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Ankle flexors neuromuscular electrical stimulation rehabilitates gait kinematics in older adults

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ABSTRACT.

Background. While ankle muscles, highly affected by aging, are highly implicated in the changes in gait kinematics and involved in the limitation of seniors' mobility, whether neuromuscular electrical stimulation (NMES) training of these muscles could impact gait kinematics in older adults has not been investigated yet.

Research question. What are the effects of 12 weeks of ankle plantar and dorsiflexors NMES training on strength and gait kinematics in healthy older adults?

Methods. Fourteen older adults (73.6 ± 4.9 years) performed a three-time per week, three months long NMES training of both ankle plantar and dorsiflexors. Before and after training, neuromuscular parameters, gait kinematic parameters, and daily physical activity were measured.

Results. The participants significantly increased their lower limb muscle mass and their plantar and dorsiflexors isometric strength after training. They reduced the hip abduction/adduction and the pelvic anterior tilt range of motion and variability during gait. However, the participants became less active after the training.

Significance. NMES training of ankle muscles, by increasing ankle muscle mass and strength, modified gait kinematics. NMES training of ankle muscles is feasible and effective to lower the hip implication and increment foot progression angle during gait. Further study should determine if this could lower the risk of falling.

Keywords: Neuromuscular Electrical Training, plantarflexors, dorsiflexors, gait kinematics, hip strategy.

1. INTRODUCTION

Thirty-five percent of people over 70 presents gait impairment (Verghese et al., 2006). The age-related decline in gait quality is a powerful indicator of older adults' capacity to perform everyday life activities (Potter, Evans, & Duncan, 1995). Gait spatiotemporal parameters, such as gait velocity and step length, may not be considered the best predictors of institutionalization or dependency (Woo, Ho, & Yu, 1999). On the other side, the variability of the different body segments' positions could be better predictors of falls; indeed, larger variability of lower limb joints was reported to be higher in fallers compared to non-fallers (Kobayashi, Hobara, Matsushita, & Mochimaru, 2014). Moreover, aging is associated with shifting from an ankle to a hip gait strategy. More specifically, during gait, older adults tend to solicit their hips at a higher extend compared to younger adults, this being reflected by a higher range of motion of this joint, and they tend to sollicitate their ankles at a lower extend, this being reflected by a lower ankle range of motion during gait reported in older adults (Kerrigan, Todd, Della Croce, Lipsitz, & Collins, 1998). Schmitz et al. (2009) reported that these age-related changes in walking neuromuscular activation, including this distal-to-proximal shift, are even present among active, healthy older adults (Schmitz, Silder, Heiderscheit, Mahoney, & Thelen, 2009). The increase in variability and the shift in gait strategy have been reported as independent from the gait slowing and one possible theoretical explanation suggests that they could be related to decreased lower-limb strength, specifically in the ankle plantarflexors (Kang & Dingwell, 2008; Kerrigan et al., 1998). The ankle strength loss engenders a lower mobilization of ankle muscles during gait (Monaco, Rinaldi, Macri, & Micera, 2009), possibly causing older adults to compensate by a higher hip muscle implication (Boyer, Johnson, Banks, Jewell, & Hafer, 2017). The age-related lowering in strength is caused by fibrosis and fat tissue accumulation, replacing muscle fibers (Evans & Lexell, 1995). Type II fibers, the fastest type, are preferentially affected by aging resulting in

slower muscle activation leading to a higher risk of falling (Evans & Lexell, 1995). The age-related distal to proximal redistribution in muscle function is a robust finding even in healthy older adults (Buddhadev, Smiley, & Martin, 2020; Schmitz et al., 2009) but the causal implication of ankle muscle has been disputed. However, a recent study showed that voluntarily increasing ankle power can decrease hip power demand, highlighting the possible positive impact of training ankle muscles (Browne, Franz, & Posture, 2019).

Physical activity's regular practice, in particular resistance training, practiced 3 times a week for 12 weeks, can reduce muscular function decline, and gait and balance can often be restored (Judge, Underwood, & Gennosa, 1993). However, structured effective training is often not accessible for older adults due to the distance between homes and physical activity centers and the practice price (Troost, Owen, Bauman, Sallis, & Brown, 2002). The high risk of falls and the fear of falling could also lead older adults to be less willing to engage in physical training, perpetuating the vicious circle that leads to sedentary behavior (Wijlhuizen, de Jong, & Hopman-Rock, 2007). An interesting alternative that could avoid these issues while allowing restoration of muscle function could be home-based training by neuromuscular electrical stimulation (NMES): the application of an electrical current through surface electrodes to the muscles to trigger involuntary muscle contractions. Indeed, in a recent literature review, we demonstrated that NMES is accessible, safe, and effective in older adults (Langeard, Bigot, Chastan, & Gauthier, 2017). One of NMES's main interests is the possibility of specifically triggering type II fibers (the most affected by aging and involved in the fall of seniors) (Kern et al., 2014), highlighting that NMES could be an interesting and convenient complement to more traditional training conditions.

Knowing that aging affects gait primarily at the ankle level (Cabell, Pienkowski, Shapiro, & Janura, 2013), NMES of ankle muscles could be of great interest. A systematic review on this topic has shown that NMES of lower limb muscles could trigger strength and mobility

enhancement in the elderly (Langeard et al., 2017). In order to optimize benefits, training of more than 8 weeks and with a frequency of 50Hz is recommended (Langeard et al., 2017).

While ankle plantar and dorsiflexors, highly affected by aging, seem to be the muscle groups the most implicated in the changes in gait kinematics and highly involved in the limitation of seniors mobility, the feasibility, and efficacy of NMES training on both of these muscle groups have never been studied (Boyer et al., 2017; Kerrigan et al., 1998). Moreover, whether NMES training could impact gait kinematics in older adults has also not been investigated yet (Langeard et al., 2017). This study aimed to determine the feasibility of 12 weeks of ankle plantar and dorsiflexors NMES training and its effect on strength and gait kinematics in healthy older adults.

2. METHODS

2.1. Participants

Adults aged between 70 and 80 years old participated in this study and were recruited between September 2015 and July 2016. They were low to moderately active [Dijon Physical Activity Score (PAS) <20]. They were examined by a physician who collected information about the total number of drugs taken and the number of comorbidities (Kaplan–Feinstein Index). Exclusion criteria included pathologies influencing the vestibular system, dementia, psychiatric or neurologic pathology, alcohol or drug dependency, a low cognitive ability not allowing the understanding of the protocol [objectified by a Mini-mental State Examination (MMSE) <26]. Baseline descriptive characteristics are summarized in Table 1. Participants were asked not to change their daily life activities during the protocol. The study has been approved by the local institutional review board and conforms to the Helsinki Declaration.

2.2.Outcome Measures

2.2.1. Neuromuscular measures

Lower limb muscle mass (cumulative from all leg muscles) was assessed through impedancemetry (Akern BIA-101, Florence, Italy; RJL Systems, Clinton Twp, MI) after the participants stayed 10min in a supine position. The estimated mass (kg) before and after the training were recorded. Ankle plantarflexion and dorsiflexion isometric strength were assessed for the right limb through an ergometer developed in the laboratory (Meldrum, Cahalane, Keogan, Hardiman, & Disorders, 2003). Participants were seated with an angle of 90° between their trunk and thighs, their right knee fully extended, and an angle of 90° between their feet and legs. The participants performed three maximal voluntary isometric plantarflexions, and three maximal voluntary isometric dorsiflexions. Each trial lasted 5 seconds, and the highest value in Newton (N) was recorded for both plantar and dorsiflexion.

2.2.2. Gait kinematic measures

Gait parameters were assessed at participant preferred pace in the gait laboratory equipped with a VICON ® system (Oxford Metrics Ltd, Oxford U.K.) using eight Bonita B10 cameras (1 million pixels, 250fps) and one Bonita 720c camera (1280 x 720, 120Hz). The room contains a straight 16 m path, and gait parameters were recorded 2 m after gait initiation and stopped 2 m before gait termination (Kobayashi et al., 2014). Four trials were performed. Thirty-nine reflective markers were positioned in accordance with the Plug-in-Gait full-body model (Vicon Motion Systems, Oxford, U.K.) on participants in underwear. This method provided the displacement in time of all body segments. The VICON signals were digitized at 100 Hz. All signals were recorded and calculated using a GIGANETLAB unit core, VICON Nexus 2, and PECS 1.1.60305. This allowed calculation of gait velocity ($m.s^{-1}$), step length (m), gait variability (%) (calculated as the coefficient of variation of the step length), step time (s), Foot Progression Angle (FPA) [the angle between the foot vector (projected into the

laboratory's transverse plane) and the sagittal laboratory axis, a positive number corresponds to an internally rotated foot], angular Range Of Motion (ROM) (the difference between the highest and the lowest angular positions) and variability of the ankle, hip and pelvic articulation [the standard deviation (S.D.) of the angular position]. The average of the four trials for all the different outcomes was collected corresponding to a total of around 80 steps.

2.2.3. Activity

Activity levels were measured during 7 days before the training started and during 7 days following the end of the training in order to control for possible changes in participants activity that a research protocol could induce, even though participants were asked not to change their daily life activities during the protocol. Actigraphs (Actiwatch 7, Neurotechnology, Cambridge, UK) were used to measure the participants' daily activity. For seven days and seven nights, the participants wore an actigraph on their non-dominant wrist. The participants identified bed and wake time through a sleep agenda. The mean number of activities per hour was calculated for daytime and nighttime and averaged over the seven recording days.

2.3.Intervention

Participants were trained at home, in autonomy, after details about the use of the electrical stimulator (Compex® SP2.0, Compex SA, Ecublens, Switzerland) was extensively explained. A picture adapted from the manufacturer manual showing the precise electrode positioning was then provided. A stimulator and the electrodes were then provided to the participants. They could practice using the stimulator and positioning the electrodes before starting the actual training. During the last visit to the laboratory, the researchers verified that the participants understood how to use the stimulator and how to position the electrodes correctly. A biphasic symmetrical square waveform with a phase duration of 400µs was used. The detailed parameters of stimulation are presented in Supplementary Material. These stimulation

parameters were established in accordance with the conclusion of a literature review advising NMES training, in order to impact gait, should last around 30 minutes, be performed between two times and four times a week for over 9 weeks, and use stimulation frequencies of 50 Hz and above (Langeard et al., 2017). During the training, the intensity of stimulation was set by the participants, as high as possible, within their tolerance threshold. The training was administered for both legs simultaneously, starting with a 30 minutes training of dorsiflexors, followed by a 30 minutes training of plantarflexors. For dorsiflexor training, two electrodes (Easysnap™, Compex SA, Ecublens, Switzerland) (50 x 50 mm) were placed on each tibialis anterior muscle. For the gastrocnemius stimulation, for each limb, one electrode (50 x 100 mm) was placed on the proximal part of the muscles, and two electrodes (50 x 50 mm) were placed on the two muscles bellies. The participants were asked to remain seated and keep their feet on the floor while relaxing their muscles. Electrode positioning was explained to the participant using pictures and written information. The training lasted for 12 weeks, three times a week. Between the first and the last month, the stimulation frequency of stimulation was increased from 50 Hz to 70 Hz. The steady time of the work phase increased from 7 to 8 seconds and the steady time of the relaxation phase decreased from 7 to 4 seconds. The number of stimulation cycles (work phase + relaxation phase) started at 42 cycles by training and ended with 52 cycles during the last month. The participants chose days and times of practice, and one rest-day between two sessions was advised. Participants were contacted by phone once a month to check the compliance with the program. Participants were asked to write the mean intensity of the training session indicated on the stimulator at the end of each session. This was used to determine the observance and feasibility (observance > 80%) of the training based on the number of participants going through the complete training and the mean number of training sessions achieved.

2.4. Statistics

The sample size calculation was based on previous research results focusing on ankle muscles' training through NMES in healthy older adults (Amiridis, Arabatzi, Violaris, Stavropoulos, & Hatzitaki, 2005; Mani, Almuklass, Amiridis, & Enoka, 2018). According to the data distribution, paired t-tests or Wilcoxon tests were used to detect changes between baseline and post-training values. Cohen's D_z effect sizes were calculated ($D=0.2$ is considered a 'small' effect size, 0.5 represents a 'medium' effect size and 0.8 a 'large' effect size) (Sawilowsky, 2009). The JASP 0.8.0.0. software was used to conduct the analyses. The significance threshold was set at $p<0.05$.

3. RESULTS

Fourteen participants were included and went through the three months of training. Ninety-four percent of the training sessions were performed. The mean intensity of training was 22.5 ± 9.5 mA for dorsiflexors and 20.8 ± 8.8 mA for plantarflexors. The intensity between baseline and the end of the training was increased by 35% for the dorsiflexors and 47% for the plantarflexors.

All the neuromuscular parameters improved after training. The mean improvement was 23% for lower limb muscle mass, 30% for plantarflexion strength, and 9% for dorsiflexion strength (Table 2). Gait velocity, step length, gait variability, and step time remained unchanged (Table 3). Pelvic anterior tilt and hip mediolateral range of motion during gait (adduction/abduction) decreased after training compared to before training. The same results were found for the angular variability of these articulations (Table 4). The FPA was more externally directed after training (-10.09° [$-12.47, -7.71$]) compared to before training (-7.84° [$-13.33, -5.35$]) (Figure 1). Finally, the daylight activity was lower after training compared to before (Table 5).

4. DISCUSSION

This protocol is the first to demonstrate the feasibility of a home-based NMES training of ankle plantarflexors and dorsiflexors in healthy older adults. The results showed that NMSE training of the ankle flexors could reduce the range of motion and the variability of the hip and the pelvis during walking by rehabilitating neuromuscular ankle function.

In accordance with previous studies, the NMES training resulted in an increased lower limb muscle mass, causing higher ankle plantar and dorsiflexors strength (Langeard et al., 2017). One previous study reported positive effects of dorsiflexors NMES training (Mani et al., 2018), and another reported positive effects of plantarflexors NMES training (I. Amiridis et al., 2005). The present study's specificity was to provide training of both muscle groups allowing to show that NMES training was three times more effective for plantarflexors (+30% in strength) compared to dorsiflexors (+9% in strength). This unequal increase could be caused by the higher age-related strength loss in plantar compared to the dorsiflexors leaving a higher progression margin for plantarflexors strength improvement (Simoneau, Martin, & Van Hoecke, 2005). The muscle strength increase was surprisingly close to the torque decrement observed after 12 years of follow-up in older adults of 73.5 years (-30.3% for plantarflexors and -9.5% for dorsiflexors) (Winegard, Hicks, Sale, & Vandervoort, 1996).

Of the two studies evaluating NMES training of ankle muscles, the first one did not evaluate gait in the participants (Mani et al., 2018), and the second noted no improvement of preferred walking speed but revealed faster maximal walking speed (I. Amiridis et al., 2005). This is in accordance with the results of the present study, where spatiotemporal gait parameters at preferred walking speed also remained unchanged. Most of the other NMES training protocols used in the past studies triggered knee extensors and flexors, yielding mostly

inconclusive results on gait parameters (Langeard et al., 2017), possibly because knees muscles are not as affected by aging (Boyer et al., 2017).

Of importance, the present study is the first to explore the effect of NMES on gait kinematics. Associated with more pronated (in-toeing) feet (Scott, Menz, & Newcombe, 2007), the weaker ankle muscles is known to engender a higher involvement of hip muscles (Judge, Davis, & Ounpuu, 1996), causing a higher hip anterior tilt (Boyer et al., 2017) and prolonged hip adduction (Judge et al., 1996). Considering the observed reduced range of motion and variability of the hip adduction/abduction angles and pelvic anterior tilt, the present intervention seems to have reduced hip implication during gait by reinforcing ankle. Increasing FPA from -7° to -10° (reduced pronation) allowed a significant restoration of FPA in seniors [normal FPA in young adults being around -13° (Seber et al., 2000)]. This rehabilitation of ankle muscle function and position could have had repercussions on hip and pelvic motion during gait. Lateral motion of the hip and anterior pelvic tilt was reduced. More than the range of motion, the variability of the angular joint position during gait at hip and pelvis level was lowered, and decreasing gait patterns variability may help prevent falls by increasing control of the whole-body position (Kobayashi et al., 2014).

This hypothesis remains to be tested in future interventional protocols but suggests that rehabilitating neuromuscular function at the ankle level could impact hip motion during older adults' gait.

However, the actimetry results suggest that NMES is not effective in promoting more active behavior in the participants when it comes to physical activity. NMES would lead to participants being less active during the day. Similar results have been reported with traditional voluntary resistance training (Laussen, Chale, Hau, Fielding, & White, 2015). NMES can also induce muscular fatigue (Gueugneau, Grospretre, Stapley, & Lepers, 2017), and participants practiced at a particularly high pace (thrice a week) for three months. It is

also possible that post-testing actimetry a few weeks after the end of the training could have brought different results; fatigue could disappear and only leaves the stronger muscle and better gait strategy. Alternatively, the effects of the intervention may also fail to be retained following training cessation. Future studies should determine these retention effects. However, these results suggest that NMES training, while safe and effective in older adults, may need to be combined with more traditional physical activity training to prevent a physical activity level reduction.

Even if most of the studies on NMES did not include a control group (Langeard et al., 2017; Mani et al., 2018), the lack of a control group in this present study could be seen as a limitation. However, the functional modifications seen in the present study could not be the consequences of participation itself, resulting in more active behaviors as the participants' activity was controlled by actimetry. Even if no consistent changes in gait kinematics are observed during repeated testing (Awad, Kesar, Reisman, & Binder-Macleod, 2013), the test-retest effect could partly impact some of the present findings, and randomized controlled trials are needed to confirm these results.

The small sample size of the present study may have resulted in an underpowered analysis. Because only the very large effects could have been detected otherwise (Cohen's $D > 1.2$), no correction for multiple comparisons was conducted, allowing the present study to detect moderate effects and above (Cohen's $D > .6$). If all the present variables were to remain in further randomized controlled trials, 29 participants per group would be necessary to detect small improvement related to NMES training of ankle plantar and dorsiflexors (G*Power 3.1). NMES rehabilitation of gait kinematics through ankle training could be particularly effective to preserve gait strategy before gait spatiotemporal parameters are affected, and therefore before substantial mobility decline occurs. While the stimulations parameters and the training frequency seem optimum in regard to the literature (Langeard et al., 2017),

training larger muscle groups could have led to spatiotemporal improvement. However, Paillard et al. (2005) reported no improved gait spatiotemporal parameters after similar rectus femoris and vastus lateralis training (Paillard et al., 2005). Paillard et al. (2005) explained that one possible reason for this lack of improvement could be that the included participants had normal gait parameters without the need to improve. The same explanation could be valid for the present study. Whether NMES training of ankle plantar and dorsiflexors could improve spatiotemporal gait parameters in a population presenting gait deficits should be tested in future studies. It might also take a longer time to integrate the gait strategy changes into changes in spatiotemporal parameters. Further studies should test the effects of NMES training on gait a few weeks after the intervention.

This study is the first report of NMES training effects on gait kinematics. The findings should be confirmed in larger subsequent studies, but they highlight that the NMES training could be a promising physical training technique in older adults. NMES training of ankle plantar and dorsiflexors in older adults is feasible at home, safe and could lead to improved neuromuscular performances and positively impact gait kinematics. While NMES might not replace traditional training, it could play a role in the global support of older adults' care by either initiating or maintaining physical activity in older adults who are too frail or too afraid of falling or in a combination of traditional training.

Conflicts of interest statement: The authors declare that they have no conflict of interest.

Ethics approval: The study met the National Ethics Committee's ethical requirements for the Research in Sciences and Technics of Physical Activity and Sports (CERSTAPS) (#2016-19-04-12). Informed consent was obtained from all individual participants included in the study.

Authors' contributions: A.L., L.B., G.L., NC, AG participated in the study design. A.L., L.B., G.L. participated in the acquisition of the data, A.L., L.B., G.L., L.B., NC, AG participated in the analysis and/or the interpretation of the data. A.L., L.B., G.L., L.B., NC, AG participated in the critical revising of the manuscript and gave final approval of this version to be published.

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TABLE1. Participants characteristics

Characteristics	Mean \pm S.D.
Age (mean \pm sd)	73.6 \pm 4.9
Women (%)	50%
BMI (mean \pm sd)	25.9 \pm 3.2
PAS (mean \pm sd)	18.5 \pm 5.8
MMSE (mean \pm sd)	28.0 \pm 1.2
Number of comorbidities (mean \pm sd)	0.36 \pm 0.8
Number of drugs (mean \pm sd)	2.6 \pm 1.7

BMI: body mass index

TABLE2. Neuromuscular parameters

	Before Training (Mean [95%CI])	After Training (Mean [95%CI])	P	T	Effect Size (Cohen's D _z)
Lower Limb Muscular Mass (Kg)	7.36 [6.01, 8.71]	9.04 [7.50, 10.58]	.014*	2.84	.759
Plantarflexion (N)	73.84 [69.64, 78.04]	96.14 [79.23, 113.05]	<.001*	4.28	1.14
Dorsiflexion (N)	39.33 [33.03, 45.62]	42.86 [36.51, 49.09]	.020*	2.65	.708

* : *significant result*

TABLE3. Spatiotemporal evaluation of gait

	Before Training (Mean [95%CI])	After Training (Mean [95%CI])	P	T	Effect Size (Cohen's D_z)
Gait Speed (m.s-1)	1.07 [0.93, 1.21]	1.08 [0.98, 1.18]	.733	.349	.093
Step Length (m)	0.61 [0.56, 0.66]	0.60 [0.57, 0.64]	.999	.000	.000
Gait variability (%)	4.8 [2.61, 6.99]	4.3 [3.26, 5.34]	.630	.493	.132
Step Time (s)	0.56 [0.53, 0.59]	0.56 [0.53, 0.59]	.677	.426	.114

TABLE4. Kinematic evaluation of gait

			Before Training Mean [95%CI]	After Training Mean [95%CI]	P	T	Effect Size (Cohen's D _z)
Ankle angles	Dorsiflexion / Plantarflexion	ROM	34.28 [24.86, 43.70]	30.45 [25.81, 35.09]	.622	.505	.135
		SD	9.72 [6.86, 12.58]	8.37 [7.26, 9.48]	.969	.040	.011
	Inversion / Eversion	ROM	0.57 [-0.44, 1.58]	1.79 [0.02, 3.56]	.380	.909	.243
		SD	0.16 [-0.12, 0.44]	0.53 [0.00, 1.06]	.424	.825	.221
Hip Angles	Flexion / Extension	ROM	40.35 [29.53, 51.17]	34.82 [32.26, 37.38]	.339	.992	.265
		SD	14.04 [10.40, 17.68]	12.42 [11.39, 13.45]	.470	.744	.199
	Adduction / Abduction	ROM	12.06 [7.89, 16.23]	8.31 [6.51, 10.11]	.042*	2.26	.603
		SD	3.93 [2.39, 5.47].	2.70 [2.13, 3.27]	.042*	2.26	.603
Pelvic Angle	Anterior Tilt	ROM	0.92 [0.75, 1.09]	0.77 [0.66, 0.88]	.034*	2.37	.633
		SD	3.13 [2.61, 3.65]	2.63 [2.24, 3.02]	.034*	2.37	.633
	Upward Obliquity	ROM	1.25 [0.96, 1.54]	1.08 [0.79, 1.37]	.424	.825	.221
		SD	4.20 [3.20, 5.21].	3.71 [2.79, 4.63]	.424	.825	.221

* : *significant result*

TABLE 5. Actimetry (number of activities per hour)

<i>* : sign ifica nt resu lt</i>		Before Training Mean [95%CI]	After Training Mean [95%CI]	P	T	Effect Size (Cohen's D_z)
	Light Ave.	243.21 [183.98, 302.44]	197.09 [165.48, 228.70]	.029*	2.45	.656
	Dark Ave	26.40 [17.97, 34.83]	21.91 [15.52, 28.30]	.241	1.23	.329

Figure 1: pre and post-training values of foot progression angle



— Before training
— After training