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Stability boots for the treatment of Achilles tendon injuries: Gait analysis of healthy participants

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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

Background: Achilles tendon injuries are commonly treated with stability boots that secure the ankle at a specific position and aim to reduce loading of the tendon. These boots allow full weight bearing by limiting the range of movement. It is, however, unknown, to what extent these boots can reduce tendon loading and if the biomechanics are altered during walking.

Research question: How do orthopedic boots influence lower extremity biomechanics during walking?

Methods: For this cross-sectional study, ten healthy participants walked with three orthopedic boots (Oped Vacoped, Kuenzli Ortho Rehab Absolut, Orthotech Variostabil) commonly used to treat Achilles tendon injuries. Kinematics and kinetics of the lower extremity of the booted leg and spatiotemporal parameters of both sides were collected using motion-capturing system and dynamometry. Each boot was tested in the maximally plantarflexed position. Group differences between boot conditions were analyzed by means of repeated-measures ANOVA and post-hoc paired *t*-test.

Results: The boot dorsiflexion range of motion differed significantly between boots with Vacoped (1.8° (0.3)) showing the smallest range, followed by Kuenzli (5.0° (1.3)) and Orthotech (7.9° (1.7)). Orthotech displayed a higher peak plantarflexion moment (1.36 Nm/kg (0.09)) than both Kuenzli (1.06 Nm/kg (0.12)) and Vacoped (1.04 Nm/kg (0.14)). Concerning loading over time, significant differences in the plantarflexion impulse were found, with the highest impulse in Vacoped (0.42 Nms/kg (0.06)), followed by Orthotech (0.29 Nms/kg (0.03)) and Kuenzli (0.25 Nms/kg (0.05)). In addition, asymmetries were seen in stance and step length for the booted and contralateral sides.

Significance: The lower extremity biomechanics were affected by the boots, with Kuenzli showing the lowest joint loading, Vacoped the smallest joint motion and Orthotech the most natural gait pattern. Future research is needed to determine the most relevant variable expressing the risk of re-rupture of the Achilles tendon in order to conclude which boot may be most favorable to use in clinical practice.

1. Introduction

Achilles tendon injuries (ATI), such as a partial or complete rupture, are common injuries in middle-aged individuals. The incidence rate for Achilles tendon rupture ranges from 2.5–37.3 per 100′000 person years, with an apparent upwards trend in recent years [1,2].

Studies on treatment methods for acute ATI and their respective benefits are contradictory. Some studies show a lower risk of re-rupture as a result of surgical treatment, while others claim equal re-rupture rates when compared to conservative treatments [3,4]. Regardless of the form of treatment, full weight bearing is part of the functional rehabilitation for acute ATI patients. Full weight bearing may start at week 1 after injury, and more than 50 % of all treatment protocols for non-operative and operative treatment allow full weight bearing after 5 weeks [5]. During functional rehabilitation, a plantarflexed ankle position and a limited range of motion are maintained to keep the two parts of the Achilles tendon in close proximity (for non-operative treatment) or reduce tension on the sutured section (for operative treatment). This, in combination with weight bearing, is crucial for effective functional rehabilitation [5,6], which has been shown to shorten the time of returning to full daily life activities without increased incidence of re-rupture. Furthermore, early weight bearing has been found to improve patient satisfaction [7–9]. With regard to the incidence of complications, immediate functional mobilization with weight bearing

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in an orthopedic boot was shown to be as safe as cast immobilization treatment [9]. Activation of the triceps surae muscle group, or stretching of the tendon by increased dorsiflexion angle, generates load, thereby promoting the healing processes that strengthens the tendon [9,10].

One treatment option for ATI is wearing an orthopedic boot, commonly used in the first 8–12 weeks after injury. The aim of this boot is to reduce Achilles tendon loading while allowing full weight bearing. Loading can be investigated by measuring the sagittal ankle angles and moments. Today, several commercial boots are available for use in functional rehabilitation in both postoperative and conservative treatments. A harder boot shaft decreases the ankle range of motion while, conversely, a soft boot results in a greater range of motion and enables the ankle joint to generate more power [11]. To date, the amount of ankle mobility and tendon loading allowed by these boots is unclear. These boots allow different ankle plantarflexion positions within the boot. How the plantarflexed position is maintained differs between boots. Some utilize wedges placed under the heel while others utilize a hard shell with a hinge joint, that can be secured at different angles, and a vacuum cushion inside. It is unknown if the different boot designs vary in their ability to keep the Achilles tendon in a position of reduced loading. The most plantarflexed position of the ankle within the boot is the most crucial in terms of reduced loading of the Achilles tendon as patients will be required to bear load on the foot in this position at the beginning of rehabilitation.

Several research groups have evaluated Achilles tendon loading during walking with an orthopedic boot via invasive optic fiber. When compared to barefoot walking, one group found a trend towards strain relief, while another group showed increased Achilles tendon load [12,13]. But noninvasive methods, such as 3D motion analysis and ultrasonography, have also been used to investigate Achilles tendon properties. These showed a decreased ankle plantarflexion moment two to six years after surgical treatment due to greater tendon stiffness indicating the long-term effects of the injury to the tissue properties and consequently the movement pattern [14].

Gait analysis comparing physiological walking patterns in orthopedic boots, casts and normal shoes, showed significant kinematic and kinetic changes in knee and hip during walking with a cast. The reduced knee flexion angle during stance, the decreased external knee flexion moment and the reduced external hip abduction moment could result in altered joint loading that may lead to adverse effects on the ipsi- or contralateral side. The orthopedic boots resulted in only minor changes of the gait pattern compared to walking in a normal shoe which led to the conclusion that boots are less likely to cause unwanted effects [15].

The aim of this study is to investigate the influence of different orthopedic boots on lower extremity biomechanics during walking. Three types of orthopedic boots that are commonly used for patients with acute Achilles tendon injuries were tested by healthy participants: Oped Vacoped, Kuenzli Ortho Rehab Absolut, Orthotech Variostabil. The boots have different designs which may alter their ability to stabilize the ankle. Boots were compared while the ankle was placed at the maximally plantarflexed position. It was hypothesized that the boot with an external shell resulted in less ankle movement but larger deviations of the knee joint from normal gait compared to the other boots, which were built internal structures to provide stability. Further, no differences were hypothesized for the comparison of the two boots without external shell.

2. Materials and methods

2.1. Study design

This study was designed as a monocentric cross-sectional study, approved by the Ethics Committee of Canton Zurich (BASEC-NR. 2018-01101). Measurements were taken at the Movement Laboratory of the Zurich University of Applied Sciences in Winterthur, Switzerland. All participants provided written informed consent prior to inclusion.

2.2. Objects and material

Ten healthy participants (5 female, age 32.5 ± 10.0 years, height 173.79 ± 7.93 cm, weight 71.93 ± 13.1 kg) were recruited by word-of-mouth. The sample size was determined with a power analysis based on data from a pilot study (G*Power, Germany). Participants were free of any acute or chronic musculoskeletal, neurological or cardiological diseases, had never before experienced issues with their Achilles tendons, and were not pregnant.

Three commercially available stability boots were used: Ortho Rehab Absolut (short: Kuenzli, Künzli SwissSchuh AG, Switzerland); Vario-Stabil (short: Orthotech, Orthotech GmbH, Germany); and VACOped (OPED AG, Switzerland). VACOped consists of a hard external shell, while the others are normal (artificial) leather boots. All three boots are recommended for the management of ATI [16–18]. For Kuenzli and Orthotech, the plantarflexion positions are achieved by inserting wedges underneath the insole to increase the heel. For VACOped, the shaft can be set to different plantarflexion positions and a wedged outsole is added (details in Appendix 1). The investigated stability boots were size 6 (females) and size 9 (males).

2.3. Procedure

All data were collected in a single session. After recording the anthropometric data, markers were placed on the lower extremities and the pelvis by one of the three examiners, according to a customized cluster marker model [19]. The examiners were either trained physiotherapists or human movement scientists instructed on marker placement. The stability boot was worn on the left side. On the right side, the participants wore the provided compensating solution for the contralateral side. For VACOped, the participants wore a neutral running shoe with the provided even up sole. Shank (left side) and foot (left and right side) markers were placed on the boots (see Appendix 2). The examiners tightened the boots to ensure proper grip. After participant preparation, a functional calibration, including neutral standing, was performed to estimate hip and knee joint centers for each boot [19]. The participants were then given time to familiarize themselves with the boot. For the test, they walked with full weight bearing within a delineated area of 10 m length at two different speeds: 1.2 m/s ± 5 % and at a self-selected, constant speed. The walking speed was defined by the average time necessary to cross the distance between two light barriers 3.5 m apart (MicroGate, Bozen, Italy). Data from ten trials were collected. Instructions from the examiners consisted only of “walk faster/slower” (when the targeted speed was not achieved) or “look straight ahead“. The trials with self-selected speed were recorded to compare the speed between boots while the trials with 1.2 m/s allow for comparison of the biomechanics without speed as confounding factor. Boot order was randomized, the self-selected speed was performed first in each boot.

2.4. Data collection and analysis

Data were collected using a marker-based, optoelectronic motion capture system (Vicon Motion System, UK, 240 Hz) consisting of 12 infrared cameras and two in-ground force plates (AMTI, USA, 1200 Hz, 50 × 46 cm). Matlab R2018 (MathWorks Inc., USA) was used to process the data and to calculate joint center and kinematics. Marker data were filtered with a 4th order Butterworth filter with a cut-off frequency of 7 Hz. Joint kinetics were determined in Bodybuilder (Vicon Motion System, UK) by an inverse dynamics calculation, using the data from the force plates and the marker trajectories. Center of pressure (COP) data were expressed in percentage of total boot length.

The neutral position for angle calculations was a static upright stance with parallel feet. Peak values for angles and internal moments, as well as range of motion (ROM), for the boot-ankle, knee and hip joints were calculated. Additionally, boot-ankle angular impulse and spatiotemporal parameters were extracted for further data evaluation. The self-

Table 1
Total range of motion of the foot with the boot during walking at 1.2 m/s. Mean (SD), n = 10, ‡significant difference from Vacoped, †significant difference from Orthotech, *significant difference from Kuenzli ($p < 0.05$).

	Total range of motion [°]		
	Kuenzli	Vacoped	Orthotech
Sagittal plane	5.0 (1.3) ‡†	1.8 (0.3) †*	7.9 (1.7) ‡*
Frontal plane	1.8 (0.6) ‡	1.2 (0.5) †*	2.3 (0.7) ‡
Transverse plane	2.5 (0.6)	2.2 (0.8)	2.0 (0.6)

selected walking speed was compared between boots.

Statistical analysis was performed using Matlab R2018. The main variables were tested for normal distribution by the Lilliefors test. Group differences were analyzed by a repeated-measures ANOVA ($p < 0.05$). In case of differences, a post-hoc paired *t*-test was performed with Bonferroni correction.

3. Results

3.1. *Boot-ankle*

All boots showed significant differences in the sagittal plane, with Vacoped displaying the smallest ROM, followed by Kuenzli and Orthotech (Table 1, Fig. 1). Foot inversion and internal rotation were shown to be <3°.

Considering the whole stance phase, Vacoped showed a boot-ankle plantarflexion moment from the beginning of the stance phase, while the other two boots demonstrated an initial dorsiflexion moment (Fig. 1). Significant differences were reported for the plantarflexion angular impulse, with the highest value in Vacoped (0.42(0.06) Nms/kg), followed by Orthotech (0.29(0.03) Nms/kg) and Kuenzli (0.25 (0.05) Nms/kg) (Table 2).

Differences were also observed for COP data (Fig. 2). The temporal course is represented by the COP for each 1 % stance phase time point. For Orthotech, this showed a longer period of anterior COP than Kuenzli, which showed a more posterior and mid-foot COP with a short phase in the anterior (toe) position. From the initial contact, Vacoped showed a COP at approximately 30 % bootlength, which shifted immediately anterior towards the toes.

3.2. *Knee and hip*

In the knee, flexion ROM was significantly lower in Vacoped (56.7 (8.2)°) compared to Kuenzli (69.1(5.6)°) and Orthotech (69.9(4.9)°). Vacoped showed an increased flexion at initial contact, with the knee staying more flexed through the stance phase compared to the other boots (Fig. 3). No difference in knee internal rotation and adduction was seen between boots. For the hip, a decreased hip adduction ROM was observed in Vacoped (13.8(2.5)°) compared with both Kuenzli (16.0 (2.1)°) and Orthotech (16.1(2.3)°). Vacoped showed a lower hip abduction and external rotation moment (0.8(0.1) Nm/kg and 0.1(0.0) Nm/kg, respectively) than both Kuenzli (1.0(0.0) and 0.2(0.0) Nm/kg) and Orthotech (1.0(0.1) and 0.2(0.0) Nm/kg).

3.3. *Spatiotemporal parameters*

Self-selected walking speed with Vacoped was significantly slower than with Kuenzli or Orthotech (Table 3). Left-right asymmetries in stance time were observed for all boots, with a longer percental stance time on the contralateral leg. Step length of the ipsilateral leg differed significantly for Kuenzli and Vacoped. Orthotech showed no difference in step lengths (Table 3).

4. Discussion

This study investigated the biomechanical effects of walking in three stability boots used in the treatment of ATI. The main outcomes of the boot-ankle biomechanics showed differences between the boots. Regarding peak angles, Vacoped with its hard shell showed the smallest ROM, as hypothesized. However, also Kuenzli and Orthotech showed differences in boot-ankle plantarflexion which was opposite to the hypothesis. Good lateral stability in all boots was observed, with small ROMs for boot-ankle inversion and internal rotation. Therefore, a high boot stiffness, as in the hard shell Vacoped, influenced the ROM of dorsiflexion.

Footwear properties also influenced ankle moments, as well as loading over time. Kuenzli displayed the smallest angular impulse and, therefore, the lowest joint loading over the gait cycle. Besides the boot shell, also the rolling of the boot sole had an important influence on biomechanics, especially on the COP and, consequently, on the boot-ankle moments. Joint loading can be reduced with a rolling of the sole that keeps the COP closer to the joint, as was seen in Kuenzli. A rolling from heel to toe was seen in both Kuenzli and Orthotech, with Orthotech having the COP on the front of the foot for a longer time. On the other hand, Vacoped's sole properties, with the missing heel contact, led to a COP which was constantly in front of the ankle joint. This is known to cause limping [20] and lead to a constant ankle plantarflexion moment. Contrary to what has been reported on lacking heel support, higher plantarflexion moments did not occurred [12].

To date, the optimal amount of movement to prevent tendon elongation and allow tendon tissue healing is unknown. Following functional rehabilitation with early weight bearing, some movement in the ankle is thought to be beneficial to the healing process and to prevent muscle atrophy. It remains unclear which boot has the ideal ROM for ATI rehabilitation. As well as enhancing the healing process, the boots should prevent tendon re-ruptures. The re-rupture mechanism of ATI during rehabilitation might be influenced by the peak or continuous loading. Which mechanism puts the tendon most at risk of re-ruptures also remains unclear. In their study, Ecker et al. found that even though most re-ruptures occurred as a result of a traumatic event, some 3 out of 11 persons suffered a re-rupture during normal walking [8]. This implies that even during normal walking activity a small peak moment is desirable. In this study, the peak moment was smallest in Vacoped and Kuenzli.

Regarding the knee, we found larger deviations from a natural gait pattern with the Vacoped than with the other two boots. This could be due to the hard shell and / or the compensating outer sole, which is not identical with the booted side, as it was seen in Kuenzli and Orthotech with the compensating shoes. Deviations from a natural gait pattern were also found in Zellers et al. Increasing the number of wedges in orthopedic boots reduced vertical ground reaction force and knee extension power [21]. Although these parameters were not collected in our study, altered knee and hip mechanics were observed. While Kerrigan et al. reported a normative peak knee flexion angle in the loading response of <20° [22], Vacoped showed a flexion angle of >30° in the loading response in this study. This flexed knee position, combined with the COP close to the toes, induced a flexion movement during loading response. The flexed knee in Vacoped might also have been the reason for the lower hip adduction ROM and smaller hip moments observed in Vacoped. This reduction in hip mechanics might be compensated by the altered knee mechanics.

For all boots, self-selected walking speed was slower than in age-

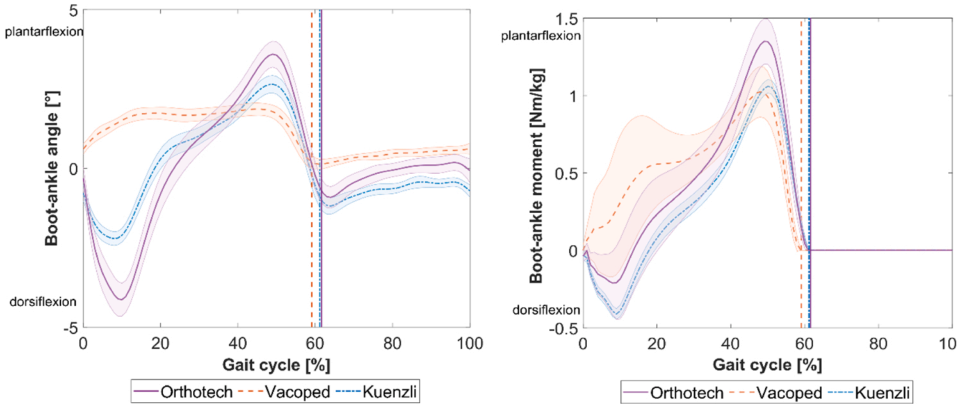

Fig. 1. Boot-ankle joint angle and moment for the side with the boot (left side) during walking at 1.2 m/s.
bold line = mean, shaded area = SD, n = 10, vertical line = toe-off, dividing stance phase (left side of line) and swing phase.

Table 2
Peak internal boot-ankle joint moments and angular impulse during walking at 1.2 m/s Mean (SD), ‡significant difference from Vacoped, †significant difference from Orthotech, *significant difference from Kuenzli ($p < 0.05$).

	Peak internal boot-ankle joint moments [Nm/kg] and angular impulse [Nms/kg]		
	Kuenzli	Vacoped	Orthotech
Plantarflexion	1.06 (0.12)†	1.04 (0.14)†	1.36 (0.09)*‡
Eversion	0.22 (0.12)	0.24 (0.11)	0.21 (0.13)
External rotation	0.10 (0.02)	0.10 (0.04)	0.09 (0.03)
Plantarflexion impulse	0.25 (0.05)‡†	0.42 (0.06)†*	0.29 (0.03)*‡

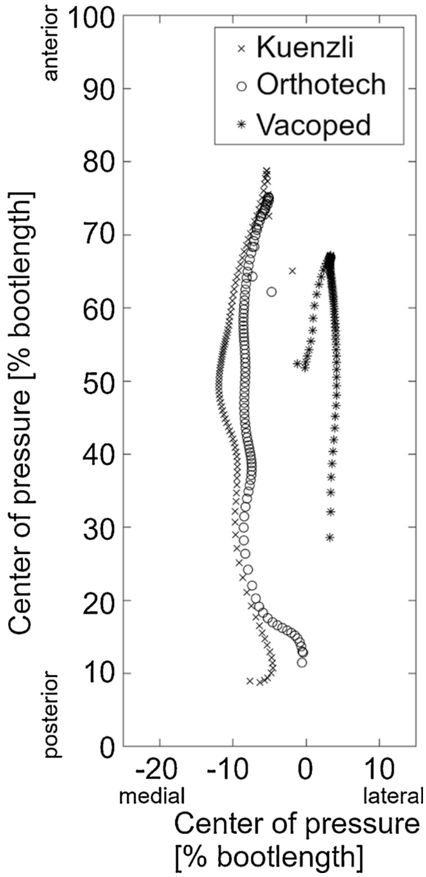

Fig. 2. Center of pressure for all boots during walking at 1.2 m/s n = 10. Coordinates [0,0] correspond to the heel marker. Each point corresponds to 1% time of the stance phase.

matched controls [23], where females had a mean gait speed of 1.34 m/s and males 1.43 m/s. This is associated with the limited movement range, which forced participants to walk more slowly. A natural walking pattern also includes symmetric step length, which was only observed in Orthotech. Step length asymmetries were seen for Kuenzli and Vacoped. For all boots, the duration of the stance phase showed asymmetries, where stance on the foot with the orthopedic boot was shorter than on the contralateral side. Such asymmetries of step length and stance duration were shown to indicate impaired walking performance [24]. It can therefore be concluded that all boots partially showed an unnatural gait pattern, with Orthotech being the closest to natural walking due to its symmetric step lengths.

To have intact stability boots, the markers on the lower leg and foot were attached to the boot and not on the skin of the participants. Radiographic techniques could be used to record the skeletal movement within the boots. However, such an approach was not feasible in the

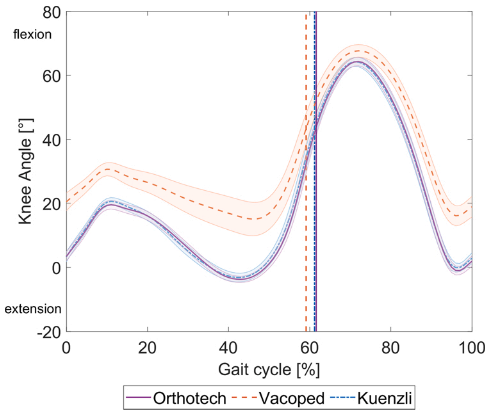

Fig. 3. Knee joint angle during walking at 1.2 m/s.
n = 10; bold line = mean, shaded area = SD, vertical line = toe-off, dividing stance phase (left side of line) and swing phase.

Table 3

Spatiotemporal parameters for the leg with boot (ipsilateral) and the compensatory side (contralateral), step length and stance for walking at 1.2 m/s, speed for self-selected walking speed Mean (SD), ‡significant difference from Vacoped, †significant difference from Orthotech, *significant difference from Kuenzli; # significant difference between ipsilateral and contralateral side ($p < 0.05$).

	Spatiotemporal parameters				
	Step length ipsilateral [cm]	Step length contralateral [cm]	Stance time ipsilateral [% gait cycle]	Stance time contralateral [% gait cycle]	Self-selected speed [m/s]
Kuenzli	72.9 (0.7)#	71.1 (0.8)#	61.2 (0.2)#	63.4 (1.3)#	1.31 (0.01)‡
Vacoped	68.7 (1.3)#	74.4 (0.6)#	59.1 (0.4)#	62.4 (0.2)#	1.17 (0.07)†*
Orthotech	71.5 (0.7)	71.5 (0.9)	61.6 (0.3)#	63.2 (0.2)#	1.31 (0.01)‡

given setting. All boots were tightened by the researchers to reduce variability between participants. This should reduce the amount of movement of the foot/leg within the boot, but the amount could not be quantified. Consequently, the actual joint angles and moments may be different from the recorded boot mechanics.

A strength of this study is that measurements were made under conditions comparable to a clinical setting. This means that the boots did not have to be cut or adjusted, such as in studies measuring Achilles tendon loading with percutaneously inserted optic fibres [12,13]. A limitation of this study is that the movement between markers of the same cluster could have occurred. By using four markers per cluster and applying a singular value decomposition [25], the resulting error is reduced compared to an approach with three markers per cluster. As exact anatomical positions might be difficult to palpate through the boots, the cluster model with marker positions not confined to precise anatomical positions reduced this error. Another limitation is the generalizability of the results for people with acute ATI, since the measurements in this study were taken with healthy participants. We assumed that boot properties were independent of health status and could be analyzed adequately using healthy participants. However, the gait pattern of ATI patients might deviate from that of the healthy population. The transferability of the current study results to ATI patients should be the subject of further investigation. Lastly, the Achilles tendon loading was not measured or estimated using a modelling approach. Instead, boot kinetics (moments and angular impulse) were calculated using an inverse dynamics approach. This allowed for a non-invasive approach but is prone to the limitations of the model.

5. Conclusion

Walking with stability boots revealed significant differences in the gait mechanics between the three models investigated. As hypothesized, VACOped had a smaller boot-ankle ROM, but also a less natural walking pattern. Contrary to the hypothesis, Orthotech and Kuenzli differed as well. Not only the material influenced biomechanical parameters, but also the design of the shoe sole and of the compensating shoe had an impact. Vacoped reduced joint loading by limiting the ROM, Kuenzli's sole properties reduced joint loading, and Orthotech allowed a more natural walking pattern. When deciding on a suitable boot for treatment of an ATI, the consequent changes in walking pattern need to be understood, so that a boot can be optimally fitted to a patient. To date, the optimal amount of movement and loading of the ankle joint desirable in functional rehabilitation of Achilles tendon injuries remains unclear. In further research, the differences between healthy individuals and ATI patients should be investigated, to ascertain whether the results of this study are transferable to the ATI population.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2021.10.009.

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