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The modulation of forward propulsion, vertical support, and center of pressure by the plantarflexors during human walking

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ABSTRACT

The gastrocnemius and soleus both contribute to the ankle plantarflexor moment during the mid- and terminal stance phases of gait. The gastrocnemius also generates a knee flexion moment that may lead to dynamic function that is unique from the soleus. This study used a muscle stimulation protocol to experimentally compare the contributions of individual plantarflexors to vertical support, forward propulsion and center of pressure (CoP) movement during normal gait. Twenty subjects walked on an instrumented treadmill at self-selected speeds with stimulating surface electrodes affixed over the medial gastrocnemius and soleus muscles. Short duration pulse trains (90 ms) were used to stimulate either the gastrocnemius or soleus at 20% or 30% of the gait cycle (GC) of random strides. Changes in ground reactions between stimulated and non-stimulated strides were evaluated to characterize the influence of each muscle on whole body movement during mid- (stimulation onset at 20% GC) and late (30% GC) stance. The gastrocnemius and soleus each induced an increase in vertical support and anterior progression of the CoP in mid-stance. However, late stance gastrocnemius activity induced forward acceleration, while both mid- and terminal stance soleus activity induced braking of forward velocity. The results suggested that the individual plantarflexors exhibit unique functions during normal gait, with the two muscles having opposite effects on forward propulsion. These empirical results are important both for enhancing the veracity of models used to predict muscle function in gait and also clinically as physicians seek to normalize gait in patients with plantarflexor dysfunction.

1. Introduction

The gastrocnemius and soleus play a crucial role in stance-phase gait mechanics in both healthy individuals, as well as those with gait abnormalities. Both muscles are active from mid-stance through the beginning of pre-swing in normal walking [1,2], generating plantarflexion moments about the ankle. Because of this similarity, the gastrocnemius and soleus have often been assumed to have similar dynamic function [3–7]. However, the gastrocnemius is biarticular, originating above the knee and generating a knee flexion moment, while the soleus is uniarticular, crossing only the ankle. This difference makes it plausible that the two muscles could induce different kinetic and kinematic patterns [8]. Indeed, musculoskeletal gait simulations suggest that plantarflexor muscle function varies throughout stance and that the two muscles influence vertical support and forward propulsion differently [9–14]. However, specific model predictions vary. For example, some studies attribute a larger forward propulsion role to soleus [9–11] while others suggest gastrocnemius plays the larger role [12–14]. Some of the differences between studies may be due to the strong dependence of muscle function predictions on musculoskeletal geometry [15] and ground contact model assumptions [16]. In particular, predictions of muscle function are substantially different depending on whether the center of pressure (CoP) is allowed to change when muscle activity is altered [16].

Insight from empirical studies can be used to refine computational models and in turn may lead to an improved understanding of the causes of pathological gait patterns such as equinus and crouch. In general, muscle function is studied by comparing altered or perturbed gait (typically via changes in muscle activity or external forces) to an unperturbed state. Various approaches have been used to empirically manipulate and assess *in vivo* plantarflexor function during gait. In an early study, Sutherland et al. [7] used a tibial nerve block to investigate plantarflexor function and concluded that the plantarflexors contribute primarily to the

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forward shift of the CoP and vertical support, while stabilizing the joint in such a way as to facilitate forward propulsion. However, a nerve block approach could not distinguish unique functions of different muscles. More recent studies have monitored changes in the gastrocnemius and soleus muscle activities when external forces and weights are introduced as a way of manipulating support and propulsion requirements. Such studies have delineated function of the gastrocnemius and soleus but produced differing opinions on which muscle makes a more significant contribution to propulsion [17–19]. A challenge with the external force and weight manipulation approach is that the perturbations are applied throughout the gait cycle, making it challenging to ascertain the influence of muscles during distinct phases. Stewart et al. have implemented an electrical stimulation protocol to individually perturb the gastrocnemius or the soleus during stance phase in normal walking and found that the two muscles induced directly opposite motion at the knee and ankle [20]. However, the implications for whole body movement have not been considered.

The purpose of this study is to use an electrical stimulation protocol with greater temporal resolution to investigate the relative influence of the gastrocnemius and soleus on support, propulsion, and CoP movement in distinct phases of normal gait. Based on prior modeling studies [9–14], we hypothesize that the gastrocnemius and soleus would both contribute to vertical support when normally active but would exhibit differential influence on forward propulsion during terminal stance. Further, we hypothesize that both muscles would influence the fore-aft location of the CoP when stimulated during mid-stance, an effect that has been suggested clinically [7] but has not been investigated in prior studies.

2. Methods

2.1. Overview

The protocol for this study was approved by the University of Wisconsin's Heath Sciences Internal Review Board. Twenty healthy young adults (age = 24.5 ± 3.0 years, mass = 66.6 ± 10.4 kg, height = 1.71 ± 0.10 m) provided informed consent and participated in this study. Subjects were asked to walk on a split-belt instrumented treadmill (Bertec, Columbus, OH) at a self-selected speed (1.1 ± 0.1 m/s) while either the medial gastrocnemius or the soleus was electrically stimulated at 20% or 30% of random gait cycles (Fig. 1).

2.2. Stimulation protocol

Surface stimulating electrodes (approximately 0.75 × 1.5 in., BioStim Pigtail Electrodes, Biomedical Life Systems, Vista, CA) were placed over the mid-muscle belly of the medial gastrocnemius and the distal-lateral quadrant of soleus. Exact electrode positions were determined by moving non-adhesive surface electrodes over the skin to find the location inducing the largest visual twitch response. Current was set at a muscle-specific level with sufficient magnitude (<50 mA) to induce a visible contraction and ankle motion in an unloaded posture. The site was marked with a pen, shaved, and cleaned with alcohol before the adhesive electrodes were placed.

Subjects performed eight 90-s walking trials at their preferred walking speed. A custom LabVIEW (National Instruments, Austin, TX) program monitored treadmill ground reactions to detect foot strike events and maintain an estimate of gait cycle duration. The program triggered a current-controlled stimulator (Grass S88, Astro-Med, Inc., West Warwick, RI) to deliver a 90 ms pulse train (four 300-μs pulses delivered at 33 Hz) to either the gastrocnemius or soleus at 20% or 30% of a random gait cycle, with 5–10 strides between stimulation pulse trains. This was done to prevent subjects from anticipating stimulated strides. Trials were performed in a randomized order, with two repeat trials for each muscle at each of the stimulation times. This protocol resulted in an average of eleven stimulated strides during each of eight 90-s walking trials. We note that delays due to electromechanical and multi-body dynamics factors resulted in the stimulation inducing changes in ground reaction forces and CoP location from 50 to 150 ms after the stimulus onset [21,22]. Hence, the stimulations resulted in induced ground reaction force and CoP changes between approximately 25% and 45% of the gait cycle, which corresponds to the major periods that the plantarflexors are considered to influence normal gait [1].

2.3. Induced ground reactions

Three-dimensional ground reactions underneath each foot were recorded synchronously at 2000 Hz. Ground reaction force data was low-pass filtered at 100 Hz (third order Butterworth filter) and normalized to body weight (Matlab, MathWorks, Natick, MA). The vertical component of the ground reactions was used to detect heel strike events. We simultaneously monitored the stimulation pulse train at 2000 Hz, which allowed us to analyze the precise time within a gait cycle that an individual muscle was stimulated. We assessed the influence of muscle stimulation on whole body movement by comparing ground reaction forces between stimulated and non-stimulated strides. To do this, we first identified the percent of the gait cycle at which the onset of muscle stimulation occurred. We then located the same point of the gait cycle in the preceding two strides. For each pair of strides (i.e. baseline vs. non-stimulated and non-stimulated vs. stimulated) we computed the average differences of the anterior ground reaction force, the vertical ground reaction force and the anterior position of the CoP (Fig. 1c and d). These comparisons were done using the average values within a series of 50 ms windows following stimulation onset. Variability in foot placement was accounted for by subtracting the mean location of the CoP in the 50 ms prior to stimulation. For each subject, we computed the difference measures for each stride, and then determined average change in forces and CoP over all of the strides in which a muscle was stimulated at a specific percentage of the gait cycle.

2.4. EMG

Pre-amplified, single differential electromyographic (EMG) electrodes (Trigno, DelSys Inc., Boston, MA) were placed on the soleus and the medial head of the gastrocnemius of the right limb. EMG activities were sampled at 2000 Hz, high-pass filtered at 20 Hz (zero-phase, third order Butterworth filter), low-pass filtered at 450 Hz (zero-phase, third order Butterworth filter) and full wave rectified. EMG signals from the stride prior to the stimulation were ensemble averaged to provide a quantitative assessment of when each muscle was normally active. EMG measures

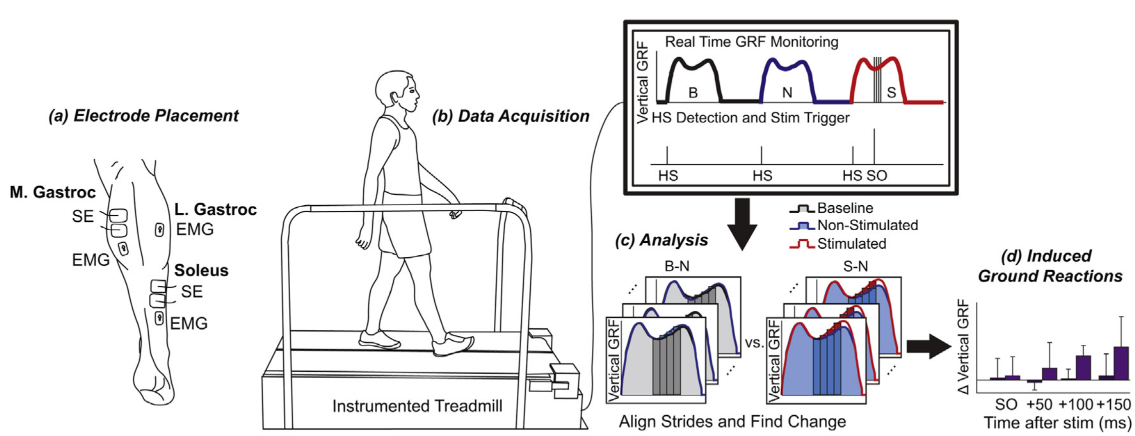

Fig. 1. Experimental set-up. (a) Stimulating (SE) and recording (EMG) electrodes are placed on the gastrocnemius and soleus muscles. (b) Subject walks on treadmill while ground reaction forces are monitored in real time to detect heel strikes (HS) and trigger stimulation at 20% or 30% of the gait cycle of random strides. The difference in ground reaction forces (GRF) is taken between two pairs of strides over 50 ms windows centered on stimulation onset (SO), +50 ms, +100 ms, and +150 ms; and (d) the mean (±standard deviation) difference is reported for baseline (B) vs. non-stimulated (N) and non-stimulated vs. stimulated (S).

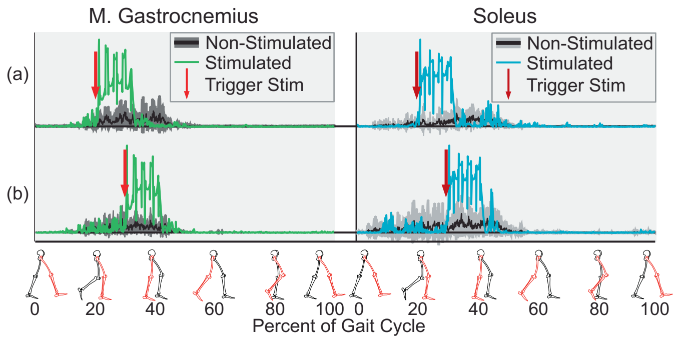

Fig. 2. Shown is the gastrocnemius and soleus EMG of a stimulated stride (note the stimulation artifact) in relation to an ensemble average of the non-stimulated EMG for a representative subject. Arrows indicate the time that stimulation was triggered. The stimulation artifact shows that (a) 20% GC and (b) 30% GC stimulations align well with gastrocnemius activity, while (b) 30% GC stimulation aligns best with soleus activation.

from stimulated strides were compared with the nominal activation profiles to better understand the timing of induced muscle activity. Our EMG recordings illustrated that stimulating the plantarflexors for 90 ms starting at 20% and 30% of the gait cycle (note stimulation artifact) induced an increase in muscle activity that was well aligned with the timing of normal EMG activity (Fig. 2).

2.5. Statistical analyses

Changes in the ground reaction forces and CoP were assessed for statistical significance using a 2-way repeated measures analysis of variance with a post-hoc Tukey's Honest Significance Test (Statistica, StatSoft Inc., Tulsa, OK) for each muscle. Factors considered were the presence of stimulation (stimulated vs. non-stimulated, baseline vs. non-stimulated) and time after onset of stimulation (i.e. 0, 50, 100, 150 ms). These analyses were repeated for both stimulation onset times (i.e. 20% or 30% of the gait cycle).

3. Results

Short-duration electrical stimulation of the gastrocnemius or soleus at specific time points in the gait cycle induce changes in the ground reaction forces and CoP position that vary substantially across conditions (Fig. 3).

The gastrocnemius contributes to vertical support throughout mid- and terminal stance while its effect on forward propulsion and CoP position depend on the stimulation onset. For stimulation onset at 20% of the gait cycle, the gastrocnemius induces a significant anterior shift of the CoP while the onset at 30% of the gait cycle shows no such effect. Conversely, for onset at 20% of the gait cycle, the gastrocnemius has no significant effect on forward propulsion, while stimulation onset at 30% of the gait cycle produce significantly increased propulsion 150 ms later.

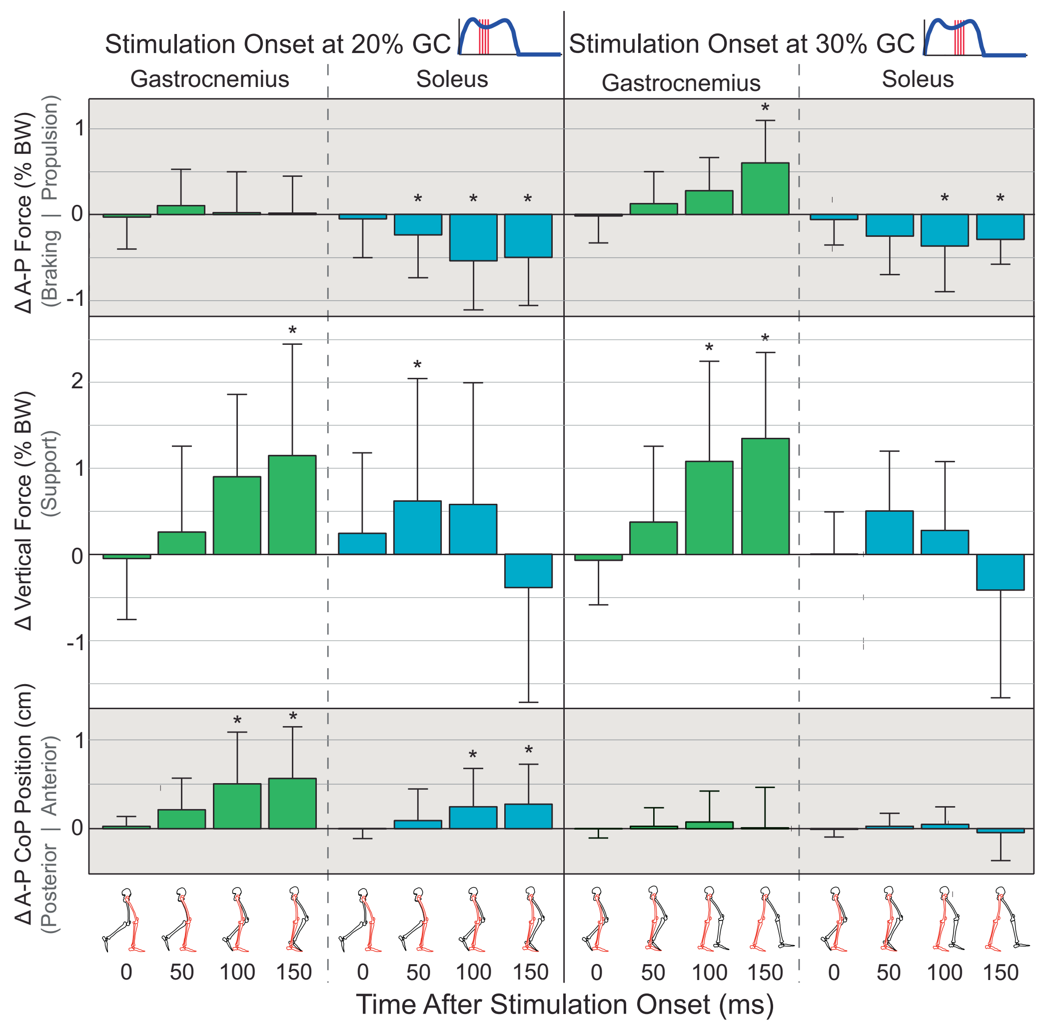

Fig. 3. The graph shows the stimulated minus non-stimulated (inter-subject mean ± 1 standard deviation) changes in anterior ground reaction forces, vertical ground reaction forces and fore-aft position of the center of pressure at specific time points after the onset of muscle stimulation. Significance is based on a comparison of stimulated vs. non-stimulated strides to non-stimulated vs. baseline strides. The results show that gastrocnemius stimulation initially induces an increase in vertical support and forward shift of center of pressure (CoP), and then later provides support and forward propulsion in mid terminal stance (30% GC stim + 100–150 ms). Activation of the soleus induces a decrease in the anterior ground reaction force at both stimulation times and induces both vertical support and a forward shift of the CoP with earlier stimulation.

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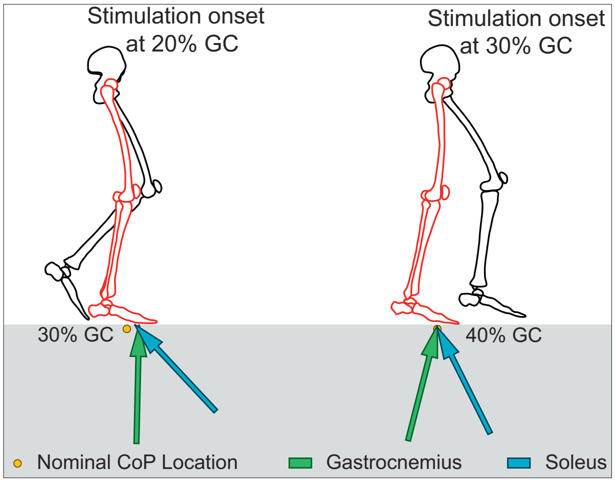

Fig. 4. Temporal influence from gastrocnemius and soleus muscles on ground reaction forces and center of pressure position. The data shown represent the maximum change in the ground reaction forces within 100 ms after the onset of stimulation, averaged across subjects. Arrows are rotated to show the direction of induced ground reactions. The small dot beneath the stance foot represents the center of pressure location in non-stimulated strides and the location of the arrow tip represents the change in location of the center of pressure in stimulated strides.

Soleus contributes to braking of forward velocity throughout mid- and terminal stance while its effects on support and CoP movement vary with stimulation onset. With stimulation onset at 20% of the gait cycle, soleus shifts the CoP forward significantly, but shows no such effect when stimulus onset is at 30% of the gait cycle. Additionally, soleus stimulation increases vertical force at both onset times, but only vertical support for stimulation onset at 20% of the gait cycle reaches statistical significance.

The directions of the group-averaged induced ground reactions for each muscle and stimulation time are illustrated in Fig. 4.

4. Discussion

Our results support the hypothesis that the gastrocnemius and soleus perform unique biomechanical functions during gait (Figs. 2 and 3). Notably, we show that in mid-stance, gastrocnemius activation induces forward propulsion while soleus activation simultaneously induces braking of forward velocity. Both muscles contribute to vertical support, and tend to cause anterior progression of the CoP during mid-stance when the foot is flat on the ground.

Prior to this study, several research groups have used computer gait models to estimate the contributions of the gastrocnemius and soleus muscles to support and propulsion [9–14]. These studies have generally agreed that both plantarflexors contribute to vertical support when normally active in stance, but differ in their assessment of the muscles' roles in inducing forward propulsion. Neptune et al. [10,11], using a planar gait model, concludes that soleus has a larger role than gastrocnemius in inducing forward propulsion of the torso during terminal stance. Liu et al. [9], using a 3D gait model, has found both muscles can induce braking early in terminal stance, but the gastrocnemius contributes more to forward propulsion later in terminal stance. Kimmel et al. [12] and Neptune et al. [14] suggest that the soleus has the potential to brake forward velocity in mid-stance, but that both muscles may induce forward propulsion in terminal stance and pre-swing. The discrepancy in these conclusions may be due to the different constraints and degrees of freedom used in each model. Our results support the idea that early soleus activation can brake forward velocity, while the gastrocnemius is capable of inducing forward acceleration of the center of mass during terminal stance.

While prior gait modeling studies have not specifically addressed the influence of the plantarflexors on CoP, some have made foot–floor modeling assumptions that would allow for the CoP movement we observe. In particular, we observe an early forward progression of the CoP during mid-stance when either muscle is stimulated at 20% of the gait cycle. This represents the foot-flat phase of gait and is an effect that could be captured in gait simulation models that include a rigid planar support [12] or bed of springs below the foot [9,13,23]. However, foot–floor contact models that require the CoP to remain constant during a perturbation would not capture this effect [5]. We note that we do not observe motion of the CoP for muscle stimulations introduced in terminal stance, suggesting that a foot–floor model that restrains CoP motion (e.g. ball and socket) is sufficient in terminal stance [12]. In general, our results most closely align with foot–floor contact representations that account for the time-varying constraints that occur throughout stance [16].

Prior empirical studies support the hypothesis that the gastrocnemius and soleus exhibit unique functions in gait. Particularly intriguing are the results of Stewart et al. [20] which show that the gastrocnemius and soleus induce directly opposing motion at the knee and ankle when normally active in stance. However, it is challenging to directly infer the influence of knee and ankle kinematics on whole body kinetics and kinematics. In another study, McGowan et al. measure changes in EMG activity in response to independent manipulations of body weight and mass, and show soleus activity to be more sensitive than gastrocnemius to body mass, which they suggest is evidence that soleus plays a larger role in generating propulsion [18]. However, an earlier study [19] has demonstrated that the gastrocnemius is more sensitive than soleus to external horizontal forces that are applied during gait, suggesting that gastrocnemius plays a more important role in propulsion. One challenge with weight, mass and external force manipulations is that the perturbation is continuously present, which could induce coordination changes throughout the gait cycle. Our experiment overcame this challenge by using a short-duration electrical stimulation protocol to increase muscle activity at select points within otherwise normal gait cycles. We then directly measure the change in ground reactions by comparing stimulated and non-stimulated strides.

Challenges with our approach include ensuring that the stimulation occurs at normal activation periods, while also being of sufficient magnitude to increment the force output of the muscle. Perry shows the gastrocnemius and soleus to be co-active through much of mid- (10%–30% of the gait cycle) and terminal (30%–50% of the gait cycle) stance, with the greatest activity in the first half of terminal stance [2]. Thus introducing 90 ms long stimulation pulse trains at 20% and 30% of the gait cycle should increase activation during the period of normal activity for both muscles (Fig. 2).

We note that soleus stimulation appears to induce smaller changes in ground reaction forces and CoP movement than the gastrocnemius. This may be due to limitations of our stimulation protocol. To address convenience and comfort issues, we used surface stimulating electrodes in this study rather than fine wire electrodes to stimulate the muscles. We positioned the soleus stimulating electrodes well below the muscle belly of gastrocnemius, lateral to the Achilles. As a result, stimulation for this muscle was limited to the distal, lateral quadrant. In this location, stimulation still produced a visible contraction of the relaxed muscle but may have had a smaller effect when the muscle was active in terminal stance.

There are a number of factors that contribute to intra- and inter-subject variability in this study. On average, our results show changes in ground reaction forces that are on the order of one percent of body weight. Subjects' tolerance of electrical stimulation, body mass or size, baseline muscle activity, and stride-to-stride variability are all factors that contribute to the magnitude of changes we are able to detect in ground reaction forces and center of pressure movement. Future studies may be able to induce larger effects on forward propulsion and support by using fine wire stimulating electrodes to induce stronger muscle contractions than can be achieved with surface electrodes.

We have also experimented with introducing stimulation starting at 40% of the gait cycle. However, this stimulation tends to occur when muscle activity is ceasing [2]. Further, the resulting mechanical changes (50–150 ms later) happen during the double support period when ground reactions under the trailing limb are decaying rapidly. We find that this makes it challenging to consistently identify the incremental forces that are induced by the muscle stimulation.

We conclude that the gastrocnemius contributes significantly to both forward propulsion and vertical support of the whole body when normally active. In contrast, normal activation of the soleus induces braking of forward velocity and vertical support. Both muscles also induce rapid progression of the center of pressure during mid-stance, an effect that should be included when using models to assess muscle function in gait.

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Conflict of interest statement

The authors confirm that there is no known conflict of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

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