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The immediate effect of foot orthoses on gluteal and lower limb muscle activity during overground walking in healthy young adults

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ABSTRACT

Background: Although foot orthoses are often used in the management of lower limb musculoskeletal conditions, their effects on muscle activation is unclear, especially in more proximal segments of the lower limb.
Research question: Primary aim: Is there an immediate effect of foot orthoses on gluteal muscle activity during overground walking in healthy young adults? Secondary aim: Is there an immediate effect of foot orthoses on the activity of hamstring, quadriceps and calf muscles?
Methods: In eighteen healthy young adults, muscle activity was recorded using fine wire electrodes for gluteus minimus (GMin; anterior, posterior) and gluteus medius (GMed; anterior, middle, posterior); and surface electrodes for gluteus maximus (GMax), hamstring, quadriceps and calf muscles. Participants completed six walking trials for two conditions; shoe and shoe with prefabricated foot orthoses. Muscle activity was normalised to the peak activity of the shoe condition and analysed using one-dimensional statistical non-parametric mapping to identify differences across the gait cycle.
Results: Activity of GMed (anterior, middle, posterior) and GMin (posterior) was reduced in early stance phase when the orthosis was worn in the shoe ($p < 0.05$). GMin (anterior) activity was significantly reduced during swing ($p < 0.05$). Muscle activity was also significantly reduced during the orthoses condition for the lateral hamstrings and calf muscles ($p < 0.05$).
Significance: Using foot orthoses may provide a strategy to reduce demand on GMin, GMed, lateral hamstring and calf muscles while walking.

1. Introduction

Foot orthoses are in-shoe devices that are often used in the prevention [1] and management of lower limb pain and injury. There is strong evidence that prefabricated foot orthoses are effective in reducing pain for people with patellofemoral pain [2], and early, positive indications that they reduce pain in people with patellofemoral osteoarthritis [3]. Furthermore, there is moderate quality evidence that foot orthoses reduce pain in people with plantar heel pain [4], and improve pain in people with 1st metatarsophalangeal joint osteoarthritis [5]. Evidence for benefits of foot orthoses in people with hip pain is lacking [6]. This is despite evidence that more than one third of podiatrists in Australia, New Zealand and the United Kingdom prescribe foot orthoses for hip pain [7].

Understanding the mechanism by which foot orthoses exert an effect on lower limb function may help to generate hypotheses for conditions where there is therapeutic uncertainty. Foot orthoses can alter lower limb kinematics, kinetics, and neuromuscular function [8,9], which are thought to minimise tissue stress and symptoms [10]. In healthy, asymptomatic individuals, foot orthoses have been found to reduce tibialis posterior activity and increase peroneus longus activity during walking [11]. The immediate effect on other muscles of the calf, hamstring and thigh are variable, with reduced activity [(medial gastrocnemius [11], (lateral hamstring, vasti muscles [12]) or no

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difference being reported (calf, thigh and hamstring [13]). In those studies, muscle activity was summarised as activity during specific phases of the gait cycle, and may not be directly comparable between studies. Open source, analytical techniques such as statistical parametric mapping (SPM) are now more accessible, and can be used to compare activity at multiple time points across the entire gait cycle without the need to reduce walking data to the comparison of variables that reflect a few specific phases of the task [14]. The use of such techniques may clarify subtle differences in lower limb muscle activity of asymptomatic individuals, when walking with and without foot orthoses.

Few studies have investigated the immediate influence of foot orthoses on gluteal muscle activity. The available evidence suggests that there is no difference in gluteus medius (GMed) muscle activity recorded with surface electromyography (EMG) electrodes when walking with foot orthoses compared to no orthoses, regardless of whether people have lower limb symptoms [15,16] or not [13]. Recordings of GMed made with surface electrodes can be confounded by 'cross-talk' from the activity of surrounding muscle [17], which could mask any potential differences in muscle activity. Intramuscular electrodes reduce this limitation as they provide more localised recordings with less potential for 'cross-talk' from surrounding muscle [18]. No study has investigated the effect of foot orthoses on gluteus minimus (GMin) muscle activity, which can only be investigated using intramuscular electrodes based on its deep anatomical location [19], that is inaccessible with surface electrodes. Of note, GMin and GMed are composed structurally [20] and functionally [21,22] of unique muscle segments, which differ with respect to their potential to control coronal plane motion [23], and are uniquely affected with hip-related symptoms [24,25]. Understanding the effect of foot orthoses on each gluteal muscle segments is necessary and could inform clinical decision-making regarding foot orthoses prescription for people where these muscles are known to be sore, tired, fatigued or impaired, such as gluteal tendinopathy [24] or hip osteoarthritis [25].

The primary aim of this study was to investigate the immediate effect of foot orthoses on gluteal muscle activity (GMed, GMin, gluteus maximus [GMax]) during walking in healthy young adults. The secondary aim was to clarify evidence for the immediate effect of foot orthoses on major muscles of the thigh and calf using SPM. We hypothesised that foot orthoses would significantly reduce the pattern of muscle activity of hip (and more distal) muscles that have a major role in the coronal plane (GMed, GMin) during walking.

2. Methods

2.1. Participants

A convenience sample of eighteen healthy young individuals (10 males; mean (SD) age = 23 (2) years; height = 170 (13) cm; weight = 68 (16) kg, BMI = 24 (2) kg/m^2) were recruited for this cross-sectional study. Participants were eligible if they completed more than two hours of sweat-inducing activity per week. Participants were ineligible if they had any hip/lower limb injury requiring treatment or limitation of physical activity within the last six months, or a history of hip/lower limb surgery or congenital hip disease. Written informed consent was obtained from all eligible participants before the commencement of any testing. This study was approved by The University of Queensland's Human Research Ethics Committee (2004000654).

2.2. Foot measures

To characterise foot mobility, each participant was assessed using the protocol described by McPoil et al. [26]. In brief, foot anthropometric measures of dorsal arch height and midfoot width were recorded in weight bearing and non-weight bearing [26]. The change in dorsal arch height and midfoot width between non-weight bearing and weight bearing conditions was used to calculate the magnitude of vertical and mediolateral foot mobility, respectively.

2.3. Instrumentation and electrode insertion

All testing was performed on the stance dominant limb [27]. Bipolar stainless steel fine wire electrodes were inserted into two segments of GMin (anterior, posterior) and three segments of GMed (anterior, middle, posterior) using previously validated [19,28] and reliable methods [29]. Surface electrodes were placed over the muscle bellies of major thigh (medial and lateral hamstring, rectus femoris, vastus lateralis, vastus medialis), and calf (medial gastrocnemius, lateral gastrocnemius and soleus) muscles according to SENIAM recommendations [30]. Skin was shaved and cleansed with alcohol wipes. EMG was recorded using a Trigno™ wireless 16-Channel EMG system (Delsys® Inc., Boston, USA). A Kistler force plate was used to determine the heel contact and toe off during initial foot strike. A foot switch (Model: 402, Interlink Electronics, California, USA) attached to the plantar surface of the heel on the stance leg was used to determine the subsequent heel contact that was not recorded on the force plate. Retroreflective markers were placed on each heel (left and right leg) to compute stride length [31], stride time and walking speed. All data were collected using the Vicon system and Nexus software (v1.8.5, Vicon Motion Systems Ltd., UK). EMG (surface and fine-wire), force plate and foot switch data were sampled at 2000 Hz. Marker trajectory data were sampled at 100 Hz.

2.4. Experimental procedure

Each participant was fitted with a pair of regular Teva walking sandals (Men's hurricane XLT, Teva, Australia, Fig. 1). Participants walked for five minutes prior to testing to acclimatise to the experimental conditions. Gait trials were performed under two conditions: 1) shoe, and 2) shoe with prefabricated, full-length unmodified foot orthoses (Custom Red, Vasyli Medical, Labrador, Australia, Fig. 1). The foot orthoses had an inbuilt arch support and 6° varus wedge (company specifications), and were made of high density ethylene-vinyl acetate (Shore A 70°). For each condition, participants were instructed to walk 6 times along a 6 m track at comfortable walking speed [32]. Trials where the walking speed was $\pm$ 5% of their average speed were rejected and repeated. The foot orthoses condition always followed the shoe condition, as this is the typical sequence conducted clinically. The foot orthoses condition occurred approximately ten minutes after the completion of the non-orthotic condition.

2.5. EMG processing and statistical analysis

Electromyography data were processed using custom scripts in R (Version 3.3.2 http://www.R-project.org/) adapted from the BiosignalEMG package (v2.1.0). Data were visually inspected for artefact. After removing DC off-set, data from each stride were high-pass filtered (Butterworth, 4th order, 50 Hz for fine-wire or 20 Hz for surface, no phase lag), full-wave rectified, then smoothed with a low-pass filter (6 Hz, Butterworth, 4th order, no phase lag). All strides were time normalised to 101 points (% gait cycle). EMG amplitude was normalised to the peak activity recorded during the shoe condition (averaged over the 6 strides). Analysis was performed separately for each muscle segment.

To compare muscle activity between the two walking conditions (foot orthoses vs. shoe), permutation testing for paired data was performed using one-dimensional statistical non-parametric mapping (SnPM) [14,33], through open-source code (spm1d version M.0.4.3; http://www.spm1d.org) in Python 2.7 using Canopy 2.1.9 (Enthought Inc., Austin, USA). Briefly, the scalar output statistic (SnPM(t)) was plotted and used to represent the difference between foot orthoses and shoe condition EMG activity at each per cent of the gait cycle. A critical threshold (α = 0.05) was determined to identify the SnPM(t) level at which only 5% of these curves would be expected to exceed. Supra-threshold clusters were identified for portions of the curve that

Fig. 1. A) the sandal used for walking with and without foot orthoses (Men's hurricane XLT, Teva, Australia). B) Prefabricated, full-length unmodified foot orthotic (Custom Red, Vasyli Medical, Labrador, Australia). C) the foot orthotic in-situ within the sandal.

exceeded this critical threshold, and the probability of this occurring was determined. Ultimately, this analysis enabled point-by-point comparison of muscle activity across the whole gait cycle, between the foot orthoses and shoe conditions. All permutations were completed for each muscle, up to a maximum of 100,000 permutations. The maximum possible permutations was for GMed anterior, soleus and hamstrings ($n = 18$; 262,144 permutations). The magnitude of difference between the two walking conditions was calculated by dividing the *t*-statistic by the square root of the sample size. Effect sizes of 0.2, 0.5 and 0.8 were considered small, moderate and large, respectively [34].

3. Results

Electromyography data were available for analysis of 18 participants for GMed anterior, soleus, and medial and lateral hamstrings; 17 participants for GMin anterior, GMed middle and posterior, medial and lateral gastrocnemius; 16 participants for GMax and GMin posterior and vastus lateralis; 15 participants for vastus medialis; and 14 participants for rectus femoris. GMin posterior electrode insertions were abandoned for two participants due to discomfort, and EMG recordings from GMed middle and GMed posterior were contaminated by artifact for one participant each. In all cases of missing data from surface electromyography related to artefact.

Mean (SD) midfoot width mobility and arch height mobility for this cohort were 9.7 (2.8) mm and 12.0 (3.0) mm, respectively, which were consistent with normative data from a similar population [35]. There were no significant differences in walking speed or stride parameters between conditions (Table 1)

Figs. 2–4 present mean group data of gluteal, thigh and leg muscle activity across the gait cycle for shoe and foot orthoses conditions. Supplementary Table S1 summarises the relative percent change between walking conditions for each muscle within epochs that differed significantly between conditions.

3.1. Gluteal muscle EMG

GMax EMG amplitude did not differ between the two walking conditions. Anterior GMed EMG was significantly reduced during early stance (0–4 % Gait Cycle (GC), $p = 0.005$ ES = 0.86–1.00) and late swing (79–81 % GC, $p = 0.015$, ES = 0.71–0.82; and, 88–100 % GC, $p = 0.008$, ES = 0.74–1.06) when walking with foot orthoses. When wearing orthoses, middle GMed was significantly reduced during stance (5–18 % GC, $p < 0.001$, ES = 0.69–1.80 and; 27–33 % GC, $p = 0.006$, ES = 0.74–0.95) and late swing (95–100 % GC, $p = 0.005$, ES = 0.75–0.99). Posterior GMed EMG was also reduced during early stance (7–13 % GC, $p = 0.009$, ES = 0.76–0.87) and late swing (96–100 % GC, $p = 0.005$, ES = 0.77–1.05). Anterior GMin EMG was significantly reduced when wearing orthoses during swing (80–82% GC, $p = 0.016$, ES = 0.79–0.84), but not during stance. In contrast, posterior GMin EMG was significantly lower when wearing orthoses during stance (8–17 % GC, $p = 0.003$, ES = 0.79–1.01), but not swing.

Table 1
Walking speed and stride parameters for each condition.

	Speed (m/s)	Stride time (s)	Stride length (m)	Toe-Off (% GC)
Shoe	1.20 (0.12)	1.13 (0.09)	1.35 (0.13)	61.8 (1.7)
Foot orthoses	1.22 (0.13)	1.13 (0.09)	1.37 (0.12)	61.6 (1.6)
P-Value	0.491	0.655	0.248	0.483

3.2. Thigh muscle EMG

During early stance (4–7 % GC), lateral hamstring EMG was significantly reduced when walking with foot orthoses ($p = 0.010$, ES = 0.77–0.86). There was no difference in EMG of the medial hamstrings or any of the quadriceps muscles between conditions.

3.3. Lower leg muscle EMG

During stance, EMG of both medial (19–25 % GC, $p < 0.001$, ES = 0.84–1.38) and lateral gastrocnemius (5–9 % GC, $p = 0.008$, ES = 0.84–0.95) was reduced during stance when wearing foot orthoses. When walking with orthoses, there was a brief but significant decrease in soleus EMG in early swing (63–64 %, $p = 0.019$, ES = 0.82–0.83).

4. Discussion

The aim of this study was to investigate the effect of foot orthoses on the pattern of gluteal and other lower extremity muscle activity during walking. The results support the hypothesis that foot orthoses could reduce activity of the GMed and GMin muscles. The magnitude of reduction ranged from 28 to 43 % relative to the peak activity recorded when walking without the orthoses. This was present both when the foot was loaded in stance and unloaded in swing. Lateral hamstrings, gastrocnemius and soleus muscle activity was also reduced.

Walking with the prefabricated foot orthoses had the greatest impact on GMed and GMin muscle activity. The magnitude of reduction was particularly large for the middle portion of GMed (43 % lower relative to peak amplitude in the shoe condition, ES = 1.80). This is a novel finding since no other studies have investigated the immediate effect of foot orthoses on GMed or GMin in asymptomatic individuals during walking. It also is in contrast to studies that have reported no difference in GMed activity during walking gait from baseline to follow-up after a period of 4 weeks of customised [13] or prefabricated orthotics [36] use in asymptomatic individuals. The differences between studies may be related to the methods employed to assess muscle activity, the method of analysis used and the time difference between conditions. Fine wire electrodes as used in our study are less prone to cross talk from surrounding muscles [17]; and we also compared between conditions using SnPM. This may have provided more sensitive technical and analytical techniques to identify differences between conditions. Measuring

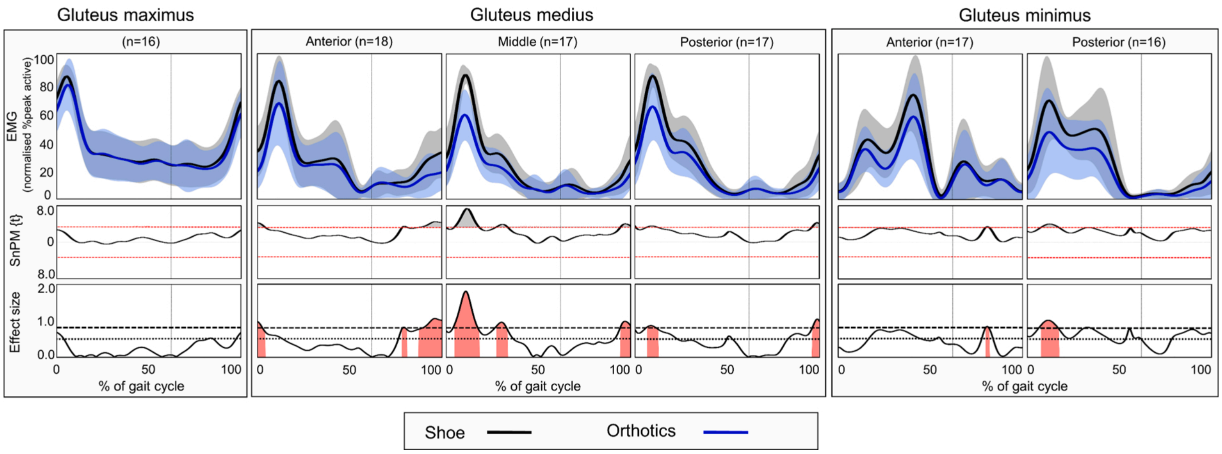

Fig. 2. Group average hip muscle electromyography (EMG) across the gait cycle (%).The top panel, shows the grand ensemble of muscle activity when walking with foot orthoses (blue) and without (black). The thick line indicates the mean and the shaded areas the standard deviation for each group. The dotted vertical lines represent toe-off. The middle panel, shows the SnPM (t-statistic) vs. percentage of the gait cycle. The red dashed line represents the critical threshold (t). The bottom panel, shows the effect size vs. percentage of the gait cycle, describing the magnitude of the effect. The black horizontal dotted lines represent the thresholds for a medium effect size (0.5) and the dashed line for a large effect size (0.8). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

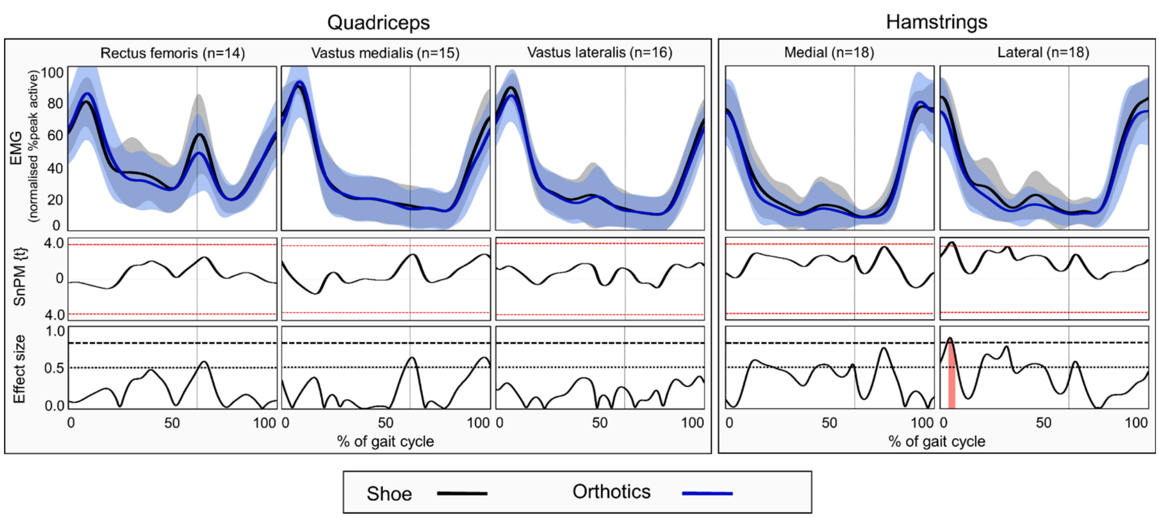

Fig. 3. Group average thigh muscle electromyography (EMG) across the gait cycle (%).The top panel, shows the grand ensemble of muscle activity when walking with foot orthoses (blue) and without (black). The thick line indicates the mean and the shaded areas the standard deviation for each group. The dotted vertical lines represent toe-off. The middle panel, shows the SnPM (t-statistic) vs. percentage of the gait cycle. The red dashed line represents the critical threshold (t). The bottom panel, shows the effect size vs. percentage of the gait cycle, describing the magnitude of the effect. The black horizontal dotted lines represent the thresholds for a medium effect size (0.5) and the dashed line for a large effect size (0.8). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

change in activity after four weeks of use may also incorporate some aspect of muscle adaptation which nullifies any immediate effects of foot orthoses.

The large effect of orthoses on GMed muscle activity can potentially be explained by a facilitation of neuromuscular control. It is unlikely to be a result of the dynamic coupling of motion between the foot and hip joints [37,38], as significant biomechanical effects of foot orthoses at the hip have not been found [39,40]. An alternative explanation is that the foot orthoses facilitate neuromuscular control of the lower limb. Medial arch support has been proposed to enhance plantar cutaneous sensation and somatosensory feedback [41]. Whether this affects gluteal muscle activity is not clear. Further work investigating a dose response of orthoses with varying degrees of arch support on hip joint kinematics and kinetics, and the relationship with muscle activity during walking, may help to clarify these mechanisms.

Walking with foot orthoses reduced the activity of all GMed segments during terminal swing. This has two possible explanations. First, GMed activity at terminal swing might be reduced simply because of the lower demand on the muscle during stance. Second, it might relate to the known modulation of hip muscle activity of the swing limb by the mechanical state of the stance limb [42]. Stance limb GMed activity accelerates the centre of mass (CoM) towards the swing limb [43], which leads to hip adduction of the swing limb, and medial foot placement [44]. To direct the CoM back to the midline, GMed activity of the swing limb is required to abduct the limb and displace the swing foot laterally. Thus, high GMed muscle activity of the stance limb strongly predicts high swing limb GMed muscle activity [42]. It follows that reduced stance limb GMed muscle activity, as with the use of foot orthoses, would reduce GMed activity of the swing limb. The mechanisms that mediate this control are unclear, but is suggested by Rankin et al. [42] to include stance hip muscle spindle proprioceptive feedback [45], cutaneous feedback from the sole of the foot [46], and/or reduced "sense of

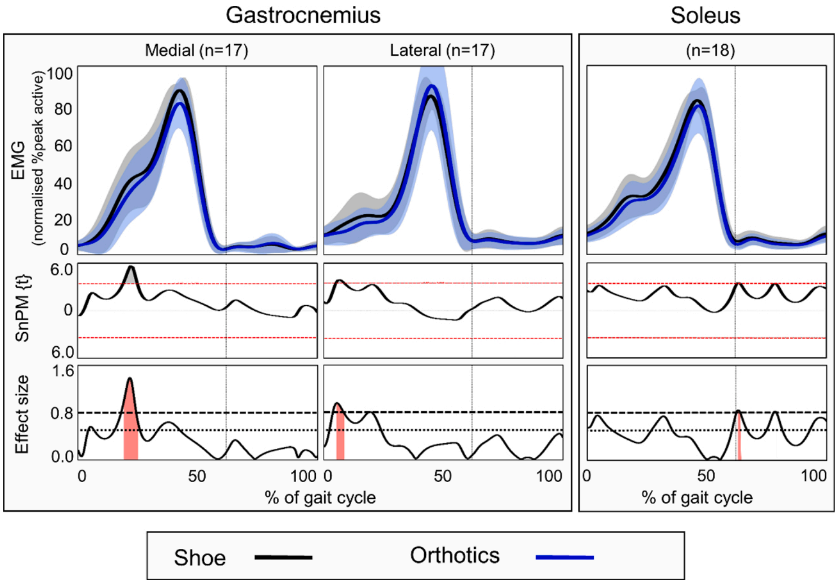

Fig. 4. Group average calf muscle electromyography (EMG) activity across the gait cycle (%).The top panel, shows the grand ensemble of muscle activity when walking with foot orthoses (blue) and without (black). The thick line indicates the mean and the shaded areas the standard deviation for each group. The dotted vertical lines represent toe-off. The middle panel, shows the SnPM (t-statistic) vs. percentage of the gait cycle. The red dashed line represents the critical threshold (t). The bottom panel, shows the effect size vs. percentage of the gait cycle, describing the magnitude of the effect. The black horizontal dotted lines represent the thresholds for a medium effect size (0.5) and the dashed line for a large effect size (0.8). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

effort" from the stance limb hip abductor muscles [47].

Lateral hamstring (biceps femoris) muscle activity reduced during the loading phase of stance (4 %–7 % GC) with foot orthoses. No other changes in thigh muscle EMG were observed. Biceps femoris long head inserts onto the fibula head. It is taut during knee extension, which drives the fibula posteriorly [48]. It can also resist tibial internal rotation torque due to its insertion onto the styloid process of the fibula [49]. In a systematic review, Mills et al. (2009) concluded that posted, non-moulded (prefabricated) foot orthoses significantly reduce peak rearfoot eversion and tibial internal rotation [8] in healthy participants. In that case, the demands for lateral hamstring muscle activity to assist with controlling tibial internal rotation (≈ 9% GC [49]) would be reduced. This may explain the reduced hamstring muscle activity observed here.

The triceps surea muscles also reduced activity during the orthoses condition. The clinical relevance of this may not however be clear across all three constituents. The gastrocnemius muscles act predominately in the sagittal plane and have a large role on vertical support and forward propulsion during stance when walking [50]. Although small, the heel lift built into the prefabricated foot orthoses would position the gastrocnemius at a slightly shortened length, and might reduce the activity required for vertical support during stance. This is supported by an incremental reduction in medial gastrocnemius EMG when walking with shoes of increasing heel height [51]. A further, selective reduction of medial gastrocnemius could be augmented by its functional contribution to ankle inversion in the coronal plane [52]. The inbuilt medial wedge of the foot orthoses may be sufficient to offload medial gastrocnemius, negating its role in control of hindfoot eversion. It is also possible that the passive stability provided by the orthoses reduces the demand for the gastrocnemius muscle to initiate ankle plantarflexion, and wind up the plantar fascia via the windlass mechanism to aid in forward propulsion [53]. These factors may potentially explain the results of the gastrocnemius medialis muscle in our study, given the timing of the differences during mid-stance. The differences observed for lateral gastrocnemius and soleus, however, are in epochs of the gait cycle with typically minimal muscle activity, and therefore questionable clinical relevance.

4.1. Clinical implications

A key finding from this study is that walking with prefabricated foot orthoses can reduce gluteal muscle activity by up to 43 % in young healthy adults. This might provide a biologically plausible justification for the prescription of foot orthoses in clinical populations to acutely offload painful or fatigued hip muscles, such as that reported in gluteal tendinopathy [24] or hip osteoarthritis [25,54]. A further clinical consideration is the potential long-term effect of orthoses wear on gluteal muscle function. It is unknown whether offloading these muscles will have beneficial or detrimental effects on function and muscle health. If negative, such changes may need to be monitored, or negated with targeted exercises.

4.2. Limitations and directions for future research

The results of this study should be considered with respect to several potential limitations. This study was conducted on asymptomatic individuals, and research is needed to determine whether foot orthoses have a similar effect on muscle activity in clinical groups, such as those with symptoms of hip pain. Of note, the periods of reduced EMG were short (between 2–13 % of the gait cycle) and additional work is required, potentially with modelling, to test the significance of such changes for mechanics. The order of testing (orthoses vs no orthoses) was not randomised. Rather, we chose to standardise the order of testing so that participants completed shoe trials first, followed by foot orthoses trials, to ensure that no carry-over effects of the orthoses to the shoe only condition. However, it should be acknowledged that the differences in muscle activity between conditions may represent the effects of order (e.g. fatigue, familiarisation). Furthermore, it is possible that the reduction in activity demonstrated with orthoses in our study represents the natural attenuation in activity over time within a session due to pooling of oedema or damage to the wires [55]. However, the magnitude of difference in our study is larger than could be explained by natural attenuation over a ten minute time-frame (up to 18 % reduction in tibialis anterior, vs up to 43 % in our study) [55]. As this study was experimental, we refrained from adjusting for multiple comparisons to protect from a Type II error. We recognise that this increases the likelihood of significant findings by chance (Type I error). Effect sizes for our primary comparisons (gluteal activity) were large (>0.69), thus less likely to imply a false positive finding.

Future work should consider several questions. Clarification of the proposed mechanisms of effect requires simultaneous biomechanical analysis to reconcile changes in muscle activity between conditions with lower limb kinematics and/or kinetics, which were not reported here. A potential dose-response with foot orthoses parameters (e.g. size of heel lift or medial wedging) could facilitate clinical prescription and would benefit from further work. Evaluation of the effect of foot orthoses on gluteal function is also required during higher demand tasks such as single limb squats or stepping tasks.

5. Conclusion

Walking with prefabricated foot orthoses reduced GMed and GMin muscle activity by up to 43 % for between 2–13 % of the gait cycle in healthy young adults. Smaller changes were observed for selected calf (medial gastrocnemius - up to 30 % reduction) and thigh (lateral hamstring – up to 19 % reduction) muscles. There was no effect on quadriceps, medial hamstring or GMax muscle activity. This study provides a foundation to explore effects of foot orthoses in individuals with symptomatic hip conditions.

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Declaration of Competing Interest

The authors report no declarations of interest.

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.2021.07.003.

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