Original article

Alterations in neuromuscular activation patterns associated with walking in short-leg walking boots

Douglas Powell a, Kurt Clowers b, Maria Keefer c, Songning Zhang d,*

a Neuromuscular Biomechanics Laboratory, Fairmont State University, Fairmont, WV, USA
b Anthropometry and Biomechanics Facility, NASA Johnson Space Center, Houston, TX, USA
c University of Texas Health Science Center, Houston, TX, USA
d Biomechanics/Sports Medicine Laboratory, The University of Tennessee, Knoxville, TN, USA

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Abstract

Background: Short-leg walking boots are a common intervention for acute and chronic lower extremity injury. Few studies have examined the neuromuscular adaptations associated with short-leg walking boots and no previous study has investigated timing characteristics of muscle activation during gait. The purpose of the current study was to examine the timing and amplitudes of muscle activation of the extrinsic ankle musculature during walking in two types of short-leg walking boots.

Methods: Eleven healthy young adults performed five level walking trials at a self-selected pace in each of three conditions: normal walking, Gait Walker and Equalizer short-leg walking boots. Ground reaction forces were collected from a force platform while surface electromyography (EMG) was collected from the tibialis anterior, peroneus longus and medial gastrocnemius. EMG signals were rectified and smoothed using the root mean squared with a 20-ms smoothing window and were normalized to the largest mean of the normal walking trials. A repeated measures analysis of variance was used to assess the effect of short-leg walking boots on the onset, duration and amplitude of muscle activation.

Results: Short-leg walking boots were generally associated with earlier onsets of muscle activation and longer durations of muscle activation. However, there was no reduction in EMG amplitude.

Conclusion: The findings of this study show that the induced alterations in muscle activation patterns may limit the short-leg walking boots.

Keywords: Electromyography; Gait; Short-leg walker; Walking; Walking boot

1. Introduction

Short-leg walking boots have become a popular alternative to traditional casting techniques for the treatment of acute injuries to the ankle and foot as well as post-surgical immobilization.1–4 Walking boots have many advantages over their fiberglass cast counterparts including the cost of use, ease of removal for cleaning, and have fewer mal-effects on gait patterns.3,4 A common use of short-leg walking boots is in the diabetic population. Specifically, individuals with a diabetic neuropathy often incur abrasive injuries to the foot which go unnoticed leading to diabetic ulcerations which often result in amputation of the digit or flesh. Short-leg walking boots have been shown to reduce plantar pressures and therefore decrease the risk of diabetic ulcerations.5–9 In addition to having advantageous plantar pressure profiles in comparison to traditional casting, short-leg walking boots have been suggested to have fewer mal-effects on kinematic, kinetics and ground reaction force patterns during gait.2–4 Previous
research has revealed that multi-joint mechanical adaptations occur during gait in a short-leg walking boot. Specifically, short-leg walking boots have been associated with smaller peak ankle eversion angles, greater ankle eversion ranges of motion, greater peak ankle plantarflexor moments, smaller peak ankle dorsiflexor moments and greater ankle inversion moments compared to normal walking. These data call into question the efficacy of short-leg walking boots in reducing motions and forces acting at the foot and ankle.

In addition to altering joint kinematics and kinetics, short-leg walking boots have been shown to alter neuromuscular activation patterns during gait. Short-leg walking boots are often prescribed to immobilize the ankle joint and to reduce muscle activity in the extrinsic musculature crossing the ankle and subtalar joints. Previous research has suggested that total contact casts and short-leg walking boots both reduce the intensity of gastrocnemius muscle activation, but that short-leg walking boots were more effective in reducing muscle activation of the gastrocnemius compared to the total contact cast. Decreases in gastrocnemius muscle activation intensity observed by Kadel et al. are not congruent with increases in plantarflexor moments observed in previous research studies investigating gait mechanics in short-leg walking boots. It has been suggested that adding a load to the distal end of a segment alters the neuromuscular activation patterns controlling that limb including both muscle activation intensity and the timing of muscle activation. Though Kadel et al. compared changes in the intensity of muscle activation in response to two methods of ankle immobilization, changes in the timing of muscle activation were not reported. Further, the quantification of muscle activation amplitude was conducted using integrated electromyography (EMG), a measure which is sensitive to changes in signal duration. Thus, a limitation of the study by Kadel et al. is that temporal data pertaining to the onset and cessation of muscle activation in response to the short-leg walking boot were not reported.

Therefore, the purpose of the current study was to examine changes in the timing and amplitudes of muscle activation of the extrinsic ankle musculature when walking in two different types of short-leg walking boots. Due to previous research findings, it was hypothesized that short-leg walking boots would be associated with (1) earlier onsets of muscle activation, (2) longer durations of muscle activation, and (3) smaller amplitudes of muscle activation when compared to normal walking.

2. Materials and methods

2.1. Participant information

Eleven healthy subjects (6 males; 5 females) participated in the current study (age: 27.4 ± 7.8 years; mass: 72.0 ± 13.4 kg; height: 1.76 ± 0.08 m). All participants were free of lower extremity injury at the time of testing and had no history of major lower extremity injury or neurological disorder. All participants signed an informed consent statement approved by the Institutional Review Board prior to participating in the study.

2.2. Experimental protocol

Each participant performed five level walking trials across a 10-m walkway in each condition (Fig. 1): normal shoes, Gait Walker short-leg walker (DeRoyal Industries, Inc., Powell, TN, USA) and Equalizer short-leg walker (Royce Medical Co., Camarillo, CA, USA). Preferred walking speed was determined using a pair of photocells (1000 Hz, 63501 IR, Lafayette Instrument Inc., Lafayette, IN, USA) from three walking trials at a self-selected speed in a randomly selected walker. Photocells were placed 1.5 m before and after the force platform and were approximately shoulder height. Walking speed was monitored and maintained within 10% of the self-selected speed during the data collection. The walker conditions were randomized and followed by the lab shoe condition.

An EMG system (600 Hz, Noraxon USA, Inc., Scottsdale, AZ, USA) and force platform (1200 Hz, American Mechanical Technology Inc., Watertown, MA, USA) were used to simultaneously collect surface EMG (sEMG) and ground reaction forces from the right limb during walking trials. Surface electrodes were placed over the muscle belly of the m. Tibialis Anterior (TA), m. Peroneus Longus (PL) and medial head of the m. Medial Gastrocnemius (MG). The skin beneath the electrodes was shaved, cleansed and abraded to minimize skin resistance. Force platform data were used to determine heel strike and toe off of stance phase. Ground reaction force and joint kinematic and kinetic data were reported elsewhere.

2.3. Data analysis

EMG signals were rectified first and then smoothed using a root mean squared method with a 20-ms moving window.

Fig. 1. The Gait Walker (A) and Equalizer (B) short-leg walking boots used in the current study.
For each muscle, onset of muscle activation was defined as a rise in the EMG signal amplitude greater than the baseline plus two standard deviations during quiet standing, lasting longer than 50 ms. Offset of muscle activation was defined as the decrease in EMG signal amplitude below the baseline plus two standard deviations lasting longer than 50 ms. Onsets were temporally normalized to the duration of the stance phase starting from heel strike (Eq. (1)). Therefore, the onset of muscle activation prior to heel strike is represented as a negative percent. Duration of muscle activity was calculated as the difference between onset and offset of muscle activity and was normalized to the duration of the stance phase (Eq. (2)). M. TA activation onsets and durations were calculated for the load response (TA-LR) and pre-swing (TA-PS) portions of the stance phase. Mean EMG (mEMG) was calculated across the entirety of the stance phase and normalized to the maximum value during normal walking.

Relative onset = \( \frac{t_{EMG_{Onset}} - Time_{HS}}{Time_{TO} - Time_{HS}} \)  
Relative duration = \( \frac{t_{EMG_{Offset}} - t_{EMG_{Onset}}}{Time_{TO} - Time_{HS}} \)

where \( t_{EMG_{Onset}} \) denotes time of EMG onset, \( t_{EMG_{Offset}} \) denotes time of EMG offset, \( Time_{HS} \) denotes time at heel strike, and \( Time_{TO} \) denotes time of toe off.

2.4. Statistical analysis

A two-factor (3 × 3, muscle × condition) repeated measures analysis of variance (ANOVA) was used to compare the effects of short-leg walking boots on the onset and duration of muscle activation as well as the mEMG of the TA, PL and MG. In the presence of a muscle by condition interaction, a post-hoc test was conducted using \( t \) tests. For all statistical tests, differences were considered significant when \( p < 0.05 \). A Bonferroni adjustment was used to correct the alpha level for multiple post-hoc comparisons. The statistical analysis was conducted using SPSS 18.0 (SPSS Inc., Chicago, IL, USA).

3. Results

Fig. 2 shows representative EMG signals and vertical ground reaction forces during normal walking (A) and when walking in the Gait Walker short-leg walking boot (B). Level walking trials were performed at 1.24 ± 0.18 m/s (mean ± SD) and were maintained across conditions.
3.1. Onset of muscle activation

Short-leg walking boots were associated with an earlier onset of muscle activation compared to normal walking (Table 1). Around heel strike, the TA muscle activation was not significantly different in the Gait Walker ($F = 2.599$, $p = 0.135$) or Equalizer conditions ($F = 3.032$, $p = 0.219$) compared to normal walking (Table 1). No differences were observed between the Gait Walker and Equalizer conditions ($F = 2.570$, $p = 0.101$). The PL muscle had significantly earlier activation in the Gait Walker condition than the normal walking condition ($F = 10.89$, $p = 0.001$); however, no differences were observed between the normal walking and Equalizer conditions ($F = 0.362$, $p = 1.000$). The Gait Walker condition was also associated with a significantly earlier PL activation than the Equalizer condition ($F = 4.621$, $p = 0.031$). Earlier onset of MG activation was observed in the Gait Walker ($F = 28.806$, $p = 0.001$) and Equalizer conditions ($F = 5.493$, $p = 0.006$) compared to the normal walking condition. No difference in onset of MG activation was observed between the Gait Walker and Equalizer conditions ($F = 2.599$, $p = 0.174$). In push-off, the onset of TA activation was not significantly different between the normal walking and Gait Walker conditions ($F = 2.984$, $p = 0.109$); however, the Equalizer condition was associated with significantly earlier onset of muscle activation than the normal walking condition ($F = 10.654$, $p = 0.006$).

3.2. Duration of muscle activation

Short-leg walking boots were generally associated with increases in the duration of muscle activation (Table 2). During load response, the TA was activated for a longer duration in the Gait Walker ($F = 15.465$, $p = 0.004$) and Equalizer ($F = 10.865$, $p = 0.005$) conditions than in the normal walking condition (Table 2). The durations of TA muscle activation between Gait Walker and Equalizer conditions were not different ($F = 0.093$, $p = 0.083$). The Gait Walker condition was associated with significantly longer PL activation than the normal walking condition ($F = 19.396$, $p = 0.001$); however, no differences were observed between the normal walking and Equalizer conditions ($F = 0.214$, $p = 1.000$). Furthermore, the Gait Walker condition had significantly longer durations of PL activation than the Equalizer condition ($F = 15.795$, $p = 0.002$). Both the Gait Walker ($F = 32.505$, $p = 0.001$) and Equalizer ($F = 24.958$, $p = 0.002$) conditions had longer durations of MG activity than the normal walking condition. The Gait Walker and Equalizer conditions did not have significantly different durations of MG activation ($F = 0.532$, $p = 0.606$). During push-off, TA activation was significantly longer in both Gait Walker ($F = 13.077$, $p = 0.003$) and Equalizer ($F = 39.266$, $p = 0.001$) than the normal walking condition (Table 2). There were no differences in TA activation between the Gait Walker and Equalizer conditions during the pre-swing phase of gait ($F = 0.142$, $p = 1.000$).

3.3. Activation intensity

Generally, mEMG values during stance were not changed when subjects performed level walking while wearing a short-leg walking boot compared to normal walking (Table 3). Specifically, there was no condition effect of the short-leg walking boots on mEMG values of the TA ($F = 0.026$, $p = 0.975$), PL ($F = 1.195$, $p = 0.351$) or MG ($F = 3.093$, $p = 0.101$).

### Table 1

<table>
<thead>
<tr>
<th>Condition</th>
<th>TA-LR (% Stance)</th>
<th>PL (% Stance)</th>
<th>MG (% Stance)</th>
<th>TA-PS (% Stance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Walker</td>
<td>−6.43 ± 16.35</td>
<td>53.19 ± 6.54</td>
<td>47.83 ± 9.20</td>
<td>93.40 ± 1.85</td>
</tr>
<tr>
<td>Gait Walker</td>
<td>−12.53 ± 17.34</td>
<td>26.04 ± 9.84</td>
<td>22.57 ± 12.81</td>
<td>85.88 ± 10.67</td>
</tr>
<tr>
<td>Equalizer</td>
<td>−10.89 ± 17.33</td>
<td>48.34 ± 17.35</td>
<td>28.26 ± 22.32</td>
<td>85.75 ± 5.93</td>
</tr>
</tbody>
</table>

Note: Negative values represent muscle activation onset prior to heel strike.

Abbreviations: TA-LR = m. Tibialis Anterior around heel strike; PL = m. Peroneus Longus; MG = m. Medial Gastrocnemius; TA-PS = m. Tibialis Anterior around toe off.

a Significantly different from No Walker (normal walking).
b Significantly different from Gait Walker.

### Table 2

The duration of muscle activity of the TA, PL, and MG expressed as a percent of the stance phase (mean ± SD). Duration of the TA was calculated during the load response (TA-LR) and pre-swing (TA-PS) portions of the stance phase.

<table>
<thead>
<tr>
<th>Condition</th>
<th>TA-LR (%)</th>
<th>PL (%)</th>
<th>MG (%)</th>
<th>TA-PS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Walker</td>
<td>26.7 ± 5.7</td>
<td>28.9 ± 6.8</td>
<td>29.5 ± 13.5</td>
<td>31.6 ± 6.1</td>
</tr>
<tr>
<td>Gait Walker</td>
<td>54.3 ± 5.5a</td>
<td>48.8 ± 9.2a</td>
<td>56.7 ± 16.2a</td>
<td>45.5 ± 7.2b</td>
</tr>
<tr>
<td>Equalizer</td>
<td>48.1 ± 5.5a</td>
<td>30.1 ± 3.2b</td>
<td>42.3 ± 9.2a</td>
<td>44.9 ± 5.1b</td>
</tr>
</tbody>
</table>

Abbreviations: TA-LR = m. Tibialis Anterior around heel strike; PL = m. Peroneus Longus; MG = m. Medial Gastrocnemius; TA-PS = m. Tibialis Anterior around toe off.

a Significantly different from No Walker (normal walking).
b Significantly different from Gait Walker.
comparing with the lab shoe condition in all muscles. Short-leg walking boots were associated with an earlier onset of all muscles. However, there were no consistent differences between the two short-leg walker conditions. These data lead to the rejection of the first hypothesis that no differences in onset of muscle activation would exist between the lab shoe condition and the two walker conditions. Only a single study has previously examined muscle activation in short-leg walkers, however timing of muscle activation was not investigated. Previous researches have investigated the neuromuscular adaptations associated with added load applied to the ankle and wrist. These research studies, however, examined neuromuscular activation patterns associated with controlling the motion of a limb in space. The current study investigated muscle activation patterns in ankle musculature when the joint was acutely immobilized via the short-leg walking boots. Earlier onset of muscle activation in the ankle musculature may be a result of resistance to the normal motion of the ankle prior to and during the stance phase of the gait cycle as a result of resisted motion by the short-leg walking boots. It has been shown that a method of responding to increased resistance to motion results in earlier activation of musculature responsible for that motion in healthy young adults.

The current data also show that the extrinsic ankle musculature was generally activated for a longer period of time when subjects walked with the short-leg walking boots. Though several research studies have investigated the changes in the amplitude of muscle activation, no previous study has presented the duration of activation of extrinsic ankle musculature. Thus, these findings are novel and may provide insight into the mechanism of function and the efficacy of short-leg walking boots. Clinically, a longer duration of muscle activation may increase the duration of muscle tension applied to the injured musculoskeletal and ligamentous structures of the foot and ankle. Some advantages of short-leg walking boots over traditional cast include shorter periods required for immobilization and rehabilitation as well as ease of removal for examination and cleaning. A longer duration of muscle activation applied to the injured site during each gait cycle may seem to limit the efficacy of the short-leg walking boots in returning the individual to normal activity levels earlier than traditional casting. Conversely, the observed increase in the duration of muscle activity may be the result of an acute application of the short-leg walking boots which may be associated with the need to increase muscles’ response to the increased inertia in the walker conditions. The longer activations of the peroneus longus and gastrocnemius in the walker conditions support previous research data that reported increased plantarflexor moments found in these the short-leg walking boot conditions. Patients in the current study were given several minutes to adjust to gait in the short-leg walking boots prior to actual testing trials; however, neuromuscular adaptations to gait in the short-leg walking boot is likely to continue for a longer period of time than the duration of these data collections. Previous research has shown that the addition of an inertial load focused at the ankle results in longer periods of muscle activation in the lower extremity. It can be postulated that the observed changes in the duration of muscle activation are in response to the increased load and that these changes would be muted with greater time of adjustment, similar to that experienced by injured patients. It is, however, unclear if a patient with ankle or foot injury would respond similarly in the walker conditions.

Short-leg walking boots are a common treatment method for acute and chronic injuries to the lower extremity. Short-leg walkers have been demonstrated to have many advantages over traditional casting techniques as evidenced by previous research studies. One reported advantage of short-leg walkers is decreased muscle activation intensity. However, the findings of the current study exhibited no change in muscle activation intensity associated with the short-leg walking boots as previously reported. These contradictory findings may be the result of methodological differences between the current study and previous research. A variety of methods has been used to determine the intensity of muscle activity including mEMG, peak RMS EMG and integrated EMG. Kadel et al. reported muscle activation using integrated EMG signals compared to mEMG values used in the current study to report muscle activation intensity. Furthermore, the previous study normalized to the mEMG of the control condition compared to peak EMG of the control condition used in the current study. An investigation of methods used to quantify electromyography signals revealed that integrated and mEMG values are similar within a given data set; however a limitation of this study is that it examined only a single condition and did not investigate the effect of changes in the duration of muscle activity. Therefore, the use of these two methodologies may lead to different numerical results and thus the interpretation of EMG results requires caution. The findings of the current study suggest that the amplitude of muscle activation remains unchanged when subjects wore short-leg walking boots. The findings of the current study seemingly contradict previous research that demonstrated a decrease in EMG amplitude. A possible reason for these differences in research findings includes the acute nature of the observed adaptation. Though each subject was offered several minutes to acclimate to each short-leg walking boot condition and reported their comfort, a longer period of time may have been required to adapt to walking in the short-leg walking boots. Further, in motor learning increased variability is associated with skill acquisition or response to perturbation. It is likely that the increased variability

### Table 3

Mean EMG amplitude of the TA, PL, and MG calculated during the stance phase of gait and normalized to peak EMG value during the No Walker condition (mean ± SD).

<table>
<thead>
<tr>
<th>Condition</th>
<th>TA (% Max)</th>
<th>PL (% Max)</th>
<th>MG (% Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Walker</td>
<td>62 ± 22</td>
<td>61 ± 32</td>
<td>70 ± 23</td>
</tr>
<tr>
<td>Gait Walker</td>
<td>63 ± 27</td>
<td>60 ± 25</td>
<td>82 ± 13</td>
</tr>
<tr>
<td>Equalizer</td>
<td>61 ± 23</td>
<td>53 ± 18</td>
<td>73 ± 17</td>
</tr>
</tbody>
</table>

Abbreviations: EMG = electromyography; TA = m. Tibialis Anterior; PL = m. Peroneus Longus; MG = m. Medial Gastrocnemius.
associated with the perturbation created by the short-leg walking boot resulted in statistically non-significant findings.

A second possible reason that no differences were found between conditions in the current study pertains to the method of normalization. Though previous research has suggested that the normalization used in the current study is a robust normalization method that accounts for differences in levels of activation based on contraction type, it is plausible that normalization to a maximum voluntary isometric contraction would have produced statistically different EMG amplitudes in response to the short-leg walking boots.

The clinical significance of this study pertains to the application of short-leg walking boots as a treatment and rehabilitation tool. The current data suggest that acute adaptations to the short-leg walking boots result in greater volumes of loading to the structures of the foot and ankle due to muscle activation, which may limit the short-term efficacy of walking boots. Therefore, it is suggested that walking boots be used in the long term treatment of foot and ankle injuries. It is postulated that with longer exposure to the short-leg walking boots, motor control would be optimized and internal loading would be minimized in response to the added structural stability provided by the walking boots. However, the long term neuromuscular adaptations to short-leg walking boots have not been directly investigated.

In conclusion, short-leg walking boots are associated with adaptations in neuromuscular activation patterns of the extrinsic ankle musculature. Specifically, an earlier onset and longer durations of muscle activation are key acute responses to short-leg walking boots. However, the intensity of muscle activation was not reduced in the current study. These alterations in muscle activation patterns may limit the efficacy of the short-leg walking boots. Future research is warranted to examine long term neuromuscular adaptations to short-leg walking boots and to the biomechanical responses to imposed leg length discrepancies associated with short-leg walking boots.

Acknowledgments

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References