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Société de Biomécanique young investigator award 2022: Effects of applying functional electrical stimulation to ankle plantarflexor muscles on forward propulsion during walking in young healthy adults

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ABSTRACT

The triceps surae muscle, composed of the gastrocnemius and soleus muscles, plays a major role in forward propulsion during walking. By generating positive ankle power during the push-off phase, these muscles produce the propulsive force required for forward progression. This study aimed to test the hypothesis that applying functional electrical stimulation (FES) to these muscles (soleus, gastrocnemius or the combination of the two) during the push-off phase would increase the ankle power generation and, consequently, enhance forward propulsion during walking in able-bodied adults. Fifteen young adults walked at their self-selected speed under four conditions: no stimulation, with bilateral stimulation of the soleus, gastrocnemius, and both muscles simultaneously. Muscles were stimulated just below the discomfort threshold during push-off, i.e., from heel-off to toe-off. FES significantly increased ankle power (+22 to 28 % depending on conditions), propulsive force (+15 to 18 %) and forward progression parameters such as walking speed (+14 to 20 %). Furthermore, walking speed was significantly higher (+5%) for combined soleus and gastrocnemius stimulation compared with gastrocnemius stimulation alone, with no further effect on other gait parameters. In conclusion, our results demonstrate that applying FES to the gastrocnemius and soleus, separately or simultaneously during the push-off phase, enhanced ankle power generation and, consequently, forward propulsion during walking in able-bodied adults. Combined stimulation of the soleus and gastrocnemius provided the greatest walking speed enhancement, without affecting other propulsion parameters. These findings could be useful for designing FES-based solutions for improving gait in healthy people with propulsion impairment, such as the elderly.

1. Introduction

Walking is a complex activity that involves the coordination of several muscles and joints to ensure the forward progression of the body while maintaining balance. Generating the forces to move forward, often called *forward propulsion*, is a fundamental aspect of healthy walking. It is generally accepted that the gastrocnemius and soleus muscles play a predominant role in forward propulsion during normal walking, despite discrepancies in their relative contribution noted between experimental (Gottschall and Kram, 2003) and modeling studies (McGowan et al., 2009; Neptune et al., 2001). By generating positive mechanical power at the ankle joint during the push-off phase (heel-off

to toe-off of the trailing leg), these muscles produce a forward-directed ground reaction force (GRF) that accelerates the center of mass forward (Hsiao et al., 2015). This propulsive force is directly linked to walking speed (Peterson et al., 2010). Any weakness or impairment of these muscles, including those induced by aging, may affect the propulsion. In addition to the reduced walking speed and step length associated with aging (Elble et al., 1991), adaptative strategies arise to compensate for the decreased ankle power generation during the push-off phase (DeVita and Hortobagyi, 2000; Judge et al., 1996). Generally, older people increase hip and knee powers, which is thought to increase the energy cost (Pieper et al., 2021) and instability of gait (Browne and Franz, 2017). Therefore, maintaining or restoring the propulsive function of

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plantarflexor muscles is critical for promoting walking and reducing the risk of falling.

Functional electrical stimulation (FES) has been proposed for improving walking function by inducing muscle contractions via low-intensity current applied to neuromuscular tissues. Extensive research has considered its impact for enhancing gait performance in individuals with neuromuscular disorders (e.g., spinal cord injuries or strokes), especially by correcting foot drop problems and propulsion deficits (Hsiao et al., 2016; Kobetic et al., 1997; Melo et al., 2015). FES application to the triceps surae during the push-off phase has been shown to increase the propulsive force and walking speed in post-stroke patients (Kesar et al., 2009). This technique may also be used as a short-term therapeutic intervention to restore the propulsive function of ankle plantarflexors muscles, thereby enhancing gait efficiency and balance in patients (Paul et al., 2008). Hence, FES constitutes an effective solution for improving the propulsive function of the ankle plantarflexors during walking in disabled people.

Recently, a systematic review concluded that FES may also be used to modify kinematics, kinetics, and spatiotemporal gait parameters in able-bodied people without causing discomfort (Aout et al., 2023). Although four studies examined the effects of applying FES to ankle plantarflexors on gait biomechanics (Francis et al., 2013; Lenhart et al., 2014; Stewart et al., 2007; Thorp and Adamczyk, 2020), only one looked at its impact on propulsion (Francis et al., 2013). This study revealed that stimulation of the gastrocnemius at 30 % of the gait cycle (for 90 ms) resulted in an increased propulsive force, while applying the same stimulation to the soleus yielded the opposite effect. Studies focusing on lower limb joint angles have consistently shown contrasting results depending on whether the soleus or gastrocnemius was stimulated (Lenhart et al., 2014; Stewart et al., 2007). It is important to consider that these results could be related to timing of stimulation. Indeed, using musculoskeletal modeling, Neptune et al. (2001) have shown that during the midstance phase (nearly at 30 % of the gait cycle), soleus contributes to decelerating forward rotation of the tibia, while the gastrocnemius accelerates knee flexion. In clear, gastrocnemius and soleus muscles have distinct actions especially during midstance, whereas they contribute synergistically to propulsion during the push-off phase (Zajac et al., 2003).

Although these findings suggest that applying FES to the plantarflexor muscles holds the potential for modulating the propulsive force during walking in healthy individuals, there are still several aspects that need to be clarified. Firstly, among the aforementioned studies, none investigated the mechanisms responsible for changes in propulsive force (e.g., ankle moment and power), nor examined the consequences on key parameters of forward progression (walking speed, step cadence, and length). Additionally, while it is generally accepted that soleus and gastrocnemius have synergistic actions during the push-off phase (Zajac et al., 2003), it remains to be verified whether stimulation of these muscles during this phase, either individually or in combination, can effectively increase propulsion. Interestingly, authors have shown that combined stimulation of two synergistic muscles in elbow flexion increases the evoked force at rest compared to stimulation of just one of these muscles, although this did not produce a greater effect during voluntary contraction (Williams and Bilodeau, 2004). To our knowledge, the comparison between the effects of combined and isolated application of FES to the soleus and gastrocnemius on gait propulsion remains unexplored in able-bodied people. Such knowledge could be useful in developing FES-based solutions for able-bodied individuals facing propulsion limitations, such as the elderly.

The aim of this study was to test the hypothesis that applying FES to the ankle plantarflexor muscles (gastrocnemius, soleus or combination of the two) during the push-off phase would increase ankle power generation and, consequently, enhance forward propulsion in able-bodied adults. Further, we explored the effects of isolated and combined soleus and gastrocnemius stimulation on forward propulsion and evoked ankle torque at rest.

2. Materials and methods

2.1. Population

Fifteen young, healthy adults volunteered for this study (13 males; age: 22 ± 3 years; height: 1.74 ± 0.09 m; and body mass: 66.7 ± 9.2 kg). None of the participants had a history of neurological, orthopedic disorders or any other conditions that could affect their walking ability. Comprehensive information about the study procedure was provided to all participants, who gave their written consent. This protocol, which complies with the Declaration of Helsinki, was approved by the local institutional review board.

2.2. FES settings

Two independent wearable two-channel stimulators (O2CHSII, Odstock Medical Ltd, UK), positioned at belt level, were used to apply electrical muscle stimulation to each leg independently. A pair of self-adhesive electrodes (5×9 cm, Axelgaard, Denmark) was placed over the belly of the gastrocnemius, encompassing both the lateralis and medialis chiefs (Fig. 1) as described in Kim et al. (2005). Another pair of electrodes (5×5 cm) was put on the soleus muscle's medial motor point, i.e., beneath the distal end of the gastrocnemius medialis (Kim et al., 2005). We customized electrode positions for each participant to avoid any observable contraction of the soleus when the gastrocnemius was stimulated, and vice versa.

The participant was then positioned in the prone position on an isokinetic dynamometer (CON-TREX MJ, Physiomed, Germany), with the ankle joint aligned with the dynamometer axis and maintained at a neutral 90° angle. Participants were instructed to stay relaxed to measure the evoked torque at rest. An asymmetric biphasic current (40 Hz; 60 mA) was employed to stimulate the muscles (Aout et al., 2023), and the pulse width was adjusted for each muscle by increasing it in steps of 0.5 units (five trials each), ranging from 0 to 9 (maximum), until discomfort was reported. The pulse width immediately preceding the discomfort threshold was taken as the maximum tolerable stimulation level. Correspondence between units and pulse width was obtained using manufacturer data and measurements with an oscilloscope. The protocol was applied to each muscle and each leg, incorporating a 5-minute rest in between. Maximal voluntary isometric contractions (MVIC) were measured for each leg after determining maximum tolerable levels. Finally, resulting ankle torques at rest were normalized against body mass (N.m/kg) and presented as a percentage of MVIC (% MVIC).

2.3. Gait protocol

Before walking trials, two footswitches were placed under the calcaneum and the first metatarsal and coupled with each stimulator to stimulate either the soleus, gastrocnemius, or both muscles simultaneously during the push-off phase of gait from heel-off to toe-off. Retroreflective markers (14-mm diameter) were fixed bilaterally on bony landmarks according to Vicon's Plug-in-Gait lower-body model (Kadaba et al., 1990). A motion capture system equipped with 14 cameras (6 Bonita and 8 Vero cameras, Vicon, UK) was used to collect the kinematic data at 200 Hz.

Then participants were asked to walk at their spontaneous self-selected speed along a 7-m walkway, wearing their own shoes. Two force plates (60×40 cm, AMTI, USA), embedded in the middle of the walkway, measured the GRF at 1000 Hz and two pairs of photoelectric cells, placed 0.45 m before and 0.60 m after the force plates, measured the gait speed. After walking familiarization trials with FES, the participants were asked to perform walking trials under four conditions: without stimulation (S_0 , control condition), with stimulation of the soleus (S_S), gastrocnemius (S_G), and both muscles simultaneously (S_{SG}). In each stimulation condition (except for S_0), targeted muscles were

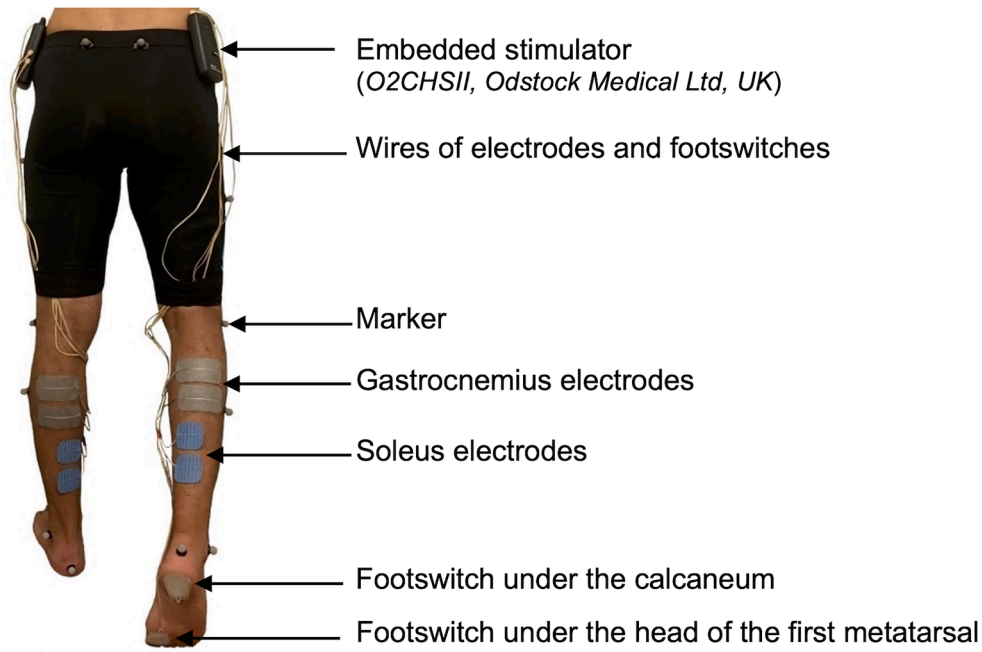


Fig. 1. FES electrodes, footswitches and marker placement on lower limbs.

bilaterally stimulated using the two wearable stimulators during the push-off phase, i.e., stimulation was triggered when the supporting heel lifted off the ground and stopped when the first metatarsal lifted off. The order of conditions was randomized, and then at least five successive trials were completed for each condition. Trials were considered valid if only the dominant foot had made complete contact with a force plate. A

5-minute rest period was respected between conditions to avoid fatigue and prevent potential after-effects from any condition.

2.4. Data processing

Data were extracted using Nexus Software (Vicon, UK) with the

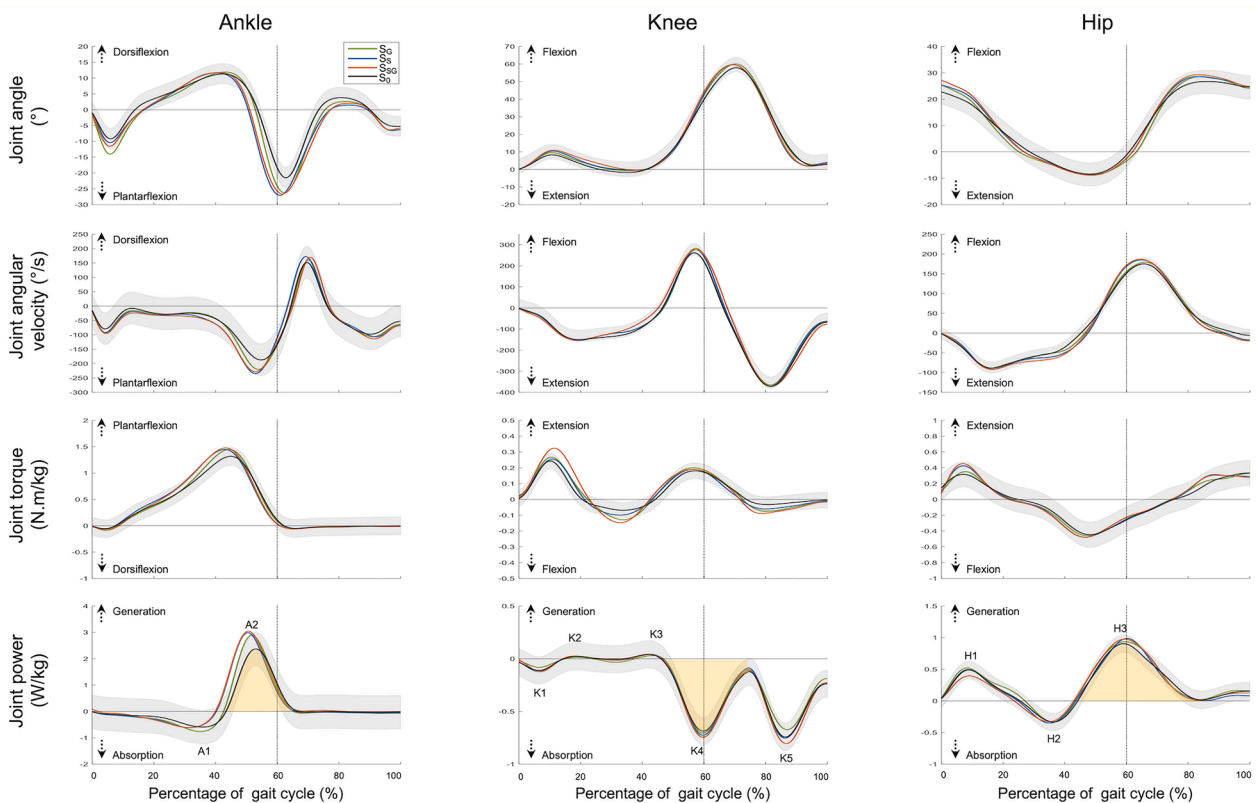


Fig. 2. Illustration of kinetic and kinematic variables for the ankle, knee, and hip joints. Mean curves for each experimental condition were represented, with only the standard deviation for the control condition displayed in gray. The analyzed work at the ankle, knee, and hip joints is represented by yellow areas under the second peak of ankle power (A2), the fourth peak of knee power (K4), and the third peak of hip power (H3), respectively.

Vicon Plug-in-Gait model (version 2.15, UK), with marker trajectories low-pass filtered using a second-order Butterworth filter (10-Hz cut-off frequency). Subsequently, data were imported into customized Matlab programs (The MathWorks, USA) to compute gait kinematics, kinetics, and spatiotemporal parameters. The analysis extended to specific joint mechanical work calculations, including the time-integral under the second peak of ankle power (A2), the fourth peak of knee power (K4) and the third peak of hip power (H3) (Cofré et al., 2011), as illustrated in Fig. 2. In line with studies on forward propulsion (Kondo et al., 2021; Riley et al., 2001a), the following variables were reported: walking speed, cadence, step length, gait phase durations, joint mechanical work, as well as peaks of anteroposterior GRF, joint angles, and joint powers. In addition, peaks of joint torques and joint angular velocities were investigated to interpret the joint power (Mentiplay et al., 2018; Riley et al., 2001b).

2.5. Statistical analysis

A repeated-measures ANOVA was conducted using Jamovi (version 2.4.8.0) to compare the evoked ankle torques at rest between the three FES conditions (S_S , S_G , and S_{SG}), focusing solely on the results pertaining to the dominant leg. Mean and standard deviation values for each gait parameter were calculated over the five trials collected in each experimental condition. Repeated-measures ANOVA with the four conditions (S_0 , S_S , S_G , and S_{SG}) as a within-subject factor were conducted on each gait parameter obtained for the dominant leg. When a significant difference was found, pairwise comparisons were performed using Holm-Bonferroni post-hoc test. Effect sizes were reported using the partial eta-squared value (η^2), which should be interpreted as small $\eta^2 < 0.01$; medium $0.01 \leq \eta^2 \leq 0.14$; and large $\eta^2 > 0.14$. The level of statistical significance was set at $\alpha = 0.05$.

3. Results

3.1. Evoked ankle torques at rest

The pulse width corresponding to the maximum tolerable stimulation threshold was on average $225 \pm 91 \mu\text{s}$ (5.5 units) for the soleus and $300 \pm 97 \mu\text{s}$ for the gastrocnemius (7 units). Seven participants tolerated the maximum setting ($390 \mu\text{s}$) on the stimulator for at least one muscle and described these pulse widths as tolerable, albeit close to discomfort.

The evoked torques at rest varied significantly according to the stimulated muscle ($P < 0.001$, $\eta^2 = 0.349$, Fig. 3), with the combined stimulation (S_{SG}) yielding the highest torque, followed by soleus (S_S) and then gastrocnemius stimulation (S_G).

3.2. Kinetic parameters

We found a significant effect of the stimulation condition (all $P < 0.001$ with medium to large effect sizes; Table 1) for peaks of anteroposterior GRF, ankle plantarflexion torque, ankle power, and also for ankle work. Post-hoc tests revealed a significant increase in anteroposterior GRF (+0.28 to 0.33 N/kg), ankle torque (+0.13 to 0.16 N.m/kg), power (+0.5 to 0.7 W/kg) and work (+0.05 to 0.10 J/kg) under all FES conditions compared to S_0 (all $P < 0.01$). No difference was found between FES conditions except for the ankle work, S_S resulting in a higher work than S_G . ANOVA revealed no significant effect for the other kinetic parameters ($P > 0.05$).

3.3. Spatiotemporal parameters

ANOVAs revealed a significant effect of the stimulation condition on gait speed, cadence, propulsion duration (all $P < 0.001$; Table 2) and step length ($P = 0.002$). Post-hoc tests indicated significant differences in these parameters between S_0 and all FES conditions, except for S_G condition regarding the propulsion duration ($P = 0.154$). Moreover, walking speed in S_{SG} condition was higher ($P = 0.014$) than S_G but not different from S_S ($P = 0.096$).

3.4. Kinematic parameters

ANOVA showed a significant effect of the stimulation condition on peaks of ankle plantarflexion angle ($P < 0.01$; large effect size; Table 3) and velocity ($P = 0.002$; medium effect size). Post-hoc tests revealed a significantly increased ankle plantarflexion angle peak ($>4.6^\circ$ on average) under FES conditions compared to S_0 ($P < 0.01$). Moreover, a significant increase in ankle plantarflexion angular velocity peak ($>50^\circ/\text{s}$) was observed in soleus ($P = 0.022$) and combined stimulation ($P = 0.014$) compared to S_0 . ANOVA showed significant effects on knee flexion ($P = 0.029$) and hip flexion angles ($P = 0.038$), but post-hoc tests indicated no significant difference ($P \geq 0.179$ and $P \geq 0.293$, respectively). No significant effect of the stimulation condition was observed

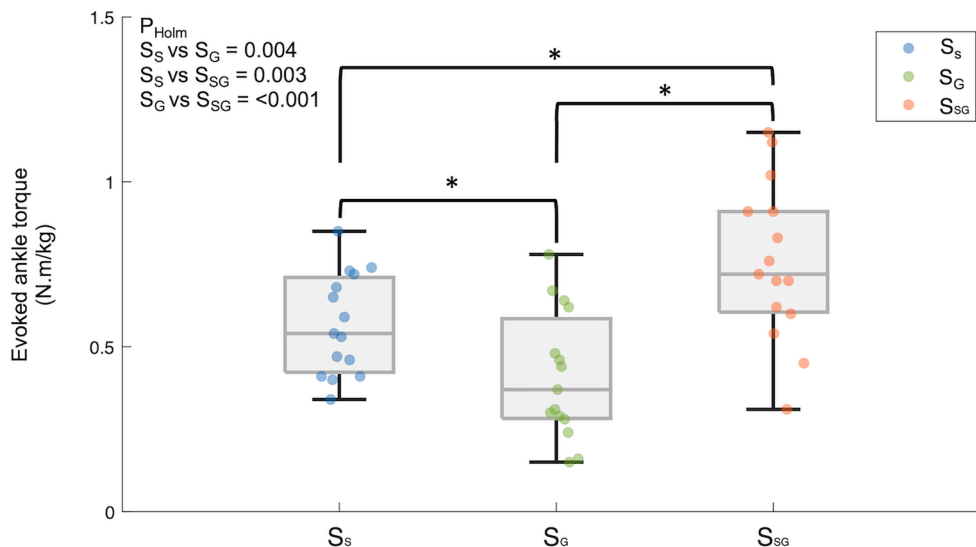


Fig. 3. Evoked ankle torque at rest normalized by subject mass for the three conditions with FES measured on the isokinetic dynamometer: gastrocnemius stimulation S_G ; soleus stimulation S_S ; and combined soleus and gastrocnemius stimulation S_{SG} . The boxplot represents the median, first and third quartiles, the whiskers being the minimal and maximal values. Dots are individual values.

Table 1

Means \pm standard deviations of the dependent variables related to the lower limb kinetics for each walking conditions with P-values of the repeated-measures ANOVAs and effect sizes (η^2). Symbols indicate significant differences: ● denotes a difference from S_0 ; ▼ from S_S ; ▲ from S_G and ★ from S_{SG} . AP: Anteroposterior; GRF: Ground reaction force.

Dependent variables	Conditions				Statistics		
	S_0 ●	S_S ▼	S_G ▲	S_{SG} ★	ANOVA P-value	η^2	
Peak of AP GRF (N/kg)	1.84 \pm 0.31 ▼▲★	2.12 \pm 0.31 ●	2.16 \pm 0.32 ●	2.17 \pm 0.28 ●	< 0.001	0.172	
Peak torque(N.m/kg)	ankle plantarflexion	1.31 \pm 0.17 ▼▲★	1.44 \pm 0.19 ●	1.44 \pm 0.22 ●	1.47 \pm 0.17 ●	< 0.001	0.106
	knee extension	0.18 \pm 0.05	0.19 \pm 0.05	0.20 \pm 0.07	0.19 \pm 0.06	0.143	0.017
	hip flexion	-0.44 \pm 0.16	-0.46 \pm 0.17	-0.45 \pm 0.16	-0.47 \pm 0.19	0.703	0.004
Peak power(W/kg)	Ankle (A2)	2.37 \pm 0.64 ▼▲★	2.94 \pm 0.55 ●	2.89 \pm 0.62 ●	3.04 \pm 0.54 ●	< 0.001	0.163
	Knee (K4)	-0.69 \pm 0.13	-0.72 \pm 0.18	-0.70 \pm 0.20	-0.74 \pm 0.24	0.738	0.011
	Hip flexion (H3)	0.90 \pm 0.14	0.99 \pm 0.26	0.92 \pm 0.21	0.97 \pm 0.26	0.198	0.025
Work(J/kg)	Ankle (A2)	0.23 \pm 0.07 ▼▲★	0.33 \pm 0.10 ●	0.29 \pm 0.08 ●▼	0.28 \pm 0.06 ●	< 0.001	0.169
	Knee (K4)	-0.08 \pm 0.01	-0.08 \pm 0.01	-0.08 \pm 0.02	-0.09 \pm 0.02	0.367	0.025
	Hip (H3)	0.22 \pm 0.11	0.26 \pm 0.10	0.29 \pm 0.12	0.24 \pm 0.13	0.573	0.022

Table 2

Means \pm standard deviations of the dependent variables related to the spatio-temporal parameters of gait for each stimulation condition with P-values of the repeated-measures ANOVA and effect size (η^2). Symbols indicate significant differences: ● denotes a difference from S_0 ; ▼ from S_S ; ▲ from S_G and ★ from S_{SG} .

Dependent variables	Conditions				Statistics	
	S_0 ●	S_S ▼	S_G ▲	S_{SG} ★	ANOVA P-value	η^2
Gait speed (m/s)	0.99 \pm 0.08 ▼▲★	1.15 \pm 0.08 ●	1.13 \pm 0.08 ●	1.18 \pm 0.08 ●▲	< 0.001	0.456
Cadence (step/min)	97.74 \pm 9.06 ▼▲★	104.57 \pm 7.24 ●	104.13 \pm 8.58 ●	104.61 \pm 8.31 ●	< 0.001	0.179
Step length (m)	0.69 \pm 0.07 ▼▲★	0.74 \pm 0.07 ●	0.73 \pm 0.08 ●	0.76 \pm 0.08 ●	0.002	0.122
Stance duration (%)	57.8 \pm 2.8	57.1 \pm 2.6	57.4 \pm 2.3	56.6 \pm 2.8	0.189	0.025
Propulsion phase duration (s)	0.32 \pm 0.03 ▼★	0.30 \pm 0.03 ●	0.31 \pm 0.03	0.29 \pm 0.03 ●	< 0.001	0.120

for the other kinematic variables ($P > 0.05$).

4. Discussion

Supporting our hypothesis, we found that FES applied to ankle plantarflexors during push-off increased ankle power and, consequently, enhanced propulsive force and forward progression parameters such as step length and walking speed. Furthermore, we noted that walking speed was increased by an extra 4.8 ± 5.5 % when the soleus and gastrocnemius were stimulated simultaneously compared with stimulation of gastrocnemius alone. The other effects on forward propulsion were similar regardless of the targeted muscles (gastrocnemius, soleus or combination of the two).

Specifically, we observed that the increases in ankle power

(22.2–28.3 % depending on the stimulation condition) and work (22.9–43.7 %) with FES were associated with concomitant increases in ankle torque (10.4–12.6 %) and angular velocity (17.2–25.2 %). These FES-induced adaptations in ankle biomechanics resulted in increased propulsive force (15.2–17.9 %) and consequently enhanced forward progression, in terms of walking speed (14.4–19.7 %), step length (5.7–11.1 %) and cadence (8.8–9.3 %). These findings are in line with the observations from previous studies which have shown that ankle plantarflexor muscles are major contributors to forward propulsion during walking (Cofré et al., 2011; Sutherland et al., 1980). Interestingly, these previous studies also reported that increased walking speed typically involves increased lower limb joint powers and a power redistribution among joints; the relative contributions of knee and hip powers increase with speed compared to the ankle one (Cofré et al., 2011). In the present study, we observed an increased ankle power without changes in knee and hip powers (K4 and H3, respectively), despite a walking speed increase. This supports that the changes observed in the present study cannot be explained only by the increase in gait speed due to possible volitional muscle contractions, but are also the result of specific adaptations induced by the application of FES to ankle plantarflexors during push-off. These findings suggest that FES has the potential to redistribute joint powers during walking. Future studies should examine whether FES may be a solution to counteract the age-related disto-proximal redistribution of joint powers, which is detrimental to dynamic balance (Browne and Franz, 2019) and gait economy (Pieper et al., 2021).

Our results are in agreement with the previous studies reporting that the application of FES to ankle plantarflexors can be used to modify gait biomechanics in young healthy adults (Francis et al., 2013; Lenhart et al., 2014; Stewart et al., 2007; Thorp and Adamczyk, 2020). However, there are discrepancies between our findings and those of these previous studies. When stimulating the soleus vs. the gastrocnemius during midstance, Francis et al. (2013), Lenhart et al. (2014) and Stewart et al. (2007) reported opposite effects on gait as stated in the introduction (increased propulsion, plantarflexion and knee flexion vs. increased breaking, dorsiflexion, and knee extension, respectively). During the push-off phase, our results reveal that the isolated and simultaneous simulations of these muscles increased the forward propulsion and the ankle plantarflexion kinematics similarly, without modifying hip and knee biomechanics. These seemingly contradictory results may be justified by the differences in FES settings, especially the stimulation

Table 3

Means \pm standard deviations of the dependent variables related to the lower limb kinematics for each stimulation condition with P-values of the repeated-measures ANOVA and effect size (η^2). Symbols indicate significant differences: ● denotes a difference from S_0 ; ▼ from S_S ; ▲ from S_G and ★ from S_{SG} .

Dependent variables		Conditions				Statistics	
		S_0 ●	S_S ▼	S_G ▲	S_{SG} ★	ANOVA P-value	η^2
Peak angle (°)	ankle plantarflexion	21.5 \pm 3.3 ▼▲ ★	26.9 \pm 4.9 ●	26.1 \pm 3.4 ●	26.6 \pm 4.6 ●	< 0.001	0.222
	ankle dorsiflexion	11.3 \pm 3.1	11.6 \pm 2.8	11.9 \pm 3.2	11.7 \pm 3.3	0.847	0.004
	knee flexion	57.7 \pm 6.7	59.3 \pm 6.0	60.0 \pm 6.3	59.5 \pm 5.7	0.029	0.019
	knee extension	5.3 \pm 2.3	4.7 \pm 2.5	4.5 \pm 2.7	4.7 \pm 2.1	0.153	0.015
	hip flexion	26.7 \pm 4.3	28.6 \pm 4.0	28.6 \pm 4.5	29.3 \pm 4.4	0.038	0.047
	hip extension	8.4 \pm 4.6	8.7 \pm 2.1	8.5 \pm 2.0	8.9 \pm 2.2	0.947	0.003
Peak angular velocity (°/s)	ankle plantarflexion	187.1 \pm 54.6 ▼ ★	234.2 \pm 50.8 ●	219.3 \pm 52.5	227.6 \pm 40.2 ●	0.002	0.043
	ankle dorsiflexion	151.9 \pm 56.5	172 \pm 48.9	159.3 \pm 45.9	169.4 \pm 51.7	0.123	0.024
	knee flexion	261.5 \pm 44.7	276.3 \pm 47.9	282.9 \pm 60.4	273.3 \pm 48.4	0.268	0.023
	knee extension	371.5 \pm 10.5	370.7 \pm 10.4	364.4 \pm 15.9	373.1 \pm 11.7	0.820	0.012
	hip flexion	174.1 \pm 15.5	185.2 \pm 19.8	179.1 \pm 23.6	186.1 \pm 28.7	0.302	0.045
	hip extension	88.5 \pm 12.6	91.1 \pm 17.9	88.6 \pm 12.7	91.2 \pm 15.0	0.546	0.008

timing (midstance vs. push-off phases). During the midstance phase, the soleus and gastrocnemius muscle function is to support the trunk and prevent leg collapse by generating vertical forces, while in the midstance to pre-swing phases, they accelerate the center of mass forward (Neptune et al., 2001; Zajac et al., 2003). This reinforces that gastrocnemius and soleus muscles have distinct actions during midstance and synergistic actions during push-off. However, it should be noted that Lenhart et al. (2014) reported enhanced hip and knee flexions when stimulating the gastrocnemius in the push-off phase (but not with the soleus) based on Tukey's post-hoc tests. Although the ANOVAs for knee and hip flexion angles were significant in our study, our post-hoc tests (Holm-Bonferroni method) did not reveal any differences between conditions. The angular changes detected in our study and others (Lenhart et al., 2014; Stewart et al., 2007) could be due to a confounding factor: the walking speed (Fukuchi et al., 2019). Future research should administer FES under speed-controlled conditions to better understand how FES influences gait biomechanics.

Regarding muscle force gain under electrical stimulation, previous studies have shown that, when electrical stimulation is superimposed on voluntary contraction, the total force generated by the muscle was not the sum of the forces in response to electrical stimulation and volitional contraction (Perumal et al., 2010; Williams and Bilodeau, 2004). Specifically, according to the phenomenological model of Perumal et al. (2010), the additional force evoked by FES declines proportionally to the volitional contraction level. Briefly, volitional and FES-induced activations overlap in targeting some motor units, since the recruitment order by voluntary activation follows the Henneman's size principle, whereas that due to FES is more random (Wiest et al., 2017). Moreover, the antidromic action potentials due to FES may collide with the volitional action potentials and reduce the motoneuron discharge rate. Our results are consistent with these previous observations. For example, we noted that FES-evoked torque at rest was 0.57 ± 0.15 Nm/kg (24.8 % MVIC) when the soleus alone was stimulated. During walking without stimulation, the voluntary plantarflexor peak torque was 1.31 ± 0.17 Nm/kg (57.2 %MVIC) and increased by 0.14 ± 0.14 Nm/kg in the FES condition (S_S). This gain corresponds only to quarter of the evoked torque at rest. It underlines the lack of a direct association between isometric torque evoked at rest and increased performance when FES is superimposed on voluntary contractions. While some loss in FES-evoked force during gait may be explained by the model of Perumal et al. (2010) in isometric condition, the muscle force-length-velocity relationship and a possible reduction of voluntary contraction may also affect the joint torque during gait. Future studies should consider studying muscle

activity (EMG) in order to better understand the interaction between FES and volitional activity during walking.

Moreover, we noted that the combined stimulation of the soleus and gastrocnemius led to the highest torque at rest and the greatest increase in walking speed ($+0.19$ m/s from S_0), although not significantly higher than the soleus FES condition. The evoked torque obtained by the combined stimulation corresponded to 42.8 ± 6.7 % of the sum of the torque produced by the stimulation of each muscle alone. However, during gait, the use of combined stimulation resulted in a small, non-significant enhancement of ankle peak power and moment compared to isolated muscle stimulation (Table 1). As we did, Williams and Bilodeau, (2004) found that combined stimulation of two synergistic muscles (biceps brachii and brachioradialis) produced greater torque at rest than stimulating the biceps alone, but did not elicit greater additional torque when superimposed on voluntary isometric contractions. Indeed, stimulating one muscle using surface electrodes may cause spillover to the other muscle, especially from the gastrocnemius to the soleus, with large pulse widths propagating deeply (Vieira et al., 2017). In other words, the measured torque did not result from a single muscle. Furthermore, although gastrocnemius and soleus stimulations resulted in comparable walking speeds, soleus stimulation produced 6.7 % more plantarflexor isometric torque at rest and a substantial increase (11 %) in ankle work during gait. This indicates that torque production in an isometric condition is not a predictor of increased walking speeds. The interaction between muscle force and multibody dynamics in gait is complex and nonlinear, emphasizing the necessity for full biomechanical analysis.

Our study has certain limitations. Firstly, the maximal pulse width was reached by seven participants, which probably slightly underestimates the effects reported in the present study. Secondly, we decided not to assess muscle activation due to FES artefacts on EMG, even though algorithms exist to remove them (Hambly et al., 2024). Finally, inter-participant variability in their mechanical (and perceptual; not reported in this paper) response to FES may require preliminary sessions to habituate to the stimulations. It is likely that a longer familiarization period to FES could lead to greater and more homogeneous gait improvement.

In conclusion, our results underline that applying FES to the gastrocnemius and soleus, separately or simultaneously during the push-off phase, enhanced forward propulsion in able-bodied adults. Simultaneous stimulation provided the greatest walking speed enhancement, although this was only found in comparison with stimulation of the gastrocnemius alone. The present findings could be particularly useful

for designing FES-based solution for improving gait in healthy people with propulsion deficits, such as the elderly.

CRedit authorship contribution statement

Thomas Aout: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Mickaël Begon:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Nicolas Peyrot:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Teddy Caderby:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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