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Surface EMG Analysis and Changes in Gait following Electrical Stimulation of Quadriceps Femoris and Tibialis Anterior in Children with Spastic Cerebral Palsy

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***Abstract*— *Purpose:* To evaluate the clinical feasibility and effect of neuromuscular electrical stimulation (NMES) therapy of quadriceps femoris (QF) and tibialis anterior (TA) muscles on improving gait and functional outcomes in children with spastic cerebral palsy (CP). *Method:* Ten children with spastic diplegic/hemiplegic CP who were in the age group of 7 to 14 years recruited from a rehabilitation institute were randomly assigned either to a control group or a NMES group. Both groups obtained conventional physiotherapy and muscle strengthening exercises. The NMES group in addition received surface electrical stimulation to QF and TA muscles for four weeks duration. *Results:* The NMES group showed significant improvements as compared to the control group in walking speed (mean difference: 7.83 meters per min, 95% confidence interval: 3.13 to 12.53, p<0.01) and cadence (mean difference: 23.33 steps per min, 95% confidence interval: 5.90 to 40.77, p<0.01). The NMES group also showed significant reduction in physiological cost index of walking or PCI (mean difference: -1.32 beats per meter, 95% confidence interval: -1.83 to -0.80, p<0.001) indicating greater energy-efficiency of walking. No significant changes were seen in EMG parameters. *Conclusions:* The findings of this study suggests that NMES therapy together with conventional physiotherapy more efficiently improves walking ability and functional outcomes as compared to conventional physiotherapy alone in children with spastic CP.**

I. Introduction

Cerebral Palsy (CP) is a static encephalopathy that is characteristically non-progressive and is accompanied with postural disturbances. CP is a fairly common disease and the most important cause of childhood disability. Current multi-dimensional therapeutic approach for CP include physical therapy, orthotics, botulinum toxin injections and specialized surgical procedures. Although electrical stimulation (ES) for functional recovery in patients with stroke is reported for nearly 50 years and is fairly well established, the use of ES in rehabilitation of CP is relatively new [1-5].

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Reducing spasticity and enhancing muscular coordination are goals of majority treatment modalities used in CP. In recent years, devices for neuromuscular electrical stimulation (NMES) are increasingly used to improve gait parameters and functional outcomes in children with spastic CP and are becoming a popular technique in physical therapy and rehabilitation practices. The most often stimulated muscle group in the thigh is the quadriceps femoris (QF). There is however a lack of uniformity over the selection of muscle group for leg. Some studies advocate stimulation of tibialis anterior (TA), while some others advocate stimulation of gastrocnemius and some do both. Most studies reported in the literature have stimulated calf muscles with or without TA. There is no clear evidence to determine the effectiveness of NMES of any group of muscles in treatment of CP. Further research is needed to help guide clinical practice, and controlled trials are required to assess the value of NMES treatment in CP [6-11]. The purpose of this study is to determine the clinical feasibility and effect of combining NMES of both QF and TA muscles along with conventional physiotherapy as compared to conventional physiotherapy alone in children with CP. The outcomes measured are changes in gait parameters and changes in surface EMG of quadriceps femoris and tibialis anterior muscles.

II. Material and Methods

The study protocol was approved by the Institute Ethical Committee (IEC). Informed consent was obtained for each child from parent or guardian. Ten consecutive children in the age group of 7 to 14 years with spastic hemiplegic or diplegic cerebral palsy (selected as per defined inclusion and exclusion criteria) participated in the study. The subjects were randomly assigned to one of the two groups: one receiving neuromuscular electrical stimulation (NMES) to quadriceps femoris (QF) and tibialis anterior (TA) muscles and physiotherapy/occupational therapy (ES arm, n=5) and another receiving only physiotherapy/occupational therapy to strengthen QF and TA muscles (control arm, n=5).

Neuromuscular electrical stimulation was applied using a portable, battery powered, current-controlled, multi-channel neuromuscular stimulator (EMS, CyberMedic Corp., Korea). The stimulation parameters used were a ramp up time period of 3 seconds followed by 14 seconds hold period, ramp down time period of 3 seconds followed by 5 seconds relaxation period. The electrical stimulation was delivered using a bi-phasic rectangular pulse of 20Hz for QF and 40Hz for TA. A pulse width of 200 microseconds was used. The current was customized depending on the tolerance of the individual, which was obtained as an average of the minimum strength and the maximum strength. By minimum current strength we mean the current required to bring about a visible contraction in a given muscle group. Similarly, maximum strength is the maximum tolerated current judged by slightest wince or discomfort for the child concerned [5]. The stimulation was applied bilaterally in alternate fashion for 20-30 minutes a day, 4-5 days per week using surface electrodes for both QF and TA muscles. Both muscles were stimulated simultaneously during the active phase of the stimulation cycle. The gait parameters (such as speed, cadence, step length etc) were recorded before therapy and at the end of 4 weeks after the start of therapy. Other outcomes like physiological cost index (PCI), functional improvement (measured using a standard Gross Motor Function Measure-GMFM 66 scale), and electromyography were also recorded before and after therapy. Baseline clinical characteristics were comparable between both groups (table 1).

TABLE 1. BASELINE CHARACTERISTICS OF SUBJECTS PARTICIPATED IN THE STUDY.

	ES group	Control group
Number	5	5
Age in years	8.75 (±2.21)	9.25(±2.98)
Gender	3(M)+2(F)	2(M)+3(F)
Thigh girth (cm)	29.25(±1.71)	31.75(±3.47)
Leg girth (cm)	20.0(±2.12)	19.75(±2.62)
Lower limb length (cm)	61.18(±4.39)	69.33(±12.07)
GMFCS Level	2.75(±0.95)	1.75(±0.5)
GMFM Score	76.75(±10.75)	79.25(±15.52)
MAS score	1	1
PCI	1.303(±0.668)	0.4386(±0.148)
Speed (meters/min)	13.41(±4.99)	22.74(±6.03)
Cadence (steps/min)	43.58(±20.67)	77.58(±18.21)
Step length (cm)	32.70(±7.59)	29.37(±4.14)

Values are mean ± SD or as indicated.

ES: Electrical stimulation. PCI: Physiological cost index. GMFM: Gross Motor Function Measure. GMFCS: Gross Motor Function Classification System - Expanded and Revised. MAS: Modified Ashworth scale.

III. RESULTS

A. Gait and functional outcomes

Within-subject comparison at the end of 4 weeks showed significant improvement in gait parameters such as walking speed (p=0.002), cadence (steps per minute) (p=0.004), and GMFM (p=0.015) as compared to base line or pre-test values in the electrical stimulation (ES) group. The other gait parameters also showed an improving trend. The control group did not show similar improvements (data not shown). These significant improvements with electrical stimulation were also apparent when the ES group was compared with the control group (table 2). We used 'change from baseline' as an outcome measure for analysis (instead of comparison of final measurements), as it minimizes a component of between-person variability in baseline characteristics [12]. The mean change from baseline and its standard deviation for different outcome measures are presented in figure 1. Our results show significant improvements in walking speed (mean difference or MD: 7.83 meters/min, 95% confidence interval or CI: 3.13 to 12.53, p<0.01), and cadence (MD: 23.33 steps/min, 95% CI: 5.90 to 40.77, p<0.01). A significant reduction in physiological cost index of walking or PCI (MD: -1.32 beats/meter, 95% CI: -1.83 to -0.80, p<0.001) was observed indicating an energy-efficient gait with electrical stimulation in CP (table 2 & figure 1). Since the study involved small number of subjects, we specifically looked into the trend of change in each participant. The speed, cadence, PCI and GMFM were found to increase in all participants in the ES arm. Only one participant in the ES arm showed a decrease in step length following stimulation.

TABLE 2. OUTCOME MEASURES IN THE ELECTRICAL STIMULATION (ES) GROUP VS. CONTROL GROUP.

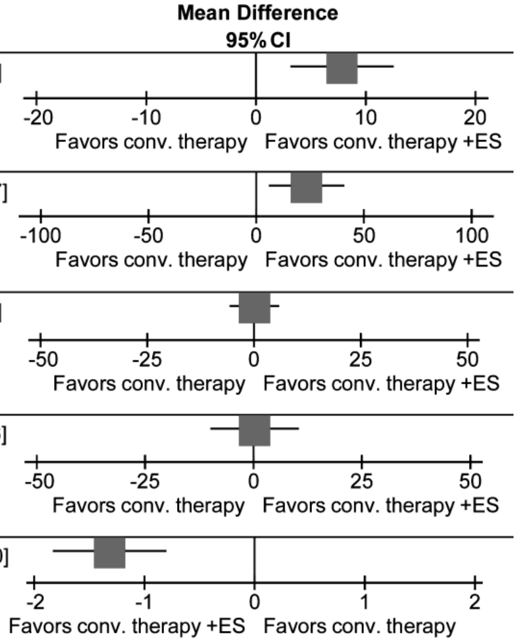
Parameters	Test	ES *Value*	ES *SD*	Control *Value*	Control *SD*	*p* value
Speed	Pre-test	13.41	4.99	22.74	6.03	0.001**
(meters/min)	Post-test	23.83	6.39	25.33	3.83	
Cadence	Pre-test	43.58	20.67	77.58	18.21	0.009**
(steps/min)	Post-test	73.99	24.14	84.67	6.54	
Step length	Pre-test	32.70	7.59	29.37	4.14	0.970
(cm)	Post-test	33.54	8.65	30.11	6.51	
PCI	Pre-test	1.30	0.67	0.44	0.15	0.000***
	Post-test	0.43	0.12	0.88	0.17	
GMFM	Pre-test	76.75	10.75	79.25	15.52	0.960
	Post-test	79.25	10.99	81.50	13.72	

*p<0.05; **p<0.01, ***p<0.001; Statistical significance
PCI: Physiological cost index. GMFM: Gross Motor Function Measure

B. Evaluation of EMG signal

Electromyography or EMG has been shown to be an useful and reliable method of evaluating patients with stroke and other neurological disorders [13]. The purpose of this section is to evaluate EMG patterns before and after electrical stimulation in children with CP. EMG data acquisition was performed using a Power Lab system (AD Instruments, Australia). The EMG was analyzed using Chart V5.2 software. Subjects were seated in a chair with the knee flexed at 90 degrees and the ankle at neutral position. Surface electrodes were placed on the skin surface over the QF and TA muscles of children with CP in both ES and control group after proper skin preparation. The EMG was recorded for 10-15 seconds by asking the child to maximally contract the muscle. This was done to ensure that the muscle was under maximum contractions while recording. The EMG data were exported as a MATLAB file and analyzed for parameters such as mean-absolute-value (MAV), root-mean-square (RMS), and maximum-amplitude-value (tables 3 to 6). The measured parameters of QF-EMG signals showed a decreasing trend in both groups. The TA-EMG parameters showed an increasing trend. However, none of these results showed statistical significance and were largely inconclusive.

Parameters	Conv. therapy and ES Mean	SD	Conv.therapy Mean	SD	Mean Difference 95% CI
Speed (meters/min)	10.416	3.834	2.582	3.749	7.83 [3.13, 12.53]
Cadence (steps/min)	30.418	14.548	7.085	13.561	23.33 [5.90, 40.77]
Step length (cm)	0.837	5.235	0.737	4.052	0.10 [-5.70, 5.90]
GMFM Score	2.5	6.881	2.25	9.404	0.25 [-9.96, 10.46]
PCI (beats/m)	-0.876	0.579	0.44	0.101	-1.32 [-1.83, -0.80]



Values are mean change from base line (i.e. post-test value minus pre-test value) and the SD of the change. Note that the outcome representation for PCI is different from other parameters. Lower PCI indicates greater improvement. (Conv.: Conventional)

FIGURE 1. OUTCOME MEASURES IN THE ELECTRICAL STIMULATION (ES) GROUP VS. CONTROL GROUP.

TABLE 3. EMG ANALYSIS OF QF MUSCLE IN THE ES GROUP

	MAV *(10^{-4} Volts)*		**RMS** *(10^{-4} Volts)*		**Maximum Amplitude** *(10^{-4} Volts)*	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Value	1.61	1.38	2.06	1.65	4.72	3.88
SD	0.63	0.29	0.80	0.22	0.66	0.82

TABLE 4. EMG ANALYSIS OF QF MUSCLE IN THE CONTROL GROUP

	MAV *(10^{-4} Volts)*		**RMS** *(10^{-4} Volts)*		**Maximum Amplitude** *(10^{-4} Volts)*	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Value	3.94	3.11	4.26	3.44	5.12	5.04
SD	0.60	2.08	0.47	1.85	0.00	0.11

TABLE 5. EMG ANALYSIS OF TA MUSCLE IN THE ES GROUP

	MAV *(10^{-4} Volts)*		**RMS** *(10^{-4} Volts)*		**Maximum Amplitude** *(10^{-4} Volts)*	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Value	1.98	2.64	2.41	2.97	5.12	4.75
SD	0.31	1.38	0.40	1.41	0.00	0.74

TABLE 6. EMG ANALYSIS OF TA MUSCLE IN THE CONTROL GROUP

	MAV *(10^{-4} Volts)*		**RMS** *(10^{-4} Volts)*		**Maximum Amplitude** *(10^{-4} Volts)*	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Value	2.51	3.86	2.55	4.16	3.50	5.12
SD	0.21	0.05	0.24	0.08	0.73	0.00

MAV: Mean-absolute-value. RMS: Root mean square value.

IV Discussion

Our objective in this study was to determine the clinical feasibility and performance of NMES for both quadriceps femoris (QF) and tibialis anterior (TA) muscles along with conventional physiotherapy for improving walking and functional ability in children with CP. The QF being a postural muscle has a lower natural firing rate close to 20 Hz, and the TA being a muscle of movement has relatively higher firing rate close to 40 Hz [14]. We therefore used a stimulation frequency of 20 Hz for QF and 40 Hz for TA muscles. Overall our results show significant improvement in important gait parameters and functional outcome measures with electrical stimulation therapy. PCI, an indirect measure of oxygen consumption, was also found to be significantly reduced indicating an energy-efficient gait with electrical stimulation in CP. Our study also demonstrated a negative correlation of pulse width with the maximum and the minimum current strength. Also, there was a positive correlation between the minimum current strength for QF muscle and the thigh girth. The minimum current strength for TA muscle was correlating with the leg length rather than the leg girth (this part of the study has been reported in [5]).

The measured parameters of the quadriceps femoris EMG (QF-EMG) signal showed a decreasing trend in our study. However, the tibialis anterior EMG (TA-EMG) parameters showed an increasing trend. Our previous experience with TA-EMG data in post-stroke FES therapy showed significant improvements in different parameters [13,15]. This finding is justified by an argument that the key function of the TA muscle is to lift the foot off the ground during the swing phase of gait cycle. Therefore, an improvement in speed is likely to be reflected in terms of improvements in TA-EMG parameters. The decrease in QF-EMG parameters in our study may be explained by possible reduction in spasticity which could not be clinically picked by using modified Ashworth (MAS) scale. Whether or not the spasticity was reduced however needs to be quantified further. Lack of significant results in EMG analysis and the limited sample size restricts us to draw further conclusions.

The change in gait parameters, functional outcomes, and energy efficiency of the gait are remarkably prominent as compared to the change in the EMG signal and the reduction in spasticity measured using MAS scale (data not shown). We therefore believe that the improvement in gait can occur through multiple other mechanisms apart from reduction of hypertonia and spasticity. Recent report suggesting changes in dynamic resources brought about by NMES therapy as the major underlying mechanism rather than decreasing stiffness strengthens our point of view [16]. Thus, further studies are needed to decipher other mechanisms which might have a potential role in determining therapeutic benefit of NMES.

In the current study, participants in both control and NMES group obtained similar conventional physiotherapy and occupational therapy sessions. The conventional physiotherapy program included routine muscle stretching, strengthening and positioning exercises. The occupational therapy program targeted activities of daily living for that age group. The control group in our study was not subjected to an additional physiotherapy that equals the time of electrical stimulation in the ES arm. We believe that an extra duration of physical therapy, as shown in some earlier studies, does not necessarily improve the motor function, and on the contrary it can result in fatigue [17].

The trend of outcome measures in the same direction in most participants in the ES arm supports the feasibility of NMES therapy in CP. Further studies employing more rigorous research designs, long term follow-up, larger sample sizes, homogeneous patient groups and investigating multiple outcomes including quality of life, cost-benefit and activities of daily living are required for the unequivocal support of our results. Despite these limitations, we feel that this study brings out clinically relevant information regarding feasibility of electrical stimulation of QF and TA in spastic CP. In conclusion, our results in combination with previous reports support the potential therapeutic benefit of surface electrical stimulation on gait and motor recovery and the NMES system as promising rehabilitation modality in children with spastic cerebral palsy.

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