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ORIGINAL RESEARCH ARTICLE

Short-Term Effects of Neuromuscular Electrical Stimulation on Muscle Architecture of the Tibialis Anterior and Gastrocnemius in Children with Cerebral Palsy
Preliminary Results of a Prospective Controlled Study

ABSTRACT

Karabay İ, Öztürk GT, Malas FÜ, Kara M, Tiftik T, Ersöz M, Özçakar L: Short-term effects of neuromuscular electrical stimulation on muscle architecture of the tibialis anterior and gastrocnemius in children with cerebral palsy: preliminary results of a prospective controlled study. Am J Phys Med Rehabil 2015;94:728–733.

Objective: The aim of this study was to explore the short-term effects of neuromuscular electrical stimulation application on tibialis anterior (stimulated muscle) and gastrocnemius (antagonist) muscles' size and architecture in children with cerebral palsy by using ultrasound.

Design: This prospective, controlled study included 28 children diagnosed with spastic diplegic cerebral palsy. Participants were treated either with neuromuscular electrical stimulation application and conventional physiotherapy (group A) or with conventional physiotherapy alone (group B). Outcome was evaluated by clinical (gross motor function, selective motor control, range of motion, spasticity) and ultrasonographic (cross-sectional area, pennation angle, fascicle length of tibialis anterior and gastrocnemius muscles) measurements before and after treatment in both groups.

Results: Cross-sectional area values of tibialis anterior (238.7 ± 61.5 *vs.* 282.0 ± 67.1 mm^2) and gastrocnemius (207.9 ± 48.0 *vs.* 229.5 ± 52.4 mm^2) ($P < 0.001$ and $P = 0.008$, respectively) muscles were increased after treatment in group A. Cross-sectional area values of tibialis anterior muscle were decreased (257.3 ± 64.7 *vs.* 239.7 ± 60.0 mm^2) after treatment in group B ($P < 0.001$), and the rest of the measurements were found not to have changed significantly in either group.

Conclusions: These results have shown that cross-sectional area of both the agonist and antagonist muscles increased after 20 sessions of neuromuscular electrical stimulation treatment. Future studies with larger samples and longer follow-up are definitely awaited for better evaluation of neuromuscular electrical stimulation application on muscle architecture and its possible correlates in clinical/functional outcome.

Key Words: Cerebral Palsy, Electrical Stimulation, Tibialis Anterior, Ultrasound, Cross-Sectional Area

Cerebral palsy (CP) is a term for a group of disorders characterized by motor function impairments that result from an abnormality or injury to the brain during early development.[1] Spasticity is the most common aspect of CP, affecting almost 80% of the cases. The scenario is usually accompanied by decreased joint range of motion and generalized lower limb muscle weakness/atrophy and connective tissue changes due to increased collagen and fat infiltration.[2,3] Recent studies reported that muscle size/architecture is pertinent to mobility levels and stage of physical activity in CP.[4] Therefore, different treatment alternatives (e.g., exercise, orthotics, botulinum toxin injections, and surgical procedures) can be used to improve range of motion, muscle strength, and therefore, stability for standing and walking of children with CP.[5,6] It has been shown that voluntary resistance exercise can increase muscle size in CP. In this regard, McNee et al.[7] were the first to demonstrate the effects of voluntary resistance exercise in gastrosoleus muscles of patients with CP. They found increases in volume, 16% after 5 wks and an additional 7% in the following 5 wks. However, this effect might be possible for only patients with sufficient voluntary muscle strength and control to perform different types of exercises or activities. In this regard, electrical stimulation can be an alternative therapeutic method used to increase muscle strength and size in children with CP, even in the absence of voluntary control.

Neuromuscular electrical stimulation (NMES) is the implementation of an electric current through electrodes to muscles. When NMES is used in functional training or activity to replace loss of function, it is referred as functional electrical stimulation.[8] The rationale to use NMES on tibialis anterior (TA) muscle is based on NMES's potential to strengthen the weak TA muscle, allow reciprocal inhibition of spastic gastrocnemius (GC), and also produce a stretch reflex for the GC.[9] Furthermore, because of motor relearning, these changes may be maintained after the treatment period. There is a great number of publications in the literature investigating the effects of NMES application in patients with CP.[6,9–15] In general, they report that NMES application improves lower-extremity range of motion, muscle strength, spasticity, and gait velocity as well as causes agonist muscle hypertrophy.[16,17]

The affected muscles of children with hemiplegic CP show reduced muscle volume, cross-sectional area (CSA), thickness, and muscle belly length compared with their nonparetic limbs or with those of healthy peers.[18] GC muscle architecture in children with CP has been investigated by using ultrasound (US) whereby fascicle length (FL) was reported to be shortened.[18,19] In another study, increased FL and decreased pennation angle (PA) and fascicular stiffness have also been observed in soleus and GC muscles after a 6-wk treatment of combined passive-stretching and active-movement training.[20] Decreased FL and increased PA are expected to accompany decreased muscle velocity/excursion and decreased force production, respectively.[21,22] The effects of functional electrical stimulation application on only agonist muscle (TA muscle) architecture have also been shown by US imaging.[23] After 3 mos of application, CSA of TA muscle was found to be increased in those patients. However, to the best knowledge of the authors, comparative effects of NMES on the stimulated and its antagonist's muscles' architecture have not been studied in children with CP.

Accordingly, the aim of this study was to explore the short-term effects of NMES application on TA (stimulated muscle) and GC (antagonist) muscles' architecture (FL and PA) and size (CSA) in children with CP. The authors hypothesized that repetitive daily TA stimulation would improve both agonist and antagonist muscles' size and architecture in children with CP.

METHODS

This study included 28 inpatients (56 legs) with CP who were rehabilitated in the study center between September 2012 and June 2013. The study protocol was approved by the local ethics committee, and the participant's parents gave written informed consent to participate.

Participants were included if they had spastic diplegic CP and aged between 3 and 14 yrs, regardless of their gross motor function classification system (GMFCS) levels. Patients with fixed deformity of the ankle joint, previous surgery within the last 1 yr or botulinum toxin injection to calf muscles within the last 6 mos, and any neurologic or orthopedic condition of the lower limbs (unrelated to CP) were excluded.

Patients (N = 28) were grouped and put in group A and group B alternatingly (patient 1 in group A, patient 2 in group B, patient 3 in group A, etc.). Although both groups underwent similar conventional physiotherapy (stretch, range of motion, balance, posture, and gait exercises), patients in group A (n = 14) also received an additional NMES treatment. Appropriate physiotherapy and NMES treatment were applied by a physiotherapist in the inpatient rehabilitation center. NMES was applied bilaterally to TA muscle for 30 mins/session, once daily, 5 days a wk, for

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4 wks. Patients were kept in supine position, and a two-channel self-adapting multimodal electrostimulator (SAMMS Mod Professional) and two surface electrodes with the size of 5.5 × 6.5 cm were used. The active electrode was placed on the one-third proximal piece of TA muscle. The electrical stimulation was administered using an intensity of 20–30 mA, sequence pulse width of 250 μs, frequency of 25 Hz, and sequence on 10 secs and then off for 12 secs. The level of stimulation was increased until contraction was observed also as the patient became more accommodated to it.

Initially and at the end of the treatment, patients underwent a comprehensive neuromusculoskeletal examination, which was composed of (1) gross motor function, (2) selective motor control, and (3) spasticity (modified Ashworth scale) by the same physiatrist (İ. Karabay) who was blinded to treatment and US assessments. Motor performance of the children with CP was evaluated according to the GMFCS. GMFCS focuses on self-initiated movement, especially sitting and walking function, and includes five levels from the most independent (level 1) to entirely dependent on assistance (level 5).[24] Selective motor control was assessed (while the patient was sitting with hips flexed and knees extended) by ankle dorsiflexion. The examiner observed the movement and muscle activation, and then it was rated from 0 to 4.[25] Spasticity was evaluated by using the modified Ashworth scale, rated from 0 to 4.

Ultrasonographic measurements of TA and GC muscles were performed bilaterally by the same physiatrist (F.Ü. Malas) who was blinded to treatment and clinical assessments, using a 7- to 12-MHz linear probe (Logiq P5, GE Medical Systems) while patients were kept in supine position. During axial imaging, the perimeter of TA (one-third proximal side of the muscle) and the medial head of the GC (the most bulky side of the muscle) muscles were manually traced, and the CSA calculations were acquired by the software of the US machine. During longitudinal imaging, the PA (the angle of insertion of muscle fascicles into the deep aponeurosis) and the FL (the length of the fascicular path between the superficial and deep aponeurosis) were measured as previously described elsewhere (Fig. 1).[26] In this regard, US has been used as a valid and reliable method for the evaluation of muscle architecture.[27,28]
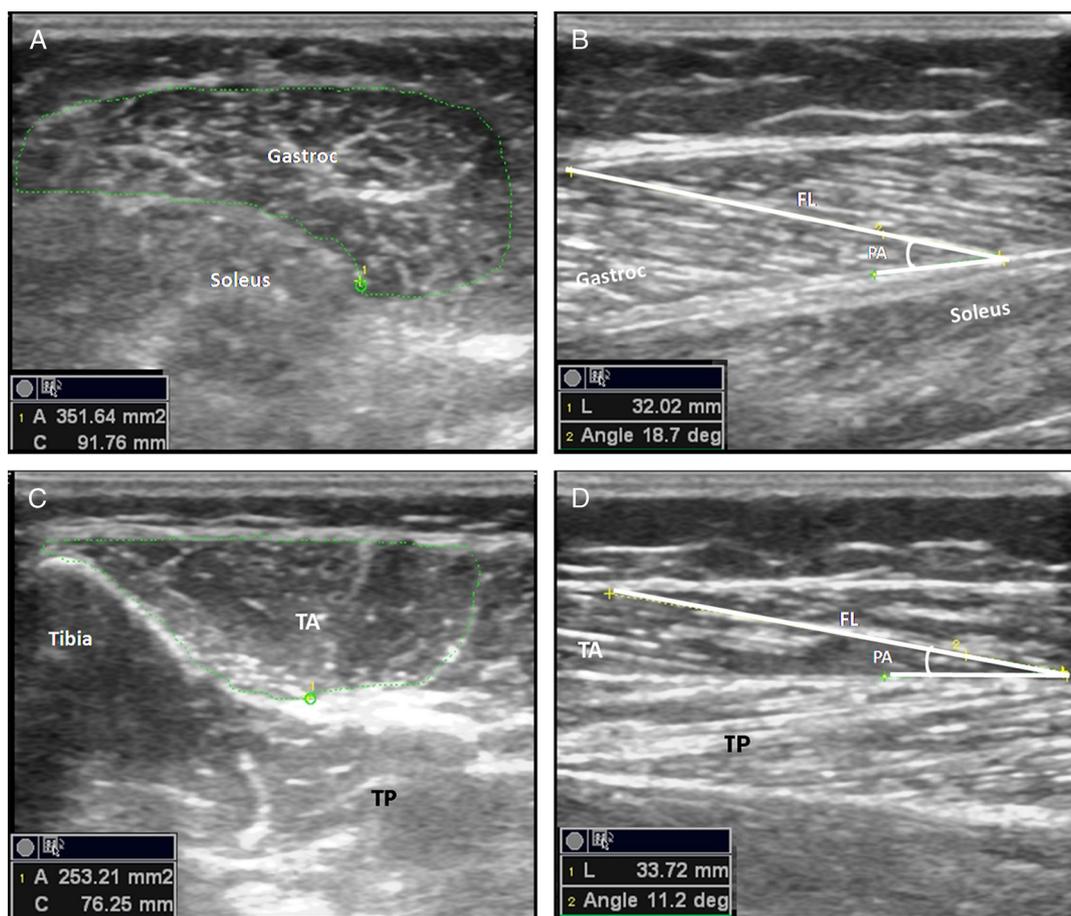

FIGURE 1 *Ultrasonographic imaging of the GC (Gastroc) and TA muscles demonstrating the measurement of CSAs (A, C) (axial views) and PAs and FLs with white lines (longitudinal views) (B, D), respectively. TP, tibialis posterior muscle.*

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TABLE 1 Characteristics of the patients

	Group A (N = 14 Patients)	Group B (N = 14 Patients)	P
Age, mos	86.5 ± 22.9 (45–125)	75.1 ± 29.0 (36–124)	0.150
M/F, %	50.0/50.0	73.3/26.7	0.118
BMI, kg/m^2	14.6 ± 1.9	15.3 ± 2.5	0.251

Age values are expressed as mean ± SD (range), sex as percentage, and BMI as mean ± SD.
BMI indicates body mass index; M, male; F, female.

On the 30th day, all of the aforementioned measurements were repeated after the patients have completed 20 sessions of daily conventional physical therapy with or without NMES.

Data are expressed as mean ± standard deviation or median (min-max). Comparisons were done using paired-samples t test or Wilcoxon's signed-rank test (within groups) and Mann-Whitney U test or χ^2 test (between the two groups) or Kruskal-Wallis test (for subgroup analysis according to GMFCS levels), where appropriate. Statistical analysis was performed by using SPSS 16.0, and statistical significance was set at $P < 0.05$.

RESULTS

All participants had completed the study. Demographic characteristics of the patients are given in Table 1. The groups were similar as regards to age, sex, body mass index, and GMFCS levels (all $Ps > 0.05$). In each group, two children (GMFCS levels 1–2) were able to walk independently, seven children were able to walk with adaptive equipment assistance (GMFCS level 3), and five patients (GMFCS levels 4–5) were unable to walk.

Table 2 summarizes the clinical characteristics and ultrasonographic measurements of the patients. Before treatment, only CSA values of TA and GC muscles were found to be significantly higher in group B than in group A (both $Ps < 0.05$). In group A, CSA values increased in TA (n = 24, 85.7%) and GC (n = 20, 71.4%) muscles after treatment, with a significant increase in their mean values as well ($P < 0.001$ and $P = 0.008$, respectively). CSA values of TA muscle were decreased after treatment in group B ($P < 0.001$). The rest of the functional (selective motor control, spasticity) and US (CSA, FL, and PA) measurements did not change significantly in either group.

Percent changes of CSA values of TA and GC muscles were found to be higher in group A than in group B ($P < 0.001$ and $P = 0.003$, respectively; see Table 3). In addition, these increases have been observed in all GMFCS subgroups (except for CSA of GC in GMFCS levels 1–2). In NMES-treated group, GC CSA increased in levels 3–5 but decreased in GMFCS levels 1–2. When compared percent changes among subgroups according to GMFCS levels, GC CSA increases were more significant in children with GMFCS levels 3–5 ($P = 0.016$), and TA CSA increases were more significant in children with GMFCS levels 4–5 ($P = 0.05$). In either group, percent changes of muscles' CSA were not correlated with age, sex, body mass index, and GMFCS levels.

DISCUSSION

The purpose of this study was to explore whether short-term NMES application had any effect on the

TABLE 2 Clinical characteristics and muscle US measurements of the patients

	Group A (N = 28 Limbs)			Group B (N = 28 Limbs)		
	Before	After	P	Before	After	P
SMC	3 (1–4)	3 (1–4)	0.317	3 (1–4)	3 (1–4)	0.317
Spasticity of GC (MAS)	1 (1–2)	1 (1–2)	0.157	1 (1–2)	1 (1–2)	0.681
TA muscle						
CSA, mm^2	238.7 ± 61.5	282.0 ± 67.1	<0.001	257.3 ± 64.7	239.7 ± 60.0	<0.001
PA, degrees	10.7 ± 2.9	11.2 ± 2.7	0.578	10.8 ± 2.6	11.5 ± 2.8	0.257
FL, mm	34.6 ± 8.7	31.6 ± 9.0	0.098	31.4 ± 5.4	31.3 ± 5.8	0.902
GC muscle						
CSA, mm^2	207.9 ± 48.0	229.5 ± 52.4	0.008	278.1 ± 68.8	264.9 ± 71.7	0.174
PA, degrees	21.6 ± 7.4	23.1 ± 6.9	0.193	21.6 ± 5.7	21.6 ± 6.2	0.961
FL, mm	21.5 ± 8.8	20.1 ± 8.3	0.064	24.5 ± 8.8	23.8 ± 7.0	0.467

Data are given as median (range) or mean ± SD.
MAS indicates modified Ashworth scale; SMC, selective motor control.

TABLE 3 Muscle US CSA changes (%) of the patients ($N = 56$ limbs)

GMFCS[a]	Group A			Group B			P_{TA}	P_{GC}
	n of Limbs	TA	GC	n of Limbs	TA	GC		
Levels 1–2	4	17.6 ± 12.0	-13.9 ± 11.2^{b}	4	-6.9 ± 5.5	-2.6 ± 8.0	0.021	0.386
Level 3	14	12.4 ± 20.0	17.8 ± 21.7	12	-13.5 ± 13.9	-5.7 ± 16.6	0.001	0.003
Levels 4–5	10	34.8 ± 30.4^{b}	14.0 ± 11.3	12	-5.6 ± 8.5	0.1 ± 8.1	0.002	0.007
Total	28	21.1 ± 25.1	11.8 ± 20.5	28	-9.2 ± 11.2	-2.8 ± 12.4	<0.001	0.003

Data are given as n or mean $\pm$ SD.

[a]GMFCS levels 1–2, walks with/without limitation; level 3, walks with adaptive equipment assistance; and levels 4–5, self-mobility is limited. [b]$P < 0.05$, CSA percent changes of the subgroups (according to GMFCS levels) within the groups.

P_{TA} and P_{GC} indicate P values of CSA changes between the groups.

muscle architecture and size of agonist and antagonist muscles in CP. Results of this study have shown that CSA of both the agonist and antagonist muscles increased after 20 sessions of NMES treatment, and this effect was significant especially in patients with low functional level.

Most of lower extremity NMES applications focus on TA stimulation either with or without GC stimulation.[9] The therapeutic effects are commonly observed after 30–60 mins/day of NMES treatment for at least 6–8 wks.[9] However, there is inadequate evidence to establish best practice guidelines. In addition, there are few studies evaluating the effects of electrical stimulation on the muscle size and architecture. A preliminary study including ten children with spastic diplegic CP (five children in volitional exercise group and five in NMES group) investigated the effects of NMES strength training using percutaneously implanted stimulation to quadriceps femoris and triceps surae.[11] They found greater increases in normalized force production of both muscles and CSA of quadriceps muscle measured by magnetic resonance imaging and an improvement in walking speed in NMES-trained group than volitional training group. Damiano et al.[23] studied the effects of functional electrical stimulation application on TA muscle of patients with CP. In that study, 14 independent ambulatory patients with a mean age of 13.1 yrs were included. When compared with the baseline values, 3 mos of functional electrical stimulation application (approximately 6 hrs/day) increased the TA muscle CSA (19.9%), and this effect (with a further insignificant increase of 4.8%) was maintained at 3-mo follow-up. In this study, when compared with the baseline values, 1-mo NMES treatment increased muscle CSAs of GC (11.8%) and TA (21.1%), especially in patients with low functional levels. However, CSA of GC was decreased in patients with GMFCS levels 1–2. This might be caused by the study's small sample size of this subgroup (four limbs of two patients).

In this study, whereas CSA values (of TA and GC) increased, PA and FL values (of TA and GC), plantar flexor spasticity, and selective motor control did not change after NMES treatment. The latter could well be due to relatively short duration of treatment and the small sample size of this study, but the finding of increased CSA is noteworthy. Previously, it has been shown that GC muscle thickness decreased in spastic muscles.[18] Likewise, the authors believe that TA NMES application can cause inhibition of the antagonist (GC) muscle, decreasing the GC muscle tonus. Eventually, GC muscle becomes normalized with a parallel increase in its CSA. The authors again think that these findings not being reflected on the clinical outcome would stem from the treatment duration and small sample size. On the other hand, TA CSA was decreased in group B. Although this finding would seem as unexpected at the first glance, it may well be attributed to the positioning of TA muscle during GC stretching or the use of ankle foot orthosis. Yet, when a muscle is immobilized/disused in a shortened position, the number of sarcomeres in parallel is reduced, resulting in muscle atrophy.[18]

Of note, the use of US in the assessment of muscle architecture would be paramount in patients with CP. Yet, in addition to various advantages of US (practical, inexpensive, noninvasive, and repeatable), lack of radiation exposure and dynamic imaging would be the two important features of its use especially in children.

On the other hand, the relatively small number of patients (nonrandomized) and the lack of substantial functional assessment and long-term follow-up can be considered as the major limitations of this study. Another limitation is the possible contribution of the between-group differences in CSA values of TA and GC muscles before treatment, especially because the more severely disabled children (who may have started with smaller CSA) responded to NMES with the largest percent change in CSA.

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To summarize, in the light of these results, the authors conclude that TA and GC muscle size increased with 1-mo NMES therapy. Future studies with larger samples and longer follow-up are definitely awaited for better evaluation of NMES application on muscle architecture and its possible correlates in clinical/functional outcome. Last but not least, US imaging seems to be promising in this regard.

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