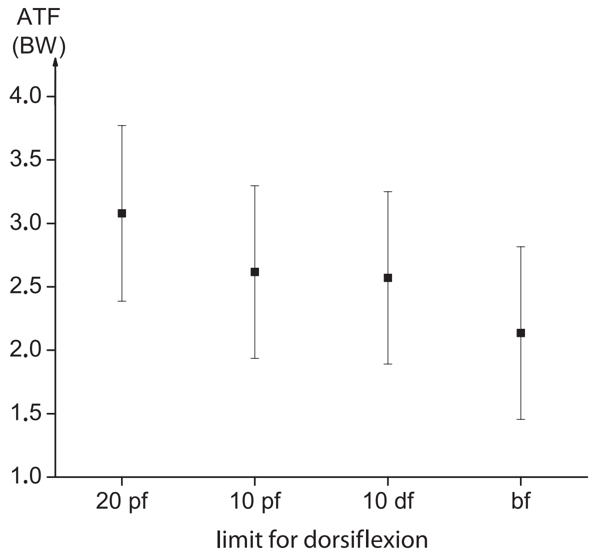

Figure 3. Mean peak force (±95% confidence interval) in the Achilles tendon expressed as a factor of body weight. pf, plantar flexion; df, dorsiflexion; bf, barefoot.

of intersubject differences in duration of ground contact, the real curve shapes would be modified and the actually observed patterns in the measured parameters would be hidden; therefore, averaged curves were not chosen.

The ATFpeak decreased progressively as restriction in dorsiflexion was lessened from 3.1 times body weight at AFO setting 20° pf to 2.1 times body weight during barefoot walking (P = .0063) (Figure 3). The ATFrate showed a tendency to increase as more dorsiflexion was allowed, with the lowest rate at AFO setting 10° pf (1999 N/s) and the highest during barefoot walking (2799 N/s; P = .0778) (Figure 4).

Soleus activity increased progressively as dorsiflexion limitation decreased (Figure 5). Soleus activity was 52% (95% CI, 36%-67%) of barefoot walking activity at 20° pf, 58% at 10° pf (95% CI, 44%-73%), and 95% (95% CI, 81%-109%) at 10° df. Activity at 20° pf was significantly lower than was activity at 10° df (P = .0004), as was activity at 10° pf (P = .0010).

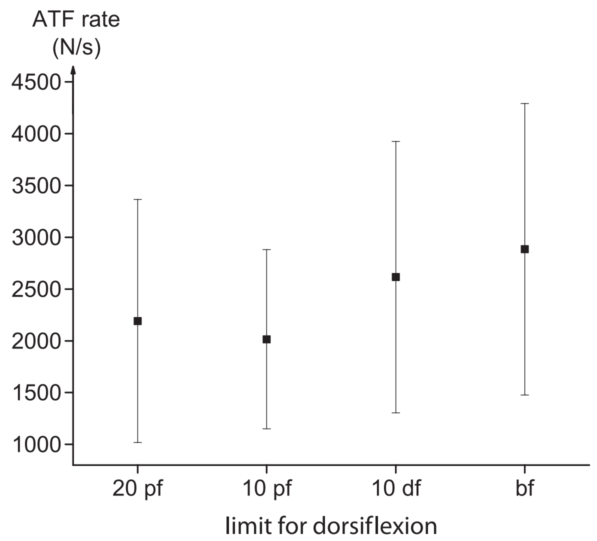

Figure 4. Mean rate (±95% confidence interval) of Achilles tendon force development in newtons/second. pf, plantar flexion; df, dorsiflexion; bf, barefoot.

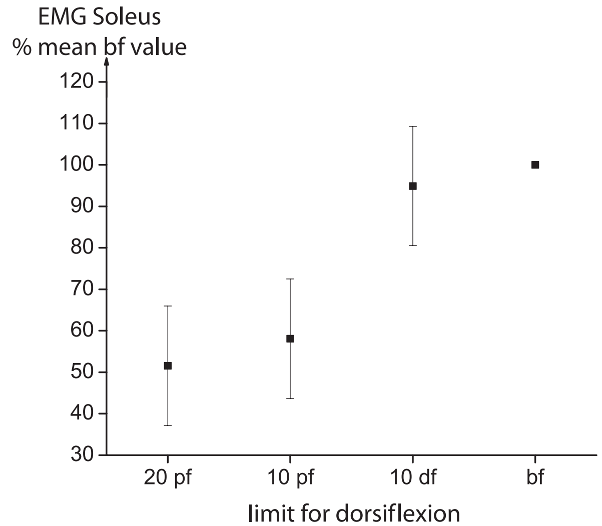

Figure 5. Mean EMG activity of the soleus (±95% confidence interval) expressed as a percentage of mean activity during barefoot walking. The mean activity found during barefoot walking is set to 100%. pf, plantar flexion; df, dorsiflexion; bf, barefoot.

Activity in the gastrocnemius muscle varied from 85% (95% CI, 72%-99%) at setting 20° pf to 108% (95% CI, 94%-121%) at setting 10° pf and 87% (95% CI, 74%-100%) at AFO setting 10° df (Figure 6). Activity at 10° df and 20° pf differed significantly from activity at 10° pf (P < .05).

Tibialis anterior muscle activity is shown in Figure 7. Activity at 10° pf was 140% (95% CI, 104%-176%), which was significantly higher than during barefoot walking.

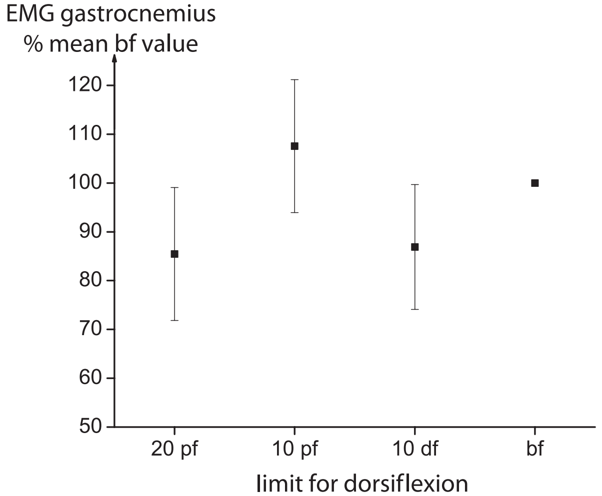

Figure 6. Mean EMG activity of the gastrocnemius muscle (±95% confidence interval) expressed as a percentage of mean activity during barefoot walking. The mean activity found during barefoot walking is set to 100%. pf, plantar flexion; df, dorsiflexion; bf, barefoot.

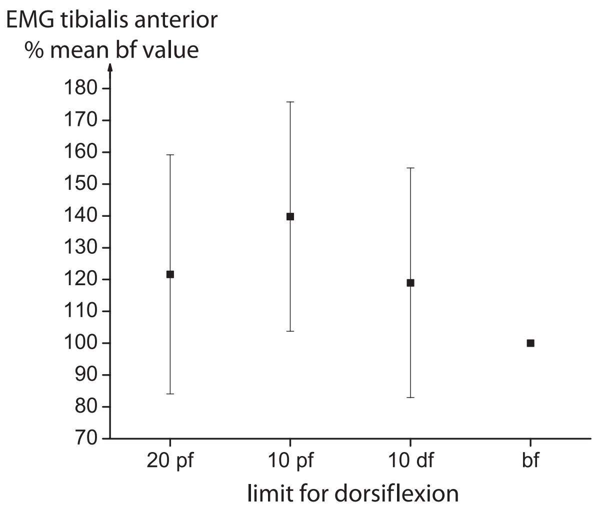

Figure 7. Mean EMG activity of the tibialis anterior muscle (±95% confidence interval) expressed as a percentage of mean activity during barefoot walking. The mean activity found during barefoot walking is set to 100%. pf, plantar flexion; df, dorsiflexion; bf, barefoot.

DISCUSSION

In this study, ATF measured with an optic fiber force transducer was significantly higher when dorsiflexion was restricted to 20° pf compared with barefoot walking, and the EMG data showed that soleus muscle activity was significantly lower when dorsiflexion was limited.

Calibrations for the optic fiber were made under static conditions, whereas measurements were made under dynamic conditions. Potential error in force prediction due to mismatch between calibration conditions and experimental conditions has been pointed out as a possible limitation of this method.[8] It has also been mentioned that the skin may affect the optic fiber during motion.[7] However, the ATF patterns previously measured with this technique[9,10] have been shown to be similar to those obtained with the buckle transducer method[15] during human walking. Consequently, the skin movements may not cause artifacts to the signals in the movement range of the ankle joint during human walking. Walking speed was not controlled as subjects were instructed to walk as relaxed as possible at their own preferred rates. However, no statistical difference was found in walking speed between walking conditions, so it is unlikely that this had any major influence on the results.

The ATFpeak was shown to be significantly higher at AFO setting 20° pf as compared with barefoot walking. According to the treatment protocol shown in Table 1, this is the initial setting used when the plaster cast is removed, 2 weeks postoperatively. At this stage in the rehabilitation protocol, patients are instructed to use crutches to relieve load from the Achilles tendon when walking, whereas in this study, no crutches were used and full weightbearing allowed. The above result indicates that if a patient was to either accidentally or intentionally support on his or her foot while the AFO was locked at 20° pf, tendon loading may exceed that encountered during barefoot walking.

The ATF was noted to be relatively high during the swing phase of walking even in the 20° pf AFO condition. There are a number of explanations for this. First, by fixing the ankle in different positions, the ATF baseline will shift. As this is a real effect observed in the fiber signal in all subjects, we did not normalize these baselines. Second, the inertial effect of the AFO will place strain on the Achilles tendon during the forward swing phase of the foot. No similar effects have been seen in previous studies in barefoot or running shoe conditions in either walking or running. The weight of the AFO provides an explanation for this difference. Third, pressure of the AFO on the triceps surae may affect the mobility of the muscle fascicles. During ground contact, the muscle belly shifts owing to muscle contraction, but when the muscle is relaxed after toe-off, muscle fascicles may be hindered or delayed in moving back due to pressure from the AFO. That is, in the AFO conditions, the muscles may be pulled up owing to the tight AFO. Also, knee kinematics may have played a role in stretching the gastrocnemius muscle during the swing phase. However, kinematic data were not collected.

The ATFrate was higher during barefoot walking than when the AFO was used, and there seemed to be a trend that restriction in dorsiflexion reduced ATFrate. The EMG activity of the soleus muscle was lower when dorsiflexion was restricted as compared with barefoot walking, which is similar to what has previously been reported.[1] The main difference in activity occurred between the settings 10° pf and 10° df.

Contrary to this, the activity of the gastrocnemius muscle did not show a clear tendency to increase as further dorsiflexion was permitted, as has been reported previously.[1,17] The AFO used for this experiment had an adjustable foot plate on a hinge that was set in different angles and allowed a limited range of motion, whereas Akizuki et al[1] used an orthosis fixed at 90° and then added heel lifts. When the AFO in this study was locked in a plantarflexed position, the subjects had to walk on their toes because there was no support under the heel. In the most plantarflexed condition, most subjects had to bend their knees to avoid limping. For anatomical reasons, bending the knee is likely to affect the gastrocnemius muscle more than it affects the soleus muscle. It has also been subjectively observed that subjects wearing this type of orthosis rotate their hips while walking.[1] It has been shown that when walking with the ankle immobilized in a cast at 20° of plantar flexion, walking with external rotation movement of the leg resulted in higher EMG activity of the medial gastrocnemius than did walking with the foot pointing forward.[4] These factors may contribute to explaining why no clear correlation between restriction in dorsiflexion and gastrocnemius activity was found in this study.

Tibialis anterior activity followed the same pattern as has previously been found, with increased activity as plantar flexion increased and then a decrease again in the most plantarflexed position.[17] Lee et al[17] argued that when the ankle is in the plantarflexed position, the tibialis anterior has to contract more strongly and rapidly to prevent foot slap. In this study, the AFO restricted plantar flexion only in the 20° pf setting, whereas the 10° pf and 10° df settings restricted only dorsiflexion to prevent excessive stretching of the tendon. This may explain the lower activity in the tibialis anterior at 20° pf than at 10° pf.

Postoperatively, the ankle is traditionally placed in plantar flexion as it is believed that this will assist in adapting the ends of the ruptured tendon after suture.[18] Costa et al[6] used an AFO that held the ankle in plantar flexion using heel wedges that gave support under the heel, and patients were encouraged to bear full weight. Two reruptures in 23 patients (8.7%) were reported. Möller et al[19] used the same type of AFO as used in the present study, and full weightbearing was encouraged after 2 weeks when the AFO was set to 30° pf. They reported 1 rerupture in 51 patients (1.7%). The ATF may be directly affected by the 2 different designs, either with or without heel support in fixed plantar flexion, although a direct comparison of this effect has yet to be published. Ankle-foot orthoses and braces that restrict dorsiflexion to neutral (90°) have been used immediately after surgical repair of the Achilles tendon with weightbearing permitted either immediately[22,23] or after 3 weeks.[13] Speck and Klaue[23] and Rantanen et al[22] reported no increased incidence of reruptures, and Kauranen et al[13] reported no increase in wound problems. These studies have not shown any increased risks with the use of AFO regardless of if they kept the ankle plantarflexed or allowed dorsiflexion to neutral. The present study shows that when an AFO with an adjustable foot plate that lacks support under the heel is used and the dorsiflexion is restricted to 20° pf, force peaks that exceed load during barefoot walking may occur. These results suggest that restricting dorsiflexion to 20° pf postoperatively may not unload the tendon as was expected. Animal studies have shown that muscles that are immobilized at less than resting length undergo atrophy, whereas atrophy is slower or absent in muscles fixed in stretched positions.[5] This would support the concept of permitting a certain amount of dorsiflexion postoperatively. On the other hand, skin perfusion over the Achilles tendon has been shown to vary with varying degrees of plantar flexion, and optimal skin perfusion was achieved at 20° pf,[21] which may support the concept of keeping the ankle in slight plantar flexion postoperatively. However, it has not been shown how this affects wound healing after Achilles tendon surgery.

Tendon loading and muscle atrophy aspects may therefore suggest advantages in increasing the dorsiflexion permitted in AFOs and/or using AFO designs that provide support under the heel. The fact that none of the clinical series discussed above reported an increased incidence of reruptures also supports greater dorsiflexion. The effect of ankle angle on wound healing and a comparison of the biomechanical properties and clinical results of different AFO designs have yet to be investigated.

CONCLUSION

This study demonstrated that full weightbearing in AFOs that restrict dorsiflexion and keep the ankle plantarflexed may result in increased forces in the Achilles tendon compared with barefoot walking, despite reduced EMG activity in the soleus.

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