EFFECT OF ENHANCED ABDUCTOR HALLUCIS CONTRACTION ON FOOT BIOMECHANICS IN GAIT

Jiaqi Lai[1], Xuehua Wu[1], Ting Yu[1], Xianyi Zhang[1]

[1] Department of Biomedical Engineering, Sun Yat-sen University, Guangzhou, China

This study aimed to investigate the effect of enhancing abductor hallucis (AbH) contraction by electrical stimulation (es) on foot biomechanics in gait. Ten healthy adults were recruited for this study. Ground reaction forces (GRFs) and navicular tuberosity (NAV) movement were recorded with and without AbH es during walking. The results showed that enhancing the AbH contraction reduced the range of motion of the NAV height (p=0.030). Meanwhile, the medial GRF was higher in the final stance and the center of pressure (COP) was laterally shifted in the whole stance phase. In conclusion, enhancing AbH contraction could stiffen the foot arch in gait and aid the body shift to the contralateral side in the final stance which may have the potential to inspire the intervention for individuals with arch collapse.

KEYWORDS: ground reaction forces, electrical stimulation, center of pressure, foot arch

INTRODUCTION: Abductor hallucis (AbH) is one of the largest intrinsic foot muscles. It has been proved that AbH plays an important role in human motion (McKeon et al., 2015) since its contraction increases with the increasing postural demand (Kelly et al., 2012) and it can control the deformation of the longitudinal arch (Kelly et al., 2014) in static postures.
In recent years, the importance of the dynamic function of AbH has been explored by researchers. The intrinsic foot muscles are continuously active while the activities of extrinsic muscles decline in the push-off phase in the gait cycle (Akuzawa et al., 2023). Therefore, when the intrinsic foot muscles were nerve-blocked, intrinsic foot muscles could not stiffen the distal foot to aid push-off against the ground during walking (Farris et al., 2019). Besides, higher AbH activation was found in individuals with chronic ankle instability than in healthy individuals after initial metatarsal contact during running tasks (Watanabe et al., 2024), as a strategy to compensate for ankle instability. These studies have indicated how the contraction characteristics of AbH influenced the kinematic characteristics of dynamic motion, revealing the importance of AbH contraction in human motion performance.
However, how AbH contraction influences the dynamic mechanical characteristics of the foot remains unclear. It may limit the understanding of the AbH's contribution in gait and design of ABH-related interventions for arch-related malfunction like arch collapse(McKeon et al., 2015). Therefore, this pilot study aimed to investigate the effect of enhanced AbH contraction on foot biomechanics during walking. We hypothesized that electrically enhanced AbH would stiffen the foot arch and thus reduce arch deformation during walking. Considering the activation characteristics of abductor hallucis in gait (Akuzawa et al., 2023), it was also hypothesized that electrically enhanced AbH activation may alter the ground reaction forces (GRFs) and shift center of pressure (COP).

METHODS: Ten healthy participants (5 female and 5 male) with no history of the neuromuscular disorder or lower limb injury in the previous six months volunteered to participate in the study (Age: 21.5 ± 1.4 years old; Height: 167.3 ± 5.8 cm; Body mass: 55.8 ± 9.1 kg). All participants gave informed written consent in accordance with the requirements of the Ethics Committee of Sun Yat-sen University. Participants were asked to keep 10s double leg standing with and without the electrical stimulation (es) of AbH to record static data. Then, they were asked to walk three times along a 10m walkway with a force platform (type: 9260AA6, Kistler, Winterthur, Switzerland, sampling at 1000 Hz) at their preferred speeds with and without the electrical stimulation of AbH. The motion trajectory of navicular tuberosity (NAV) was recorded by a 14-camera optical motion capture system (Prime^{X} 41, Optitrack, USA, sampling at 100 Hz). A trial was recorded when the walking speed was within the 5% error of the preferred speed of the participant.

A constant-current electrical stimulator (Digitimer DS7A, Digitimer, Hertfordshire, UK) was connected to electrodes with the cathode connected to the motor point of AbH and anode to the 1st metatarsal phalangeal joint (1MPJ) in gait with ABH es (James et al., 2018). Continuous square-wave (1ms wide pulse, 100 Hz) pulses were delivered to AbH with maximum tolerated current intensity. The determination of the motor point of AbH followed the protocol described by James et. al.(James et al., 2018). A 7 × 4cm matrix was drawn on the skin overlying the AbH with the navicular tuberosity serving as the reference point. A hand-held pen electrode (Motor Point Pen Electrode, Digitmer, Hertfordshire, UK) acted as a cathode and the anode was fixed over the 1MPJ. A single square-wave (1ms wide pulse) pulse with increasing current intensity was delivered systematically over each point of the matrix until a clear and visible twitch was observed by the researcher, indicative of the AbH motor point. The current intensity in gait via direct muscle stimulation was then determined by delivering a 5s train of square-wave pulses (1ms wide pulse) at 100 Hz with current intensity starting at 1 mA and increasing in 0.5 mA increments until reaching the maximum tolerated current intensity of the volunteer, the evoked force was recorded by a uniaxial force transducer. The mean maximum tolerated current intensity was 4.6 ± 2.0 mA, producing 6.8 ± 4.0 N AbH force.
All acquired data were analyzed using custom MATLAB routines (version R2021a, MathWorks, Natick, USA). The statistical parametric mapping (SPM) approach was used for the statistical analyses of one-dimensional data (https://spm1d.org/index.html). The paired sample t-test method was used to compare the differences in NAV height and range of motion (ROM) between the natural condition and the AbH es condition in SPSS 26.0 (SPSS, IBM, USA). The hypothesis test was performed at a significance level of 0.05.

RESULTS: The height of NAV with AbH electrical stimulation during double leg standing was significantly higher than that in the normal situation (p=0.027, see Figure 1A), while the ROM of NAV height was lower with AbH electrical stimulation in gait than that in the normal situation (p=0.030, see Figure 1B).

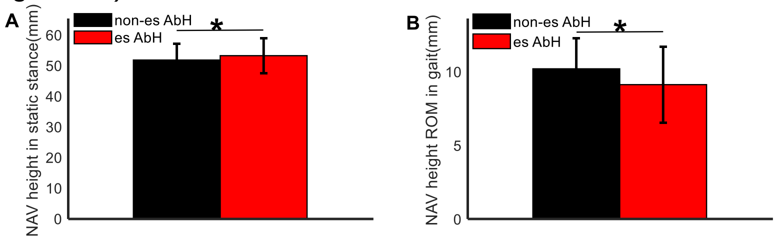

Figure 1 NAV height characteristics with and without electrically stimulating AbH. (A) NAV height during the static stance; (B) range of motion of NAV in gait. *p<0.05. Abbreviation: AbH=abductor hallucis; es = electrical stimulation; ROM = range of motion; NAV = navicular tuberosity.

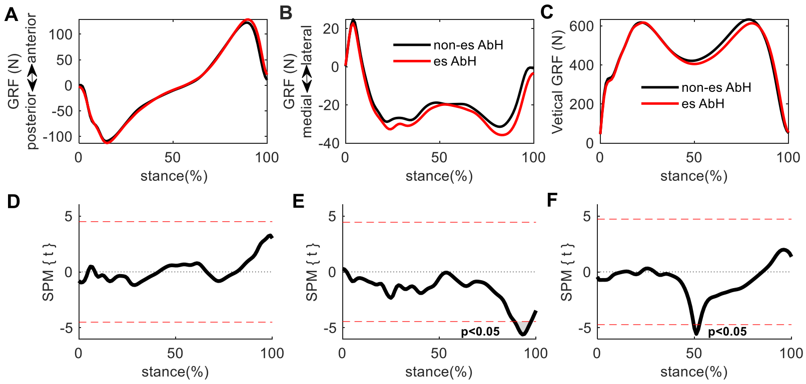

Figure 2 The GRFs with and without electrically stimulating AbH in gait. (A) anterior-posterior GRF; (B) medial-lateral GRF; (C) vertical GRF; (D), (E) and (F) are the SPM results corresponding to (A), (B) and (C). Abbreviation: AbH=abductor hallucis; GRF = ground reaction force; es = electrical stimulation; SPM = statistical parametric mapping.

The SPM result showed that there was no significant difference in anterior-posterior ground reaction force (GRFap) between gait with and without electrically stimulating AbH (see Figures 2A and 2D). The medial ground reaction force (GRFml) was higher in the terminal stance with

electrically stimulating AbH than under the natural condition (see Figures 2B and 2E) while the vertical ground reaction force (GRFvertical) was significantly decreased in the midstance with electrically stimulating AbH (see Figures 2C and 2F).
The SPM result showed that there was no significant difference in the anterior-posterior center of pressure (COPap) between gait with and without electrically stimulating AbH (sees Figure 3A and 3C) while the center of pressure was more lateral in gait with electrically stimulating AbH than under the natural condition (see Figures 3B and 3D).

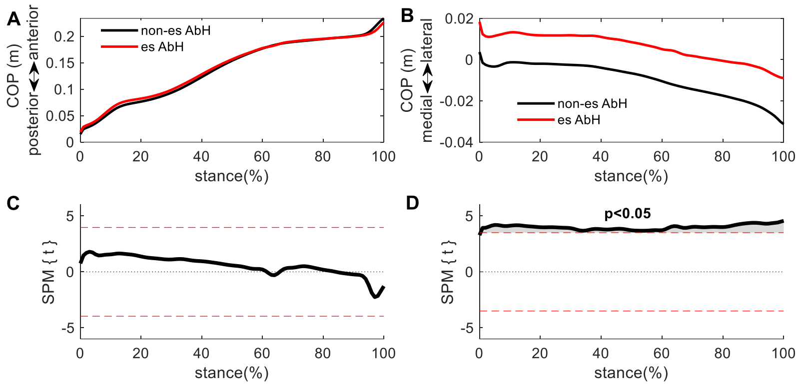

Figure 3 The center of pressure in gait with and without electrically stimulating AbH in gait. (A) anterior-posterior center of pressure; (B) medial-lateral center of pressure; (C) and (D) are the SPM results corresponding to (A) and (B). Abbreviation: AbH=abductor hallucis; COP = center of pressure; es = electrical stimulation; SPM = statistical parametric mapping.

DISCUSSION: The foot kinematic effects of AbH contraction were reported in the introduction. Thus, this study set out to test whether electrically enhanced AbH contraction resulted in the alteration of foot arch height and foot biomechanics in gait. Stimulation of AbH could increase the foot arch height in statics posture and stiffen the foot arch in gait by reducing the ROM of NAV height, which is consistent with previous studies on static postures (Kelly et al., 2014). Though the previous study showed that the stiffness of the foot arch was not altered by the nerval block of intrinsic foot muscles(Farris et al., 2019), our results showed that increasing the contraction of AbH would reduce the range of motion of NAV height. It indicated that the increase of the AbH contraction will further stiffen the foot arch in gait, but the weakening of AbH contraction may not affect the arch stiffness, possibly due to other foot muscles supporting the foot arch to compensate for weak AbH.
A novel aspect of our study was the use of electrical stimulation in addition to three-dimensional ground reaction force to provide detailed insights into the biomechanical capability of AbH. Our results showed that enhancing the AbH contraction could increase the medial GRF in the final stance of gait. In line with our result, a previous study suggested that individuals with relatively stiff arches experience a greater ground reaction force in the medial-lateral plane of motion, as compared with those with more flexible arches(Zifchock et al., 2019). Besides, the magnitude and direction of GRFml depend mostly on the relationship between the position of the body's center of mass and the location of the foot. Therefore, the increase of medial GRF in the final stance suggested that increasing AbH contraction accelerated the center of mass medially toward the contralateral lower extremity by increasing the medial GRF during the push-off phase in gait, which is swinging forward and preparing to make the next foot contact with the ground(John et al., 2012). This result suggested that enhanced AbH activation may potentially be used to improve the gait push-off biomechanics of the individuals with overflexible foot arch (Zifchock et al., 2019). Besides, our results showed the vertical GRF with electrically stimulating AbH was lower in the midstance of gait than that without electrically stimulating AbH. The vertical GRF in midstance was related to the plantar fascia load (Boonchum et al., 2022). The significant reduction of vertical GRF in midstance found in this study could be explained as the effect of AbH contraction on foot arch stiffness to protect load on the fascia over midstance (Boonchum et al., 2022).
Additionally, the center of pressure is also affected by the increase of AbH contraction. Enhancing AbH contraction contributes to the more lateral COP in gait, indicating the reduction

of the foot medial loading. Previous studies showed that the COP of individuals with flatfeet was more medial than individuals with neural feet (Yan et al., 2020) which was associated with medial soft tissue injury risks(Williams et al., 2001). It may indicate that the individual with flatfeet may be possible to reduce the risk of injury by increasing the AbH contraction to decline the foot medial loading.

CONCLUSION: This study investigated the effect of the increase of AbH contraction via electrical stimulation on foot biomechanics in gait. Increasing AbH contraction could stiffen of foot arch in gait and aid body shift to the contralateral side in the final stance of gait. Besides, increasing AbH contraction contributed to decreasing the foot medial load by shifting the COP laterally, which could potentially be used to reduce medial injury risk in individuals with arch collapse.

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