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Effects of a Single Electrical Stimulation Session on Foot Force Production, Foot Dome Stability, and Dynamic Postural Control

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Context: Mounting evidence suggests neuromuscular electrical stimulation (NMES) as a promising modality for enhancing lower limb muscle strength, yet the functional effects of a single electrical stimulation session for improving the function of the intrinsic foot muscles (IFM) has not been evaluated.

Objective: To investigate the immediate effects of an NMES session compared with a sham stimulation session on foot force production, foot dome stability, and dynamic postural control in participants with static foot pronation.

Design: Randomized controlled clinical trial.

Setting: Laboratory.

Patients or Other Participants: A total of 46 participants (23 males, 23 females) with static foot pronation according to their Foot Posture Index (score $\geq$ 6) were randomly assigned to an NMES (n = 23) or control (n = 23) group.

Intervention(s): The NMES group received a single 15-minute NMES session on the dominant foot across the IFM. The control group received a 15-minute sham electrical stimulation session.

Main Outcome Measure(s): All outcome measurements were assessed before and after the intervention and consisted of foot force production on a pressure platform, foot dome stability, and dynamic postural control. Statistical analysis was based on the responsiveness of the outcome measures and responder analysis using the minimum detectable change scores for each outcome measure.

Results: In the NMES group, 78% of participants were classified as responders for at least 2 of the 3 outcomes, compared with only 22% in the control group. The relative risk of being a responder in the NMES group compared with the control group was 3.6 (95% CI = 1.6, 8.1]. Interestingly, we found that all participants who concomitantly responded to foot strength and navicular drop (n = 8) were also responders in dynamic postural control.

Conclusions: Compared with a sham stimulation session, a single NMES session was effective in immediately improving foot function and dynamic postural control in participants with static foot pronation. These findings support the role of NMES for improving IFM function in this population.

Key Words: neuromuscular electrical stimulation, intrinsic foot muscles, foot strength, foot deformation

Key Points

- Neuromuscular electrical stimulation showed promising clinical effects on foot function after one 15-minute session.
- Participants randomized to the neuromuscular electrical stimulation group enhanced foot force production, foot dome stability, and dynamic postural control of their stimulated foot.
- Activating the intrinsic foot muscles through neuromuscular electrical stimulation may enhance their functional role, but the mechanism underlying this improvement remains unclear.

The human foot is a complex structure with multiple joints and degrees of freedom that play important roles in static and dynamic activities. As the first interface between the body and the ground, the foot absorbs the forces from ground contact, supports body weight during stance, and generates forces for propulsion.[1] The intrinsic foot muscles (IFM) are the main local foot stabilizers and part of the active and neural subsystems that comprise the foot core system.[2] Authors[3,4] of previous studies demonstrated a potential role of the IFM in supporting the functional half dome of the foot. Several researchers have advocated for IFM strengthening in managing injuries such as plantar heel pain,[5] lateral ankle sprains, and chronic ankle instability.[6] In addition, recent evidence[7,8] suggested that these muscles are more likely to provide forefoot stability for push-off against the ground, challenging the theory that the source of rigidity in this phase was linked to the stretch of the plantar aponeurosis via toe extension (*windlass mechanism*). This highlights the need for interventions that enhance the IFM contribution to foot dome stability.[9]

The short foot exercise is a popular intervention for training control and capacity of the IFM.[10] Individuals with overpronated feet reduced their foot deformation and demonstrated improved dynamic postural control after training.[11] Nevertheless, this exercise remains challenging and requires good volitional control of the IFM, especially the abductor hallucis (AbH)—a muscle that is difficult for healthy people to activate.[12,13] To counter this difficulty, multiple sessions of neuromuscular electrical stimulation (NMES) augmented the recruitment of the IFM, improved foot plantar pressure patterns and foot dome stability,[14,15] and indirectly enhanced AbH strength and activity in comparison with the short foot exercise alone.[16] Remarkably, even a single 20-minute NMES session on the AbH induced an immediate and long-lasting effect that improved the raising of the functional half dome of the foot.[17] These promising outcomes were recently confirmed by Shimoura et al,[18] who reported that 1 NMES session on the AbH muscle immediately improved its activity, muscle strength, and hallux valgus angle during exercise. However, whether a single NMES session compared with a sham stimulation would enhance foot strength, foot stability, and dynamic postural control, as reported after a several-session NMES strengthening protocol, remains unclear. Also uncertain is whether the changes in these outcomes are true improvements beyond the error of the instruments used to capture them.

When investigators evaluate IFM strengthening and its potential effects on foot control, assessing foot strength is critical yet challenging. A method for evaluating maximal foot strength using a pressure platform has been described in which toe flexion against the platform allows for a valid and repeatable measurement of foot force production.[19] Interestingly, the authors reported that standing toe flexion on a pressure mat engaged the AbH more than a custom toe-flexion device. As the IFM and especially the AbH play important roles in foot dome stability during standing[3,4] as well as dynamic postural control,[11] whether a single NMES session on the AbH would alter these outcome measures is unknown. We therefore aimed to evaluate the effects of a single NMES session on foot force production against a pressure platform, foot dome stability, and dynamic postural control in participants with static foot pronation. We hypothesized that compared with a sham stimulation session, 1 NMES session would result in meaningful improvements in foot strength, foot dome stability, and dynamic postural control on the stimulated side.

METHODS

Participants

We prospectively enrolled 46 participants using the following inclusion criteria: (1) age between 18 and 60 years; (2) foot posture index (FPI) between +6 and +12, indicating *slight* (+6 to +9) or *marked* (+10 to +12) pronation (Figure 1)[20]; and (3) no experience with any type of electrical stimulation. Exclusion criteria were (1) a history of foot and ankle sprain or pain in the past 3 months; (2) a leg or foot fracture in the past year or severe foot deformity; (3) neurologic impairment in the lower limb or vestibular balance impairment (diabetes mellitus, lumbosacral radiculopathy, or soft tissue disorder [Marfan or Ehlers-Danlos syndrome]); (4) contraindication to NMES (pacemaker, seizure disorder, or pregnancy); or (5) previous foot strengthening experience (NMES or IFM strengthening exercises). All participants gave written informed consent, and the study protocol was approved a priori by the local Swiss ethical committee (#2020-0053) and registered on ClinicalTrials.gov (identifier NCT04421794). The entire study (participant evaluation, interventions, and data collection) took place at the Physiotherapy Department of the La Tour Hospital (Meyrin, Switzerland) from July to September 2020.

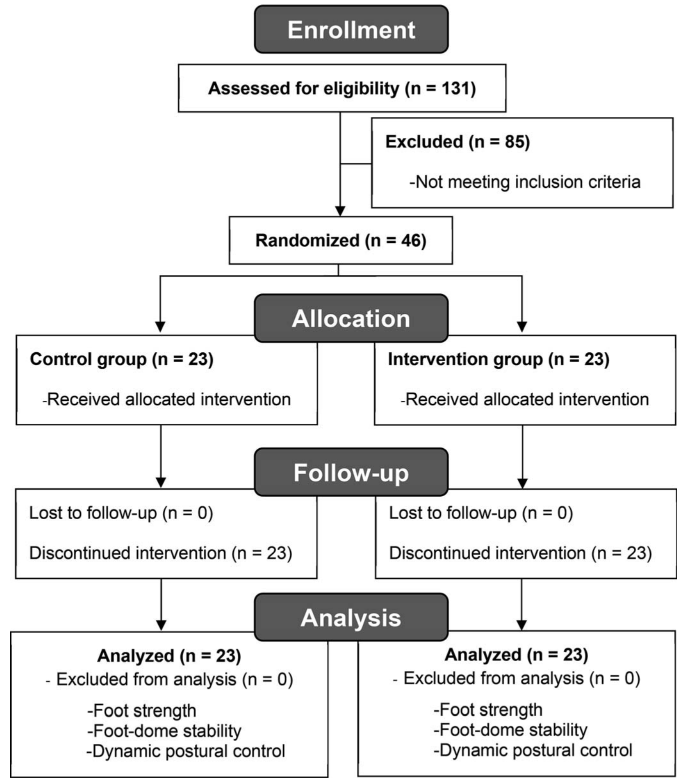

Figure 1. Consolidated Standards of Reporting Trials flow diagram.

Randomization and Blinding

We randomized participants into 2 groups: intervention (NMES) or control. The randomization was performed by an independent researcher using a permuted block-randomization technique with blocks of 5 or 6 participants on a 1:1 ratio. Although all participants were blinded to the intervention allocation until the study ended, the physiotherapist in charge of the outcomes (R.T.) was aware of each participant's allocation.

Preintervention and Postintervention Evaluations

General demographic information was collected to identify any group differences in age, height, body mass index, FPI, or *lower limb dominance* (as determined by asking the foot preference in 2 out of 3 activities [response to push, step-up, and ball kick]).[19] The first session was a familiarization session in which participants were exposed to the outcome measurements of interest: foot strength, foot dome stability, and dynamic postural control. The second session occurred 7 days after the first session and consisted of the *preintervention* (at 10 minutes of rest before the intervention) and *postintervention* (10 minutes after) measurements. Outcome measurements were performed on each limb (dominant and nondominant) in random order before and after the intervention.

Foot Strength (Metatarsophalangeal Flexion on Pressure Platform). Foot force production was assessed using a pressure platform (model FDM-THQ; Zebris Medical GmbH) with 1 video camera (model SC-1 SYNCCam; Zebris Medical Gmbh). While standing, participants placed their foot on the treadmill (same model as the pressure platform; in static mode with speed at 0 km/h) with the knee fully extended in single-legged stance with a pitch-fingers technique to reduce trunk fluctuation (see Supplemental Figure, available online at https://doi.org/10.4085/1062-6050-0561.21.S1). They were subsequently instructed to flex the metatarsophalangeal (MTP) joints as hard as possible on the pressure platform and maintain this position for 5 seconds before relaxing. We chose this isolated active MTP joint flexion (pushing) task without associated interphalangeal joint flexion (gripping) task as it increases the contribution of the IFM and targets the AbH.[21] After an incremental warmup of 10 submaximal (50% to 90%) voluntary isometric contractions, 3 maximal voluntary isometric contractions (MVICs) were performed on each foot separated by 30-second rest intervals. We defined *maximal force under the forefoot or toes* as the highest peak force (100-millisecond window) recorded from the highest of the 3 MVICs and normalized it by participant body weight. During each MVIC, a physiotherapist determined whether the individual lifted the heel and inspected fluctuations in the gravity line or trunk posture using the Zebris camera and center-of-pressure displacement. If any of these events occurred, the trial was discarded and repeated.

Foot Dome Stability. We assessed foot dome stability using the sit-to-stand single-limb navicular drop test with a caliper (resolution = 0.02 mm). This test measures the difference between the distance of the marked prominent navicular tuberosity to the ground in the seated position and after participants place their entire weight on the foot of interest in single-limb stance while the other foot rests lightly on the box. This position in single-legged stance was selected because it elicits greater activation of the AbH and elucidates the muscle's contribution to resisting foot dome deformation in static stance.[22] We repeated this measure 3 times for each limb and calculated the average value for statistical analyses.

Dynamic Postural Control. We assessed dynamic postural control performance on the instrumented tool (Move2Perform) using the modified Star Excursion Balance Test in 3 directions: anterior, posteromedial, and posterolateral. In accordance with current recommendations,[23,24] each participant performed 4 practice trials in each direction to avoid learning effects and 3 test trials in each of the 3 directions. The modified Star Excursion Balance Test was executed barefoot using a single-limb stance while reaching with the other limb as far as possible along the defined direction. We discarded and repeated a trial if the participant (1) lifted the stance foot, (2) lost balance, (3) used the reaching foot to provide considerable body weight support, (4) lifted the hands from the hips, or (5) exhibited all of these.[23] We normalized the reach distance to the respective stance-limb length and recorded the average of the 3 normalized reach distances for each test condition.

Intervention and Control Groups. Participants allocated to the intervention group (NMES) or the control group received stimulation on the dominant foot via a portable stimulator (model Compex 2; Medicompex SA). Transcutaneous electrical nerve stimulation (TENS) was used as the sham stimulation as it was only effective for reducing pain if used at the strongest intensity that remained comfortable in healthy participants.[25] For this protocol, the sham TENS treatment was set to the lowest intensity detectable by the participants. All of the protocol details are shown in Figure 2 and were developed according to previous recommendations.[9,25] The placement of electrodes and IFM stimulation reactions can be seen in the Supplemental Video (available online at https://doi.org/10.4085/1062-6050-0561.21.S2).

Statistical Analyses. Our sample-size calculation was based on the hypothesis that 1 session of NMES would increase foot strength by 1.0 ± 1.1 N/kg compared with the control group. With a statistical power of 0.8, an α error probability of .05, and a potential dropout rate of 5%, we included 46 participants (23 participants in each group).

Demographic Differences

To determine whether the randomization process had resulted in differences between the studied groups in key demographic characteristics that may influence foot behavior, independent *t* tests (or Wilcoxon rank sum tests) were performed for each of the continuous demographic variables assessed preintervention (age, height, weight, body mass index, and FPI). The Fisher exact test was used to identify differences in distribution of the dichotomous data (sex and limb dominance). The a priori α level was set to .05.

Minimum Detectable Changes for the Outcome Measures

Intraclass correlation coefficients (ICCs) for test-retest reliability of the nondominant foot (no NMES or TENS application) were calculated using a 2-way random-effects model, single measurement, absolute agreement for foot strength ($ICC_{2,1}$), and multiple measurements for foot dome stability and dynamic postural control ($ICC_{2,3}$). We calculated the standard error of measurement (SEM) and minimum detectable change (MDC) for all outcomes of interest based on the pooled SD (SD_{pooled}) and ICC values as follows:

$$\mathrm{SEM} = \mathrm{SD}_{\mathrm{pooled}} \sqrt{(1 - \mathrm{ICC})}, \quad (1)$$

$$\mathrm{MDC} = \mathrm{SEM} \times \sqrt{2}, \quad (2)$$

$$\mathrm{MDC} = \mathrm{SD}_{\mathrm{pooled}} \sqrt{1 - \mathrm{ICC}} \times \sqrt{2}. \quad (3)$$

The MDC was used to indicate whether the difference in a certain outcome was within or beyond the typical measurement error. The changes calculated for the treatment foot between the preintervention and postintervention evaluations were then interpreted according to the MDC values calculated for each outcome of interest.

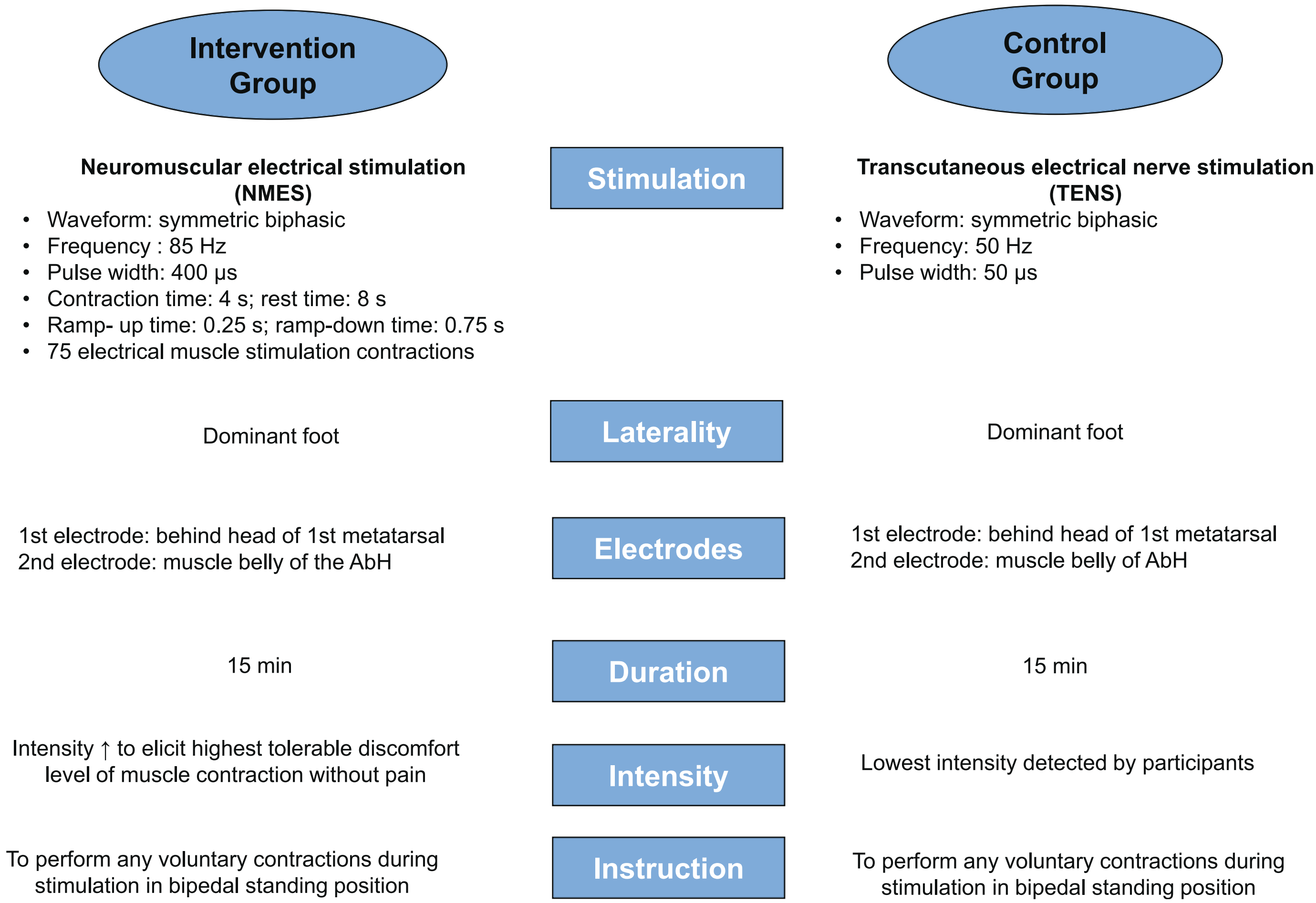

Figure 2. Intervention and control groups protocol details. Abbreviation: AbH, abductor hallucis.

Analysis of Responders Versus Nonresponders

To examine the changes due to NMES or sham stimulation (TENS), we first calculated the pre-post change in the dominant limb. To explore the trends in change scores between the groups, we conducted independent *t* tests (or Wilcoxon rank sum tests) and calculated the Hedges g effect sizes with 95% CIs across all outcome measures. We then examined whether the changes for individuals in each group exceeded the established MDC from the responsiveness analysis. Those who exceeded the MDC for an outcome measure were coded as *responders*, whereas those who did not exceed the MDC were coded as *nonresponders*. From the responder identification, we also classified participants in each group as responders in foot strength, foot dome stability, dynamic postural control, or combinations of the 3 outcomes. To be considered a responder to dynamic postural control, a participant had to exceed the MDC in at least 1 direction. To determine the magnitude of differences in the responder rates between the NMES and control groups, we calculated the relative risk (RR) for exceeding the MDC with corresponding 95% CIs. The RR 95% CIs that did not cross 1 indicated that the responder rate was statistically significant between groups. The relative risk increase (RRI) was calculated as (RR − 1) × 100 and represents the risk increase or decrease (%) of exceeding the MDC for the NMES group compared with the control group. Statistical analyses were performed using R (version 3.6.2; R Foundation for Statistical Computing).

RESULTS

All 46 included participants completed both sessions of the study, leaving 23 participants in each group for statistical analysis (Figure 1). Before the intervention, the NMES and control groups did not differ in demographics (Table 1) or limb characteristics (dominant or nondominant). The ICC, SEM, and MDC values for each outcome generated from the nondominant (no-stimulation) foot are presented in Table 2. Preintervention and postintervention values as well as the change score comparisons are shown in Table 3.

Foot Strength and Foot Dome Stability

The preintervention and postintervention results for each group are provided in Table 3. Foot strength and foot dome stability were different between groups with large effect sizes. For foot strength, the NMES group had 13 out of 23 (56.5%) responders (Figure 3), whereas the control group had 5 out of 23 (21.7%) responders (RR = 2.6 [1.1, 6.1]; RRI = 160.0%). For foot dome stability, 16 of 23 participants (69.6%) in the NMES group exceeded the MDC (Figure 3) compared with 4 of 23 (17.4%) in the control group (RR = 4.0 [1.6, 10.1]; RRI = 300.0%).

Table 1. Participant Preintervention Characteristics Stratified by Group (NMES Versus Control)

Variable	Group, No. (%) NMES (n = 23)	Control (n = 23)	*P* Value
Male sex	12 (52.2)	11 (47.8)	1.000
Foot dominance			.608
Right	22 (95.7)	20 (87.0)	
Left	1 (4.3)	3 (13.0)	
Foot Posture Index			1.000
Slight pronation	20 (87.0)	20 (87.0)	
Increased pronation	3 (13.0)	3 (13.0)	
Score	7.6 ± 1.4 (7.1, 8.2)	7.5 ± 1.2 (7.0, 8.0)	.821
Age, y	37.9 ± 9.4 (34.0, 41.7)	37.4 ± 10.0 (33.3, 41.5)	.878
Body mass index	23.6 ± 3.0 (22.3, 24.8)	23.7 ± 2.7 (22.6, 24.8)	.728
Height	170.1 ± 9.0 (166.4, 173.8)	169.3 ± 8.7 (165.8, 172.9)	.733
Weight	68.3 ± 10.4 (64.1, 72.6)	68.4 ± 11.6 (63.7, 73.1)	.982

Abbreviation: NMES, neuromuscular electrical stimulation.

Dynamic Postural Control

The preintervention and postintervention results for each group are presented in Table 3. Changes in the anterior direction between groups were not significant. The posteromedial and posterolateral direction change scores were different between groups with moderate effect sizes. In the anterior direction, the NMES group had 9 of 23 (39.1%) responders (Figure 3), whereas the control group had 11 of 23 (47.8%) responders (RR = 0.8 [0.4, 1.6]; RRI = −18.0%). In the posteromedial direction, the NMES group had 9 of 23 (39.1%) responders (Figure 3), whereas the control group had 6 of 23 (26.1%) responders (RR = 1.5 [0.6, 3.5]; RRI = 50.0%). In the posterolateral direction, the NMES group had 15 of 23 (65.2%) responders (Figure 3), whereas the control group had 8 of 23 (34.8%) responders (RR = 1.9 [1.0, 3.5]; RRI = 88.0%). With an improvement in at least 1 direction, the NMES group had an 87.0% responder rate, and the control group had a 69.6% responder rate (RR = 1.3 [0.9, 1.7]; RRI = 25.0%).

Responder Analysis for Multiple Outcome Measures

Regarding improvements in multiple outcome measures, the NMES group had 8 of 23 participants (34.8%) who were classified as responders to all outcomes (Figure 4), whereas the control group had no responders (RR = 17.0 [1.0, 278.3]; RRI = 1600.0%). Considering the combination of foot dome stability and dynamic postural control and the combination of foot strength and dynamic postural control, the NMES group had 10 of 23 participants (43.5%) classified as responders (Figure 4) compared with 5 of 23 participants (21.7%) in the control group (RR = 2.0 [0.8, 4.9], RRI = 100.0%). None of the participants in the NMES group (0%) experienced an absence of improvement in any of the outcome measures compared with 3 of 23 (13.0%) in the control group, classified as nonresponders.

Table 2. The ICC, SEM, and MDC Values for All Outcome Measures

Variable	ICC	SEM	MDC
Foot strength, N/kg	0.86	0.5	0.7
Navicular drop, mm	0.96	0.4	0.5
Dynamic postural control, direction, %			
Anterior	0.99	0.5	0.8
Posteromedial	0.93	1.9	2.7
Posterolateral	0.97	1.5	2.2

Abbreviations: ICC, intraclass correlation coefficient; MDC, minimum detectable change; SEM, standard error of measurement.

DISCUSSION

In this study, we aimed to evaluate the immediate effects of a single NMES session versus a sham stimulation session on foot strength, foot dome stability, and dynamic postural control in participants with static foot pronation. Compared with the control group, our NMES group meaningfully enhanced their forefoot force production and foot stability, thereby confirming our first hypothesis.

Foot Strength

The NMES group displayed a higher responder rate (56.5%) than the control group (21.7%), resulting in a 160% increase in their risk of exceeding the MDC. These results are in accordance with previous reports[16,18] of improved AbH strength and activity (%MVICs) after 1 or several sessions of NMES on the IFM.

The mechanism behind the acute effect of NMES on the IFM could be explained by the hyperexcitability of their motor units and prolonged synaptic facilitation.[17,26] However, the exact underlying mechanism for the improvements remains unknown, as we did not measure any neurophysiological factors involving the motor-neuron pool of these muscles. Still, our results suggested that NMES can enhance the volitional IFM recruitment for performing MTP joint flexion, which could be explained by the anatomic and neurophysiological characteristics of the IFM. Indeed, the AbH is known to possess few motor units relative to its physiological cross-sectional area and thus has a high innervation ratio[27]; researchers[28] speculated that the flexor hallucis brevis was also innervated by a relatively small number of motor units and capable of recruiting very high forces.

Regarding the role of NMES intensity, Ebrecht et al[29] found that NMES did not clearly enhance the AbH cross-sectional area or reduce navicular drop after several sessions. Yet they allowed participants to set the individual intensity level close to discomfort. This procedure most likely led to an insufficient dose of electrical stimulation to elicit changes in volitional recruitment. Our participants' mean intensity after 15 minutes was 72.3 ± 60.1 mA versus 29.2 ± 6.8 mA after 8 weeks in the Ebrecht et al[29]

Table 3. Participant Pre- and Postintervention Dominant-Limb Foot Strength, Foot Dome Stability, and Dynamic Postural Control Stratified by Group (NMES Versus Control)[a]

	Group, Mean ± SD (95% CI)		NMES Versus Control		
Variable	NMES (n = 23)	Control (n = 23)	*P* Value	Hedges *g*	95% CI
Foot strength					
Metatarsophalangeal joint flexion: MDC = 0.7 N/kg					
Pre	5.1 ± 1.0 (4.7, 5.5)	5.0 ± 1.0 (4.6, 5.4)			
Post	6.0 ± 1.3 (5.5, 6.5)	5.1 ± 0.9 (4.7, 5.5)			
Δ Post − Pre[b]	0.9 ± 0.5 (0.7, 1.1)	0.2 ± 0.8 (−0.2, 0.5)	**<.001**	1.06	0.44, 1.68
Foot dome stability					
Navicular drop: MDC = 0.5 mm					
Pre	8.0 ± 2.7 (6.9, 9.1)	7.2 ± 2.3 (6.3, 8.2)			
Post	6.6 ± 2.9 (5.4, 7.8)	7.3 ± 2.3 (6.3, 8.2)			
Δ Post − Pre	−1.4 ± 1.7 (−2.1, −0.8)	0.0 ± 0.5 (−0.2, 0.2)	**<.001**	−1.15	−1.78, −0.52
Dynamic postural control, direction					
Anterior: MDC = 0.8%					
Pre	62.7 ± 5.2 (60.6, 64.9)	61.9 ± 5.7 (59.5, 64.2)			
Post	63.4 ± 4.7 (61.4, 60.3)	62.1 ± 5.2 (60.0, 64.2)			
Δ Post − Pre	0.6 ± 1.7 (−0.1, 1.3)	0.3 ± 1.9 (−0.5, 1.0)	.546	0.20	−0.38, 0.78
Posteromedial: MDC = 2.7%					
Pre	104.7 ± 8.4 (101.3, 108.1)	103.5 ± 5.6 (101.2, 105.8)			
Post	107.5 ± 7.7 (104.4, 110.7)	104.2 ± 6.6 (101.5, 106.9)			
Δ Post − Pre	2.8 ± 3.5 (1.4, 4.2)	0.7 ± 2.8 (−0.4, 1.8)	**.023**	0.66	0.06, 1.26
Posterolateral: MDC = 2.2%					
Pre	101.8 ± 6.5 (99.1, 104.5)	99.1 ± 10.3 (94.9, 103.3)			
Post	104.5 ± 7.0 (101.7, 107.4)	99.7 ± 10.4 (95.5, 104.0)			
Δ Post – Pre	2.7 ± 3.8 (1.2, 4.3)	0.6 ± 3.5 (−0.8, 2.1)	**.027**	0.58	−0.02, 1.17

Abbreviations: MDC, minimum detectable change; NMES, neuromuscular electrical stimulation; Post, postintervention; Pre, preintervention.

[a] Values in bold indicate significant *P* values (<.05).

[b] Difference between Post and Pre values.

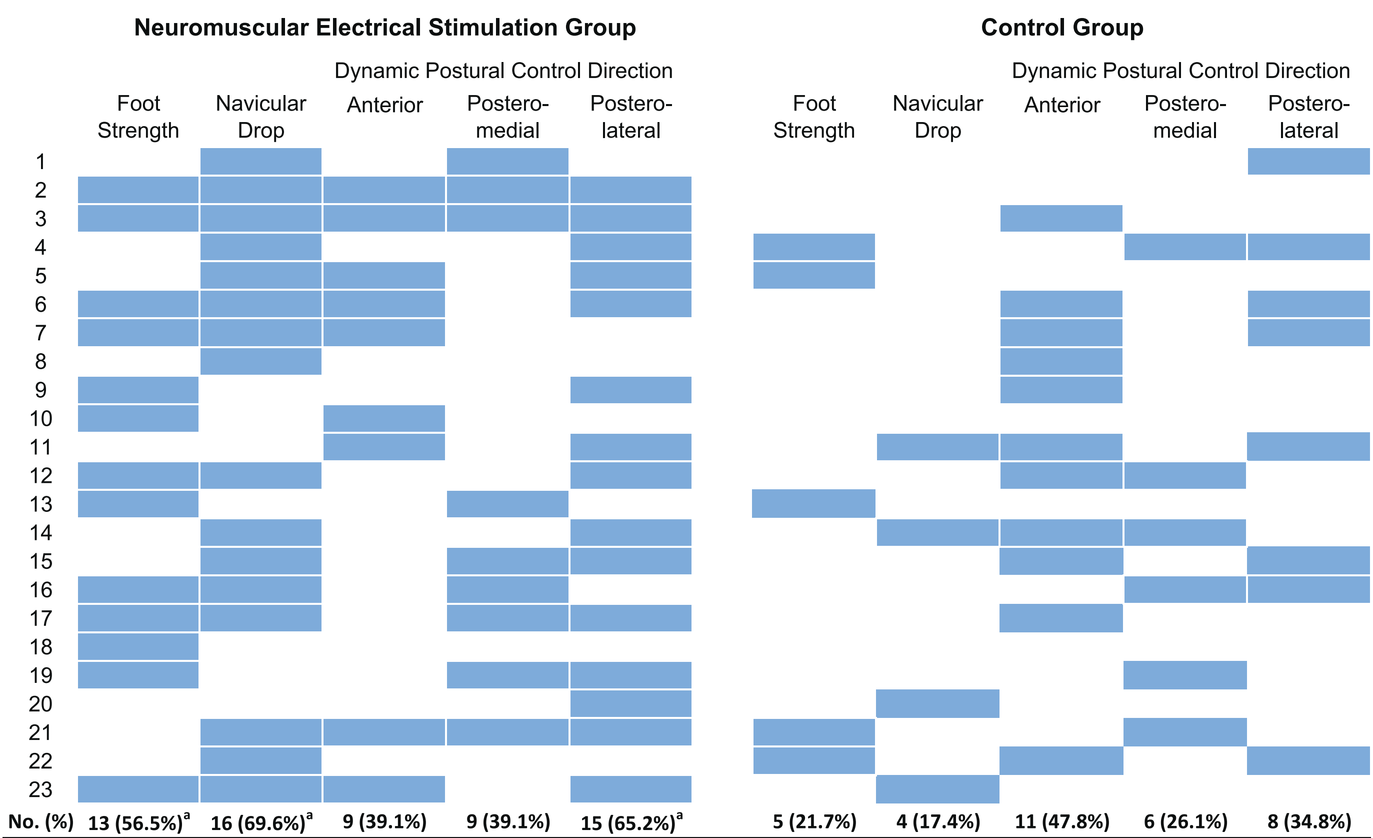

Figure 3. Pattern of responders to each outcome measure (neuromuscular electrical stimulation versus control). [a] Statistically significant based on the relative risk CI at 95%.

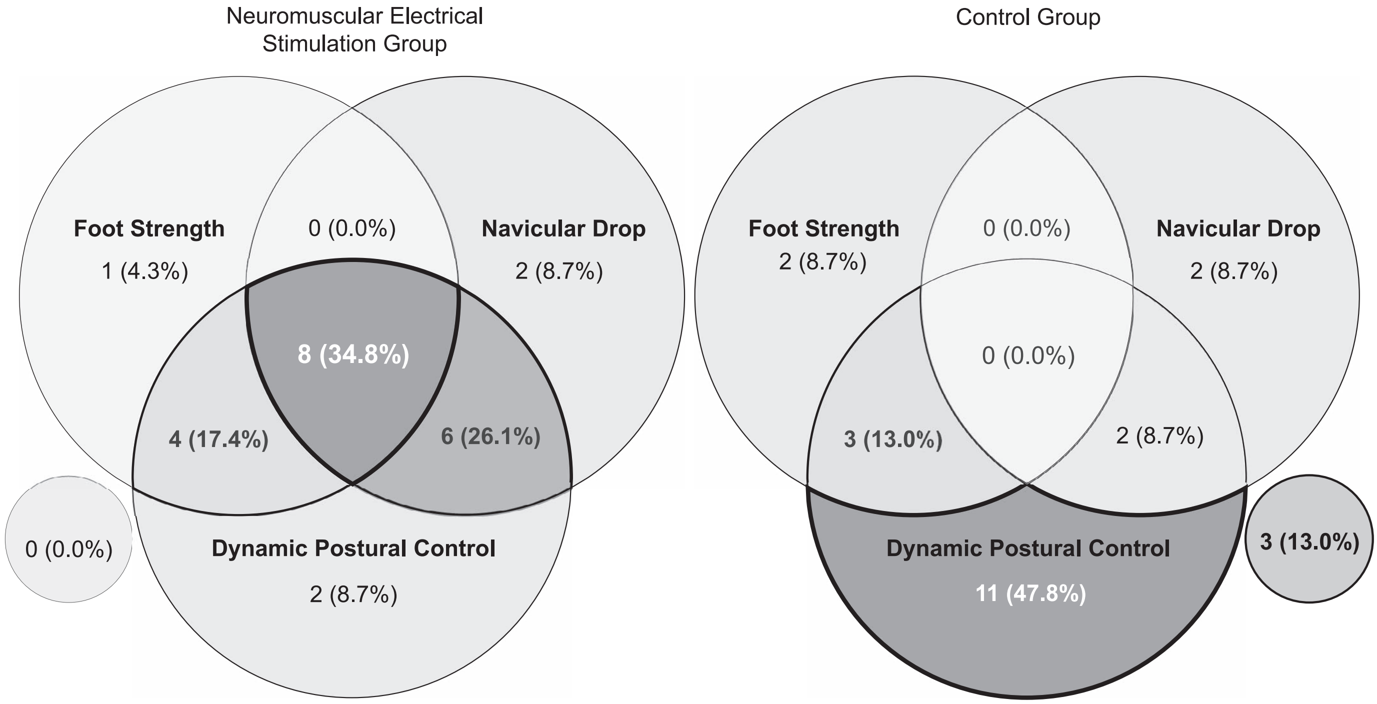

Figure 4. Rate of responders to multiple outcome measures (neuromuscular electrical stimulation versus control).

study. Given the large variability in tolerance to NMES-induced discomfort,[30] the SD in our NMES group reflected much greater variation among participants. This may indicate that intensity needs to be participant specific rather than standard. Our results highlight the importance of adjusting the NMES intensity according to each individual's highest discomfort tolerance. Overall, this preliminary finding confirms the simple and time-efficient intervention of using NMES to enhance MTP force production, which can serve as a basis for future investigators to assess the neurophysiological mechanisms associated with this improvement.

Foot Dome Stability

The NMES group displayed a higher responder rate (69.6%) than the control group (17.4%) in navicular drop reduction as a measure of foot dome stability. The RRI demonstrated that the NMES participants were 4 times more likely to exceed the MDC, with CIs that did not cross 1. Our results are consistent with those of previous authors[11,14] who noted a navicular drop reduction in double-legged stance after NMES or a short foot-strengthening protocol. Our outcomes in combination with prior evidence of these mechanical effects of NMES on the IFM may be of clinical relevance in restoring forefoot-rearfoot coupling behavior[26] and counteracting excessive foot dome deformation.[4]

Our findings elucidate the role of the IFM in foot dome stability. Navicular drop measures the sensitivity of these muscles to counteracting deformation at the subcortical level at which participants did not volitionally model their foot. Similarly, our protocol (navicular drop assessment in single-legged stance) imposed a greater demand on the IFM than navicular drop assessment in double-limb stance and so potentially increased their contribution to foot dome stability.[22] However, this result could be generalized only for activities in static stance, as the authors[7,8] of recent studies challenged this stabilization role in dynamic activities such as walking or running. Although the IFM may play an important role for foot dome stability and proprioceptive feedback in static stance,[31] we believe that the extrinsic foot muscles are greater contributors in supporting the foot dome in midstance during running or sprinting, when the foot is subjected to greater loads.[7] Finally, the higher rate of responders in foot strength and foot dome stability among the NMES group suggested that participants with static pronated feet are likely good responders to this type of intervention. Indeed, only 1 session enhanced their ability to consciously recruit the IFM and unconsciously increased the control of foot dome deformation.

Dynamic Postural Control

The NMES and TENS groups displayed responder rates of 87.0% and 69.6%, respectively, for at least 1 direction. To our knowledge, we are the first to show that only 1 NMES or low-level sensory stimulation session (TENS) positively affected dynamic postural control beyond the MDC (based on the nondominant limb).

These outcomes may be explained by improvements in the neural subsystem of the foot core system.[2] The anatomical positions and alignments of IFM are advantageously positioned to provide immediate sensory information via the stretch response about changes in foot segment motions.[2] This sensory information is supplied by the muscle spindles, which are the sensory receptors located in skeletal muscle and present in greater density in the IFM than in the extrinsic foot muscles.[32] Thus, with the IFM considered our primary source of proprioception,[31] NMES stimulation might enhance muscle spindle activity, leading to better sensory information for maintaining postural control. As well, both sensory and NMES stimulation may enhance the sensitivity of the plantar cutaneous receptors, which also play an important role in the regulation of postural control.[33,34] Based on our findings, the roles of NMES and sensory stimulation in improving dynamic postural control warrant further investigation.

Of the 3 reaching directions, the NMES group had the highest responder rate in the posterolateral direction, followed by the posteromedial direction, compared with the control group. These directions may create frontal-plane demands that require greater IFM contribution to control-foot ankle inversion and eversion.[35] Additionally, in single-legged stance, mediolateral postural sway was correlated with IFM and especially AbH activity ($r = 0.62$), with increasing activity observed during sway of the medial border of the foot.[22] Therefore, an increase in IFM activation after a single NMES session may enhance participants' ability to keep the forefoot region, and particularly the first ray, in contact with the ground to improve their stability in the posterolateral direction. However, the absence of significant differences in the rate of responders between groups in other directions suggests that improving dynamic postural control is multifactorial and does not rely solely on active foot control but also on proximal muscle and motor control.[23] Thus, from a clinical perspective, future researchers should examine the effects of multiple NMES sessions, different types of stimulation, or both in combination with proximal strength exercises to improve dynamic postural control among participants with static foot pronation.

Multioutcome Responder Rate

We found that 78% of the participants in the intervention group responded to a minimum of 2 outcomes compared with only 22% in the control group (RR = 3.6 [1.6, 8.1], RRI = 260.0%). Additionally, none of the participants in the control group responded to all 3 outcomes simultaneously. Interestingly, all the NMES participants who concomitantly responded to foot strength and navicular drop (n = 8) were also responders to dynamic postural control. These observations have major clinical implications that support the possible link among our 3 outcome measurements: foot strength, foot dome stability, and dynamic postural control. They also deepen previous explanations of the importance of IFM activation in foot dome stabilization during single-legged stance as well as MTP joint flexion strength for maintaining the toes on the ground during a dynamic postural task. In sum, this final analysis supports and reinforces the role of NMES in immediately and simultaneously improving foot strength, foot dome stability, and dynamic postural control outcomes.

Limitations

Our investigation had several limitations. Due to the paucity of existing literature on the topic, the sample-size calculation was based on our experience. We only included participants who demonstrated static pronation with no associated conditions. Also, we did not obtain follow-up measures and hence cannot draw conclusions on midterm or long-term effects.[17] Additionally, the study design was single blinded, not double blinded; participants were blinded to the intervention, but the preintervention and postintervention measurements were assessed by an unblinded investigator. This absence of blinding increased the potential bias; however, the outcomes were objectively assessed using validated and reliable techniques. Finally, because we targeted immediate effects, we calculated the MDCs based on measurement errors. Nonetheless, even if some of our results were greater than the MDC, they did not indicate whether this degree of change was clinically meaningful. In the absence of minimal clinically important differences, we provided an incomplete answer as to the importance of these findings for participants or clinicians.[36]

CONCLUSIONS

After only 1 electrical stimulation session, 78% of the NMES participants responded to 2 or 3 outcome measures, compared with only 22% in the control group. Interestingly, the NMES participants who responded to both foot strength and dome stability were also responders to dynamic postural control. These findings support the role of NMES on the IFM in injury-prevention programs designed for a healthy population. They also open the door to future evaluations of the effects of NMES sessions on sport performance or in the treatment of conditions such as lateral ankle sprains and chronic ankle instability, in which dynamic postural control and MTP joint flexion strength deficits are known to be important factors to consider.

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SUPPLEMENTAL MATERIAL

Supplemental Figure. Subject position during foot strength evaluation.

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Supplemental Video. The video illustrates the placement of the electrodes under the medial longitudinal arch to stimulate the intrinsic foot muscles and the foot behavior when the stimulation was applied.

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