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► **To cite this version:**

Thomas Aout, Mickaël Begon, Nicolas Peyrot, Teddy Caderby. Redistribution of lower limb joint work during gait in healthy young adults using functional electrical stimulation. *Multidisciplinary Biomechanics Journal*, 2025, 49th congress of the Société de Biomécanique, 10.46298/mbj.14474 . hal-04737945v2

**HAL Id: hal-04737945**

**<https://hal.science/hal-04737945v2>**

Submitted on 31 Jan 2025

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# Redistribution of lower limb joint work during gait in healthy young adults using functional electrical stimulation

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Received date: 06/04/2024

Accepted date: 28/06/2024

Publication date: 31/01/2025

**Keywords:** walking, joint work, ankle muscles

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Published by Société de Biomécanique

## 1. Introduction

Ankle plantarflexor muscles, particularly soleus and gastrocnemius muscles, are major contributors to forward propulsion during healthy walking (Neptune et al. 2001). By generating positive ankle work during the push-off phase of gait, these muscles contribute to producing the propulsive force accelerating the whole-body forwards. Any impairment in the force-generating capacities of these muscles may therefore alter propulsion during gait. For instance, it has been shown that age-related weakness in these muscles contributes to decreased ankle work, leading consequently to a decreased gait speed in older adults (Browne and Franz 2019). As an attempt to compensate, older adults increase the work at proximal joints, i.e., hip and knee, which may in turn increase their instability and energy expenditure during walking compared to their young counterparts. Designing solutions to enhance the plantarflexor propulsive function could therefore help reduce the risk of falling and promote walking activity in the elderly. Functional electrical stimulation (FES) is a solution to restore the propulsive function of the plantarflexors in disabled people, such as post-stroke patients (Kesar et al. 2009). Furthermore, we recently showed that applying FES to gastrocnemius and soleus separately or simultaneously, induced an increase in ankle work during gait and consequently led to an increase in propulsive force and gait speed in young healthy adults (Aout et al. 2024). These changes were also accompanied by increased hip work, probably due to the faster gait. Thus, to date,

it remains unclear whether these changes in the joint work of the lower limb were exclusively ascribed to FES, as gait speed was increased. This study aimed to investigate the effects of applying FES to gastrocnemius and soleus, separately and simultaneously, on the joint work of the lower limb during walking at controlled speeds in young healthy adults.

## 2. Methods

### 2.1 Population

Fifteen healthy young adults volunteered for this study (13 Males; age:  $22 \pm 3$  years) and gave their consent after being fully informed of the test procedure.

### 2.2 Experimental setup

Before walking trials, two footswitches were placed under the calcaneum and the first metatarsal of each foot and coupled with two wearable stimulators (O2CHSII, UK) able to stimulate either the soleus, gastrocnemius, or both muscles for each lower limb. Retroreflective markers were fixed bilaterally on bony landmarks according to Vicon's Plug-in-Gait lower-body model. A 14-camera motion capture system (Vicon, UK) was used to collect the kinematic data at 200 Hz. Two force plates (60x40 cm, AMTI, USA), embedded in the middle of a walkway, measured the forces at 1000 Hz, and photoelectric cells were used to measure the gait speed. Participants performed five walking trials along a 7-m walkway at controlled walking speed in six randomized conditions by pairs: 1) Soleus stimulation ( $S_s$ ); 2) No

stimulation at the same speed as  $S_S$  condition ( $WS_S$ ); 3) Gastrocnemius stimulation ( $S_G$ ); 4) No stimulation at the same speed as  $S_G$  condition ( $WS_G$ ); 5) Combined stimulation of the Soleus and Gastrocnemius muscles ( $S_{SG}$ ); 6) No stimulation at the same speed as  $S_{SG}$  condition ( $WS_{SG}$ ). Target gait speeds were beforehand determined by asking subjects to walk at their self-selected speed under each stimulation condition ( $S_S$ ,  $S_G$  and  $S_{SG}$ ). The stimulation was applied during the push-off phase, i.e., from heel-off to toe-off, at the maximum tolerable intensity (just below the pain threshold).

### 2.3 Data processing

Data were extracted using Nexus Software with the Vicon Plug-in-Gait model, with marker trajectories low-pass filtered using a 10-Hz second-order Butterworth filter. These data were then processed into custom Matlab programs for analysis of gait kinematics, kinetics, and spatiotemporal parameters. This analysis extended to positive mechanical work for each joint, calculated as the time-integral of positive joint power during the gait cycle. The relative contribution of each joint to the total positive work of the lower limb in the sagittal plane was calculated by dividing the positive work at each joint by the sum of the positive work values of the three joints (ankle, knee, hip) and expressed in percentage.

### 2.4 Statistical analysis

Two-way repeated measures ANOVAs were conducted to assess the effects of FES (with and without) and muscles targeted (soleus, gastrocnemius, and both simultaneously) on gait parameters. Only the effects of FES and FES  $\times$  Muscle interaction were reported. The level of statistical significance was set at  $P < 0.05$ .

## 3. Results and discussion

ANOVA revealed no significant effect of FES on gait speed, step length, step frequency, and peak of anteroposterior ground reaction force ( $P > 0.05$ ). In contrast, we found that FES significantly increased ankle positive work ( $P = 0.004$ ; Table 1). This is consistent with our early findings (Aout et al. 2024). We previously showed that FES applied to ankle plantarflexors (soleus, gastrocnemius, or both simultaneously) produced an increase in ankle positive work and power, which in turn contributed to an increase in gait speed. In the present experiment, gait speed was controlled to compare the effects of FES at similar gait speeds. Our present results

indicate that, contrary to ankle work, the positive knee work decreased under FES when walking at the same speed ( $P = 0.002$ ), while positive hip work was not affected ( $P > 0.05$ ). Consequently, FES induced an increase in the ankle contribution to the total lower limb positive work ( $P = 0.001$ ), and a decrease in the contribution of knee ( $P < 0.001$ ). The contribution of hip joint to positive total work remained unchanged ( $P > 0.05$ ). These results suggest that applying FES to plantarflexors during push-off leads to a proximal-to-distal redistribution of the joint work of the lower limb when walking at similar speeds. Future studies should examine whether FES could be used to reverse or attenuate the distal-to-proximal redistribution of joint work of the lower limb associated with aging (Browne and Franz 2019).

**Table 1.** Joint work and relative contribution.

Variables		$WS_S$	$S_S$	$WS_G$	$S_G$	$WS_{SG}$	$S_{SG}$
Positive Work	Ankle (J/kg)	0.24±0.02	0.26±0.03	0.25±0.02	0.27±0.03	0.25±0.03	0.26±0.03
	Knee (J/kg)	0.08±0.01	0.08±0.01	0.09±0.01	0.07±0.01	0.09±0.01	0.08±0.01
	Hip (J/kg)	0.21±0.03	0.20±0.03	0.20±0.03	0.20±0.03	0.22±0.03	0.22±0.03
Relative contribution	Ankle (%)	45.6±3.4	47.4±4.0	46.7±3.5	49.1±3.5	44.9±3.8	46.5±3.8
	Knee (%)	15.8±3.0	14.9±2.4	16.2±2.7	13.9±3.0	15.7±2.2	14.1±2.4
	Hip (%)	38.6±4.4	37.7±4.4	37.1±4.2	37.1±4.2	39.4±4.9	39.4±4.2

Without Stimulation (WS) and Stimulation (S) conditions for soleus (<sub>S</sub>), gastrocnemius (<sub>G</sub>) and both muscles (<sub>SG</sub>)

## 4. Conclusions

FES may be used to redistribute joint work of the lower extremity during walking in young healthy adults. Applying FES to ankle plantarflexors during push-off phase increased positive ankle work and decreased positive knee work during walking at similar speeds.

## Funding

This work was supported by a Regional Research Grant from the Réunion Region (#338715) and European Regional Development Fund. This work is part of the e-WALKING project (ANR-22-CE19-0009) funded by the French National Research Agency.

## Conflict of interest statement

The authors report no conflict of interest.

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