



Full length article

## Changes in gait mechanics and muscle activity with wedge height in an orthopaedic boot

Jennifer A. Zellers<sup>d</sup>, Luke A. Tucker<sup>b</sup>, Jill S. Higginson<sup>c</sup>, Kurt Manal<sup>c</sup>, Karin Grävare Silbernagel<sup>a,\*</sup>

<sup>a</sup> University of Delaware, Department of Physical Therapy, 540 South College Ave, Newark, DE, USA

<sup>b</sup> North Carolina State University, Department of Biomedical Engineering, 21 Current Dr, Raleigh, NC, USA

<sup>c</sup> University of Delaware, Department of Mechanical Engineering, 540 South College Ave, Newark, DE, USA

<sup>d</sup> Washington University School of Medicine in St. Louis, 4444 Forest Park Ave, St. Louis, MO, USA

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### ABSTRACT

**Background:** Orthopaedic boots with wedging are commonly used in the treatment of individuals with Achilles tendon rupture to immobilize the foot in plantar flexion and approximate tendon ends.

**Research question:** To describe changes in muscle activity of the triceps surae and gait mechanics with the use of wedges in an orthopaedic boot immediately and after an accommodation period.

**Methods:** Muscle activity of the triceps surae and gait parameters (vertical ground reaction force, knee extension power, gait speed) were collected using surface electromyography and motion capture in 12 healthy individuals. Participants walked in an instrumented orthopaedic boot with 0, 3, and 5 wedges tested in random order. Participants were provided a one hour accommodation period where time spent walking was collected. This was followed by a repeat assessment of triceps surae activity and gait.

**Results:** Peak and integrated EMG in the medial gastrocnemius ( $p = 0.001$ ,  $p < 0.001$ ) and soleus ( $p = 0.010$ ,  $p < 0.001$ ) significantly decreased with increasing number of wedges. Peak and integrated EMG had a slight but non-significant decrease with increasing number of wedges in the lateral gastrocnemius ( $p = 0.151$ ,  $p = 0.077$ ). Vertical ground reaction force decreased ( $p = 0.019$ ) and peak knee extension power increased ( $p = 0.003$ ) with increasing number of wedges. There were no statistically significant differences in gait speed with wedges ( $p = 0.450$ ). There were no significant changes in EMG or gait parameters from pre- to post-accommodation period.

**Significance:** A combination of factors yield decreased triceps surae activity in individuals wearing an orthopaedic boot with wedges – decreasing loading on the immobilized limb and shifting power generation proximally.

### 1. Introduction

Individuals with Achilles tendon rupture demonstrate permanent deficits in structure and function of the triceps surae [1–3]. Additionally, changes in biomechanics at 5+ years following injury have been described, with the ankle plantar flexion power contributing less and knee extension power contributing more to running and jumping tasks on the ruptured side [4]. It has been suggested that healing within the first few weeks to months after rupture heavily influences an individual's long-term functional recovery [5].

One of the critical components of early recovery is use of casting or an orthopaedic boot with wedging aimed at positioning the ankle in plantarflexion to promote apposition of tendon ends. Immobilization of

the ankle in this position is commonly used in the first 8 weeks after injury, with the amount of wedging gradually being weaned after the first few weeks. Despite receiving a standardized initial treatment strategy, patient outcomes after Achilles tendon rupture are highly variable [6]. Because individuals do not respond uniformly to a uniform treatment, a comprehensive understanding of how the triceps surae functions with the use of an orthopaedic boot is an important step in understanding variability of patient response to treatment and optimizing recovery of the lower limb after this injury.

Prior work has suggested that triceps surae activity with walking decreases when the ankle is positioned in plantar flexion with an orthosis [7,8]. Akizuki et al., found use of an orthopaedic boot without wedging reduced combined soleus and gastrocnemius activity by 21%,

\* Corresponding author.

E-mail addresses: [jzellers@udel.edu](mailto:jzellers@udel.edu) (J.A. Zellers), [latucker@ncsu.edu](mailto:latucker@ncsu.edu) (L.A. Tucker), [higginso@udel.edu](mailto:higginso@udel.edu) (J.S. Higginson), [manal@udel.edu](mailto:manal@udel.edu) (K. Manal), [kgs@udel.edu](mailto:kgs@udel.edu) (K. Grävare Silbernagel).

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and the addition of a 1 inch heel lift reduced activity by 43% compared to normal walking [7]. Fröberg et al. investigated changes of EMG in a hinged ankle brace (without wedging but with a dorsiflexion stop) and found the gastrocnemius and soleus activity to be affected differently with increasing plantar flexion [8]. Because Achilles tendon rupture seems to disproportionately affect the soleus and medial gastrocnemius architecture [9,10], identifying the effect of wedging on individual muscles along with accommodation to immobilization in plantar flexed positions could provide clinically useful information to guide early treatment recommendations.

Immobilization impacts both muscle activity and gait mechanics. Prior work has demonstrated that use of heel wedging in the absence of ankle immobilization [11] as well as ankle immobilization in the absence of wedging [12] reduces ground reaction forces. Vertical ground reaction forces have been reported to further reduce following a 1 h accommodation period [12]. In the context of heel wedging without ankle immobilization, no changes in knee moments were found with the addition of up to 2 cm of heel lift [11]. While it would seem intuitive that a combination of ankle immobilization and wedging would decrease vertical ground reaction forces during walking, experimental data of the combined effects of wedging with immobilization would be helpful in better understanding the effect of this treatment strategy on gait mechanics.

Lower extremity mechanics also change with tendon injury. Individuals with a history of Achilles tendon rupture demonstrate a shift of power generation away from the ankle and toward the knee during functional tasks such as jumping several years after injury [4,13]. Lower ankle contribution and higher knee contribution has been found to be more pronounced in individuals with structural tendon elongation [4,5,13]. However, it seems reasonable to anticipate that locomotor strategies in which the knee would have increased contribution to power generation could be adopted while immobilized early in recovery. In addition to tendon dysfunction, immobilization may encourage an individual to adopt strategies that continue to underload the ankle when immobilization is discontinued.

The primary purpose of this study was to describe changes in muscle activity of the soleus, medial gastrocnemius and lateral gastrocnemius along with lower extremity gait mechanics with the use of different heights of wedges in an unhinged, off-the-shelf orthopaedic boot. Based on previous work [7,8], we hypothesized that muscle activity would decrease with increasing wedge height. From a biomechanics standpoint, we hypothesized that walking while immobilized with wedging would reduce vertical ground reaction forces but increase knee extension power due to the inability of the ankle to contribute to the generation of lower extremity power. In a clinical context, these accommodations could potentially predispose individuals to adopt a strategy of triceps surae disuse along with altered biomechanics (decreasing use of the ankle and increasing use of the knee) during functional tasks very early in recovery from Achilles tendon rupture. A secondary purpose of this study was to investigate whether changes in muscle activity or walking mechanics occurred following a free-living accommodation period. The intention of including an accommodation period was to observe whether individuals substantially change their walking pattern or converge on a single walking strategy when provided with time to become more familiar with walking in the orthopaedic boot.

## 2. Methods

### 2.1. Participants and study design

Twelve participants with healthy Achilles tendons and no history of Achilles tendon rupture were included in this study. There were 5 male and 7 female participants, with a mean(SD) age of 26(11) years (range: 20–53 years) and BMI of 25.1(2.8) kg/m<sup>2</sup>. Healthy individuals were studied in order to be able to investigate wedge conditions without putting a healing tendon at risk. Preliminary peak EMG data from 6

individuals was used to perform a power analysis, which indicated 12 participants would be required to achieve a power of 0.95 to detect changes in muscle activity. Participant demographics were collected, including dominant lower extremity defined as, “the leg you would use to kick a ball.” The right lower extremity was the dominant lower extremity in all participants. This study was approved by the University of Delaware Institutional Review Board and all participants provided their written, informed consent.

Data collection was split into three portions – pre-assessment, free-living accommodation period, and post-assessment. For the pre-assessment, participants completed a maximum voluntary contraction (MVC) for electromyography (EMG) normalization followed by gait assessment using EMG and motion capture. For the gait assessment, participants were fitted with an Aircast™ AirSelect walking boot (provided by DJO Global) with 0, 3, and 5 foam wedges, adding 0 cm, 3.3 cm, and 5.5 cm, respectively, of foam underneath the heel. The boot was placed on the right leg of every participant, and the order of wedge conditions throughout the pre-assessment was randomized across participants using a random number generator. During the free-living period, participants were instructed to return to their normal activity for one hour while wearing the orthopedic boot with 5 wedges. After the hour, participants returned to the gait lab for a post-assessment, where gait assessment with 5 wedges and MVCs were repeated. Because we believed the 5 wedge condition would provide the largest pre- to post-assessment change, this was the only condition included in the free-living period and post-assessment.

### 2.2. Gait analysis

During the pre- and post-assessments, kinematic and kinetic walking gait data were collected using 8 infrared cameras (Vicon Motion Systems Ltd) collecting at 120 Hz and 1 in-ground force plate (Bertec Corporation) collecting at 1080 Hz. Data was collected and synchronized with Nexus 1.8.5 (Oxford Metrics). A previously described marker set [14] incorporating 39 reflective markers were placed on the participant’s pelvis, thighs, shanks, and feet (Fig. 1).

Participants were asked to walk “like they were crossing a cross-walk,” looking straight ahead at their self-selected walking speed across a gait lab while gait kinetics and kinematics were recorded. Participants were instructed to look straight ahead and across the room; trials were discarded if they began targeting the force plate or if the full stance phase was not performed on the force plate of interest. Each condition was repeated until 5 trials were retained. Because participants naturally varied their self-selected walking speed with changes in wedge number, we felt that coercing gait speeds to a preset window would misrepresent the strategies participants used to accommodate for wedging. In order to mitigate concerns regarding coercion of gait speed with concerns regarding the effect of gait speed on resultant biomechanical metrics,

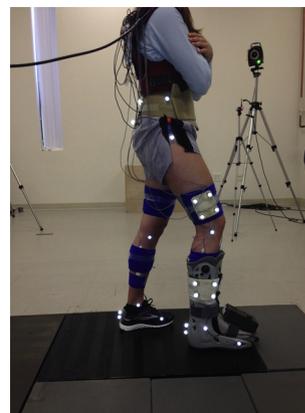


Fig. 1. Marker set utilized for motion capture and walking boot.

the 3 trials from each condition that narrowed the overall range in walking speeds within participant were selected for data analysis. The three selected trials for each condition were averaged. Crutches, while commonly used in the very early stages post-injury, were not used in the context of this study. This was partially to avoid complicating the analysis with variability of crutch use and partially due to patients being recommended to walk without crutches prior to discontinuing immobilization (typically by 4 weeks post-injury) [6,15].

### 2.3. Electromyography

During the pre- and post-assessments, wired, double differential, surface electrodes (Motion Lab Systems) were placed on the medial gastrocnemius, lateral gastrocnemius, and soleus of both legs per SENIAM guidelines [16]. Before placement, the skin was shaved and abraded with an alcohol wipe. Electrodes were removed after the pre-assessment and replaced for the post-assessment due to concerns about electrode shifting or sweating during the free-living period. During both assessments, participants performed an MVC for the plantar flexors by performing a standing, bilateral heel-rise against maximum, manual resistance provided at the shoulders. EMG was collected at a sampling rate of 1080 Hz.

### 2.4. Instrumented walking boot

Participants wore a novel instrumented orthopedic boot throughout the study. A traditional orthopaedic boot (Aircast™ AirSelect) was outfitted with two thin film carbon nanotube sensors that were placed approximately at the rearfoot and forefoot. The data acquisition unit and wires were housed in a lightweight casing positioned on the walking boot. For analysis of the free-living period, data was processed in a custom Matlab code to yield time spent walking.

### 2.5. Signal post-processing

All motion capture and EMG post-processing was performed using automated scripts in Visual 3D software (C-Motion, MD). To account for the walking boot, the right ankle was considered a fixed joint. Peak vertical ground reaction force and gait speed were assessed, and inverse dynamics were used to estimate knee extension power during stance phase.

Raw EMG signals were passed through a 4<sup>th</sup>-order, bandpass Butterworth filter with cutoff frequencies of 30 Hz and 350 Hz to remove noise. The signal was rectified and smoothed with a 100 ms root mean square filter and then normalized to the participants' peak MVC. Peak EMG and integrated EMG (iEMG) during stance phase were used for analysis.

### 2.6. Statistical analysis

Descriptive statistics are reported as means and standard deviations (SD). Repeated measures analysis of variance (ANOVA) was used to analyze change in peak and integrated EMG as well as gait mechanics (gait speed, vertical ground reaction force, and knee power) across wedge conditions. When there was a statistically significant effect of wedging, pairwise comparisons were used to compare individual wedge conditions. Because all analyses were within-subject comparisons, vertical ground reaction force was not normalized to body weight.

Paired t-tests were used to assess for changes in gait mechanics and muscle activity from pre- to post-assessment as a measure of accommodation. The coefficient of variation was calculated and Levene's test for homogeneity of means was used to assess whether the amount of variance decreased following an accommodation period.

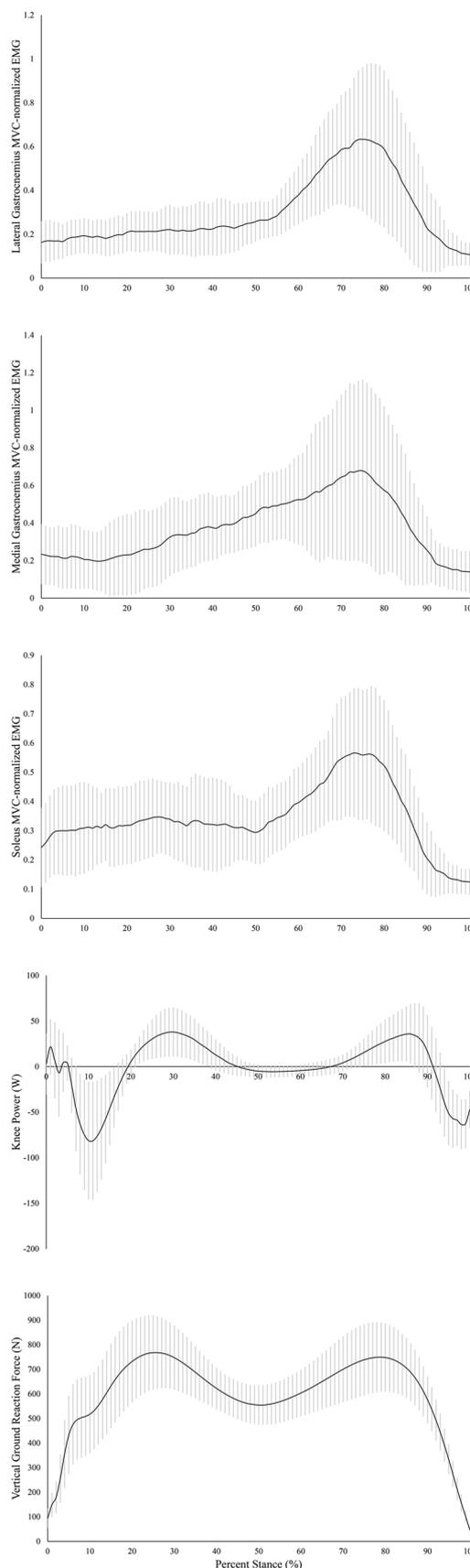


Fig. 2. Ensemble curves of variables of interest.

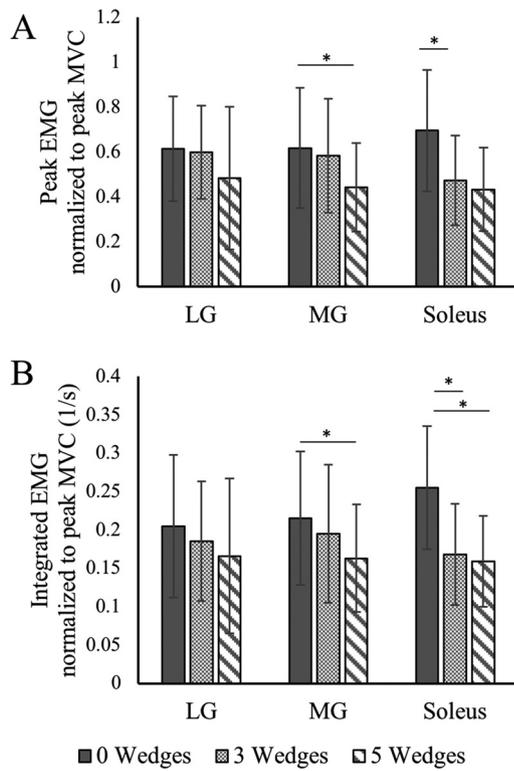


Fig. 3. Change in muscle activity with wedge height. \* Indicates significant pairwise comparison ( $p < 0.05$ ).

### 3. Results

#### 3.1. Effect of wedge height on triceps surae activity and gait mechanics

Ensemble curves for the variables of interest in the 0 wedge condition are shown in Fig. 2. Peak EMG in the medial gastrocnemius ( $p = 0.001$ ,  $\eta_p^2 = 0.463$ ) and soleus ( $p = 0.010$ ,  $\eta_p^2 = 0.342$ ) significantly decreased with increasing number of wedges (Fig. 3). Peak EMG also decreased in the lateral gastrocnemius, but this change was not significant ( $p = 0.151$ ,  $\eta_p^2 = 0.171$ ). Analysis of iEMG showed similar results, as iEMG in the medial gastrocnemius ( $p < 0.001$ ,  $\eta_p^2 = 0.506$ ) and in the soleus ( $p < 0.001$ ,  $\eta_p^2 = 0.518$ ) significantly decreased with increased wedging (Fig. 3). Lateral gastrocnemius iEMG decreased with increased wedging, but this was not significant ( $p = 0.077$ ,  $\eta_p^2 = 0.207$ ).

Analysis of gait mechanics showed decreasing vertical ground reaction force with increasing number of wedges ( $p = 0.019$ ,  $\eta_p^2 = 0.301$ ) (Table 1). With increased number of wedges, peak knee

**Table 1**  
Effect of Wedging on Gait Biomechanics.

	Wedge Condition			p-value	Partial $\eta^2$
	0 wedges	3 wedges	5 wedges		
Peak vGRF (N)	808(149)	794(135)	774(125)	<b>0.019</b> ‡	0.301
Peak Knee Extension Power (W)	69.7(26.3)	92.4(35.6)	101.3(45.5)	<b>0.003</b> *‡	0.410
Self-Selected Walking Speed (m/s)	1.20(0.24)	1.18(0.25)	1.17(0.25)	0.450	0.070

Bolding indicates  $p < 0.05$  for main effect of wedging. \*indicates significant ( $p < 0.05$ ) pairwise comparison between 0 and 3 wedges, ‡ indicates significant ( $p < 0.05$ ) pairwise comparison between 0 and 5 wedges. vGRF = vertical ground reaction force.

**Table 2**  
Pre- to Post-assessment Change Within Limb.

Variable of Interest	Pre-assessment	Post-assessment	P-value
Peak EMG			
Medial Gastrocnemius	0.443(0.200)	0.491(0.173)	0.300
Lateral Gastrocnemius	0.484(0.271)	0.435(0.256)	0.321
Soleus	0.434(0.186)	0.365(0.165)	0.370
Integrated EMG			
Medial Gastrocnemius ( $s^{-1}$ )	0.163(0.066)	0.175(0.061)	0.487
Lateral Gastrocnemius ( $s^{-1}$ )	0.166(0.080)	0.154(0.084)	0.433
Soleus ( $s^{-1}$ )	0.159(0.059)	0.144(0.073)	0.592
Gait Mechanics			
Peak vGRF (N)	774(125)	763(124)	0.349
Gait Speed (m/s)	1.16(0.25)	1.19(0.25)	0.356
Peak Knee Extension Power (W)	101.3(45.5)	89.1(49.3)	0.267

vGRF = vertical ground reaction force.

extension power significantly increased ( $p = 0.003$ ,  $\eta_p^2 = 0.410$ ). (Note that peak knee extension power included the entire stance phase and was not consistently at the impact or propulsion phase.) There were no statistically significant differences in gait speed with increasing number of wedges ( $p = 0.450$ ,  $\eta_p^2 = 0.070$ ).

#### 3.2. Accommodations to use of orthopaedic boot with wedging

Participants walked for a mean(SD) of 7(5) minutes (range: 3–17 minutes) during the one hour free-living period. There were no differences in peak EMG or iEMG in any muscle between pre- and post-assessment. There were also no differences in peak vertical ground reaction force, gait speed, or knee extension power between pre- and post-assessments (Table 2). There was no change in group variability pre- to post-assessment in peak EMG, iEMG, vertical ground reaction force, gait speed, or knee extension power (Table 3).

### 4. Discussion

This is the first study to identify differences in the patterns of muscle activation with increasing number of wedges. Both soleus and medial gastrocnemius activity decreases with the introduction of wedges in an orthopaedic walking boot. However, it seems that soleus activity decreases substantially with moderate amounts of wedging with no further decrease in muscle activity with additional wedging. The medial gastrocnemius, on the other hand, progressively decreases with increasing numbers of wedges. From a gait mechanics standpoint, despite the tendency to off-load the booted limb, knee extension power increased with the addition of wedges. It seems that there are a combination of factors that yield decreased triceps surae activity in

**Table 3**  
Results of Group-Level Coefficient of Variance (COV) Testing Pre- to Post-assessment.

Variable of Interest	Pre-assessment COV	Post-assessment COV	P-value
Peak EMG			
Medial Gastrocnemius	45%	35%	0.506
Lateral Gastrocnemius	56%	59%	0.795
Soleus	45%	45%	0.797
Integrated EMG			
Medial Gastrocnemius ( $s^{-1}$ )	40%	35%	0.733
Lateral Gastrocnemius ( $s^{-1}$ )	48%	55%	0.860
Soleus ( $s^{-1}$ )	37%	51%	0.804
Gait Mechanics			
Peak vGRF (N)	21%	21%	0.734
Gait Speed (m/s)	16%	16%	0.972
Peak Knee Extension Power (W)	45%	55%	0.835

vGRF = vertical ground reaction force.

individuals wearing an orthopaedic boot with wedges – decreasing loading on the immobilized limb, shifting power generation proximally, and putting the musculotendinous unit in a shortened/slack position. Additionally, it seems that individuals modify walking strategy very quickly when using the orthopaedic boot and limited changes are observed with additional time to accommodate.

How and when to optimally wean a patient from wedging and immobilization is debated. Theoretically, it seems there should be a balance between trying to prevent damage to the tendon (such as re-rupture or elongation) and providing the tensile forces needed to promote healing of the musculotendinous unit. A common approach to weaning from an orthopaedic boot after Achilles tendon rupture is to progressively decrease the number of wedges before discontinuing the boot entirely. Taken together with the findings of this study, it may be that during this weaning process, the gastrocnemii are progressively activated whereas the soleus may not be recruited during gait until all wedges have been removed. This may partially explain why the soleus is more prone to signs of chronic atrophy, including fatty infiltration of the muscle belly [10]. Clinically, it may be that additional care should be taken to specifically target and progressively load the triceps surae muscles and Achilles tendon early in recovery and while weaning from the walking boot. Loading the soleus throughout the time that an individual is using any amount of wedging may be particularly important given the tendency for this muscle to be inactive [10].

Contrary to the findings reported by Sandberg et al. [12], we did not observe any accommodation in gait mechanics or muscle activity with a free-living period. This is likely because there are large changes in walking gait that happen immediately upon modifying the boot, and any changes with additional time to accommodate to its use are more subtle. This could also be because our participants did not spend an adequate amount of time walking during that period despite participants being provided the same amount of acclimation time as reported in the Sandberg et al. study. Motor learning studies investigating the time for healthy populations to acclimate to forced alteration of gait – such as split belt treadmill walking – have required 5–10 minutes of continuous walking before gait variability decreases [17,18]. An average of 7 min of discontinuous walking may not be long enough to show accommodation.

While these findings are seemingly unsurprising in hindsight, they were counter to our original hypothesis. We anticipated that participants would walk more than 7 min on average and that they would converge on an “optimized” walking strategy. What we observed, however, was that even in the context of participating in a study where they knew their step counts would be monitored, people opted not to walk very much, potentially due to discomfort from the boot. We observed large variability between individuals, particularly with regard to muscle activity, and the group as a whole did not converge towards a single gait strategy by the post-assessment. This is clinically interesting and may explain high variability in early patient outcomes after Achilles tendon rupture [6,19]. In addition to factors such as initial treatment and rehabilitation, the unique strategy an individual takes when walking in a walking boot and amount of walking an individual chooses to perform may be factors to consider when devising rehabilitation and patient education protocols.

#### 4.1. Study limitations

There are several limitations to this study. This study investigated changes in muscle recruitment and gait mechanics using an unhinged boot, and the findings of this study should not be generalized to a hinged orthosis. Because markers were placed on the boot and the participants’ ankles were not visualized, subtle movements in the ankle occurring within the boot were not accounted for in the model and could increase the observed knee power. Additionally, this study investigated individuals without Achilles tendon rupture. While pain is not usually a limiting factor in this patient population, factors such as

muscle inhibition from swelling or other causes may alter findings in a patient population. Finally, participants did complain of discomfort at the area of the 5<sup>th</sup> metatarsal head and under the heel, which some participants reported limited the amount of walking performed during the free-living period. Despite these limitations, we did find immediate alterations in gait strategy in individuals who should show less propensity toward off-loading as they have not sustained an injury. These changes in biomechanics and muscle activation are consistent with what is observed in the long-term in individuals with Achilles tendon rupture.

## 5. Conclusions

Triceps surae activity decreases and changes in gait mechanics are observed when walking in an orthopaedic boot with increasing number of wedges. Individuals seem to adapt their walking strategy very quickly with changes in wedging but do not converge on an optimal walking strategy when allowed time to acclimate. The effect of number of wedges on muscle activity differs between muscles, which may be important to consider in the context of rehabilitating individuals after Achilles tendon rupture. These findings suggest that further investigation into the effect of immobilization strategy early after Achilles rupture (i.e. hinged versus unhinged orthoses, wedging inside versus outside of the orthopaedic boot, customization of the walking boot) is warranted to identify a more optimal immobilization strategy that balances tendon protection with normalizing muscle activity and gait mechanics for the prevention of long-term dysfunction.

### Author statement

Zellers: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration

Tucker: Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing

Higginson: Software, Validation, Writing – review & editing, Supervision

Manal: Software, Validation, Writing – review & editing

Grävare Silbernagel: Conceptualization, Writing – review & editing, Supervision, Funding acquisition

### Conflict of interest statement

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