Neuromuscular Electrical Stimulation Versus Volitional Isometric Strength Training in Children With Spastic Diplegic Cerebral Palsy: A Preliminary Study

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Neuromuscular Electrical Stimulation Versus Volitional Isometric Strength Training in Children With Spastic Diplegic Cerebral Palsy: A Preliminary Study

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Background. To date, no reports have investigated neuromuscular electrical stimulation (NMES) to increase muscle force production of children with cerebral palsy (CP) using high-force contractions and low repetitions. *Objective.* The aims of this study were to determine if isometric NMES or volitional training in children with CP could increase muscle strength and walking speed and to examine the mechanisms that may contribute to increased force production. *Methods.* Eleven children with spastic diplegia were assigned to an NMES training group or to a volitional training group. Participants in the NMES group had electrodes implanted percutaneously to activate the quadriceps femoris and triceps surae muscles. The volitional group trained with maximal effort contractions. Both groups performed a 12-week isometric strength-training program. Maximum voluntary isometric contraction (MVIC) force, voluntary muscle activation, quadriceps and triceps surae cross-sectional area (CSA), and walking speed were measured pre- and post-strength training. *Results.* The NMES-trained group had greater increases in normalized force production for both the quadriceps femoris and triceps surae. Similarly, only the NMES group showed an increase in walking speed after training. Changes in voluntary muscle activation explained approximately 67% and 37% of the changes seen in the MVIC of the NMES and volitional groups, respectively. Quadriceps femoris maximum CSA increased significantly for the NMES group only. *Conclusions.* This study was the first to quantitatively show strength gains with the use of NMES in children with CP. These results support the need for future experimental studies that will examine the clinical effectiveness of NMES strength training.

Key Words: *Cerebral palsy—Strength training—Electrical stimulation—Muscle activation—Cross-sectional area—Hypertrophy.*

Low muscle force production in children with cerebral palsy (CP)[1] can potentially be explained by several observed factors: decreased central nervous system (CNS) motor unit recruitment and discharge rates,[2] increased antagonist coactivation during agonist contractions,[3,4] and changes in muscle morphology, including atrophy.[5-7] Although strength training for a variety of patient problems has received much attention,[8-11] it is not typical practice with clinicians who treat individuals with CNS dysfunction. This bias against the use of strength training for patients with CNS dysfunction is due to the unsubstantiated belief that high-effort voluntary contractions may promote an increase in muscle spasticity and tone.[12] Recently, however, strength training in individuals with post-stroke hemiparesis and CP has produced positive effects.[13-18] For example, strength-training studies in children with CP have demonstrated improvements in gait speed, stride length, amount of knee flexion at foot strike, and gross motor function.[13,14,18] A systematic review by Dodd and colleagues[19] of strength training in children with CP concluded that existing evidence suggests that training can improve muscle force production. There were no reports of increased spasticity following training in the reviewed literature. The authors suggested that more rigorous studies are needed to make any definitive conclusions.

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Children with CP demonstrate large deficits in voluntary muscle activation compared to typically developing children (~20%-40% less).[2] Using voluntary contractions for strength training children with CP, therefore, may not produce forces that are sufficient to induce muscle hypertrophy. Neuromuscular electrical stimulation (NMES) is an alternative strength-training technique used to treat adults with deficits in voluntary muscle activation following total knee arthroplasty.[20-22] A number of studies have reported the use of NMES in children with CP[23-28]; however, none of these studies has adequately documented strength or has used NMES protocols that have been shown to increase strength in other populations.[10,29-32]

This study compared the effects of NMES and voluntary isometric strength training in children with spastic diplegia due to CP using high-force (targeted forces ≥ 50% of maximum voluntary isometric contractions), low-repetition contractions (1 × 15, 3 times a week) and investigated which physiologic mechanisms contribute to changes in force production. We hypothesized that the NMES-trained group would experience greater gains in isometric force production, muscle cross-sectional area, and walking speed after a 12-week program compared to a voluntary-trained group. Conversely, we hypothesized that the voluntary-trained group would experience greater gains in voluntary muscle activation than the NMES group because of a practice effect from performing MVICs throughout the training period. The data presented in this preliminary report are part of an ongoing randomized trial to examine if NMES training can improve muscle strength, walking speed, and energy expenditure during gait over that of volitional training in children with spastic diplegia.

METHODS

Participants

Children between the ages of 8 and 12 years (at the time of recruitment) with spastic diplegic CP were recruited from an outpatient clinic at Shriners Hospitals for Children, Philadelphia, Pennsylvania, USA. They were assigned to a group that would perform either NMES or volitional training. A physical therapist and an orthopedic surgeon screened children to determine if they were eligible to participate in this study. Inclusion criteria were as follows: (1) a diagnosis of spastic diplegic CP; (2) a designation of level II or III on the Gross Motor Function Classification System[33]; (3) between the ages of 7 and 12 years at time of recruitment; (4) cleared for risk of hip subluxation or dislocation; (5) < 40 degrees scoliosis; (6) well-controlled seizures or seizure-free; (7) visuoperceptual skills and cognitive/communication skills sufficient to follow multiple step commands and to attend to tasks associated with data collection; (8) no history of lower extremity surgery in the previous 12 months; (9) passive range of motion of at least 20 degrees of hip abduction, a popliteal angle ≤ 45 degrees, and ankle dorsiflexion to at least neutral with the knee extended and the foot in subtalar neutral; (10) ≤ 10 degrees flexion contracture at the hips and ≤ 5 degrees flexion contracture at the knee.

Eleven children participated in this study. These children were drawn from 12 participants in a pilot study with three groups—NMES, volitional, and control. Four children were randomized to the electrical stimulation group, 5 to the volitional group, and 3 to the control group. Two of the children originally randomized into the control group elected to reenter the study in the NMES group after initial participation. The results from these 2 children were pooled with the original 4 participants in the NMES group for this analysis to increase statistical power. Because we had low power with only 3 participants in the control group, we report the data from the 2 treatment groups, the NMES group consisting of 6 children (3 males; mean age, 10 years 7 months; SD, 2 years 5 months) and the volitional group consisting of 5 participants (3 males; mean age, 10 years 5 months; SD, 2 years 4 months). All children and parents or guardians were informed of the purpose and experimental methods of this study and gave written and verbal consent and assent to participate. The experimental procedures were approved by the Human Subjects Review Boards of the University of Delaware and Temple University (for Shriners Hospitals for Children, Philadelphia).

Experimental Procedures

Electrode implantation. Children who were assigned to the NMES group had percutaneous intramuscular electrodes implanted bilaterally to stimulate the quadriceps femoris and gastrocnemius muscles. While under general anesthesia, electrodes (Memberg electrodes, NeuroControl Corporation, Cleveland, OH, USA) were implanted close to the femoral nerve for stimulation of the quadriceps femoris and near the motor points of the medial and lateral gastrocnemius muscles. The muscle was first stimulated percutaneously with a 26-gauge needle connected to the cathode lead of the stimulator. When the desired stimulated response was obtained, the depth of the probe was measured and the angle of insertion with respect to the skin was noted. Sequentially, a 19-gauge sheath and then a 15-gauge sheath were placed over the probe to widen the opening. Next, the probe and inner sheath were removed and the electrode, mounted on a 26-gauge needle, was inserted into the 15-gauge sheath. The stimulated response was tested periodically during the procedure to

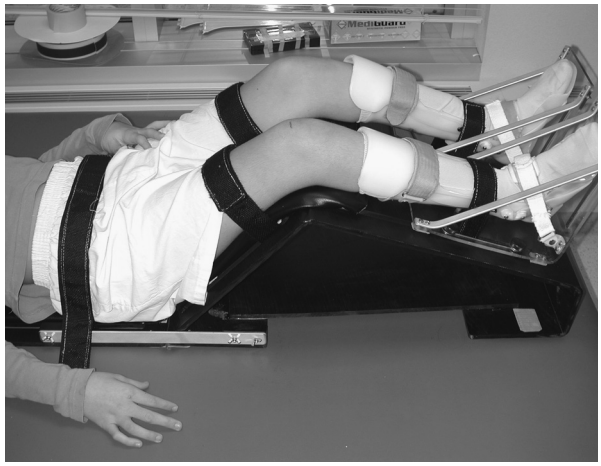

Figure 1. Custom-built exercise board used for neuromuscular electrical stimulation and volitional strength-training programs. The hips are positioned in 50 degrees of flexion, knees in 60 degrees of flexion, and the ankles in neutral.

ensure that the desired response was maintained. The 15-gauge sheath was removed, and the electrode tip remained anchored within the muscle. The electrodes were then routed subcutaneously to a common exit site on the anterior-medial thigh. The exit sites for the electrodes were covered with gauze and self-adhesive occlusive dressings. Patients were allowed to heal for 2 to 3 weeks before stimulation began.

NMES Strength Training

Once patients healed, they returned to establish training dosages and to become accustomed to the sensation of the electrical stimulation. The electrically elicited contractions were dosed to achieve a maximum tolerated contraction force by adjusting the stimulus pulse duration between 5 and 200 μs while using a current amplitude of 20 mA and a pulse frequency of 50 pps (StIM System, NeuroControl Corporation). The training dose of the NMES was measured as the peak force of the maximum tolerated electrical contraction divided by the maximum voluntary isometric contraction (MVIC) force as measured on a computer-controlled dynamometer (see below for position and device description). The targeted stimulation dose was to elicit a force ≥ 50% of the patients' MVIC.

The children in the NMES group performed the electrically elicited contractions without voluntary effort on a custom-built exercise board that held the hip joints in 50 degrees of flexion, the knees in 60 degrees of flexion, and the ankles in neutral (Figure 1). The children were instructed to relax during stimulation. Only one muscle group was exercised at a time. An isometric contraction was 15 seconds in duration, which included a 3-second ramp-up time. The stimulator was programmed to perform 1 set of 15 contractions for each side such that the contractions alternated from right to left. The left-side contraction was initiated 15 seconds after the right-side contraction terminated, and each side was allowed 45 seconds of rest before its subsequent contraction. Thus, each muscle contracted with a 15-second on and 45-second off duty cycle, and the right and left sides were out of phase by 30 seconds. A total of 15 minutes of exercise were required to train each muscle group. The children performed this training 3 times per week for 12 weeks for both quadriceps and triceps surae muscles. Subject compliance was monitored with a hand-written logbook and a compliance meter within the stimulator. The parents or guardians and children were instructed in the setup procedures and were given written instructions with illustrations for NMES strength training. After 6 weeks of training, the children returned for an interim assessment. During this session, the pulse duration was increased as tolerated to further increase the force produced by the stimulation, the training dose was remeasured, and compliance data were recorded from the stimulator and logbook. In addition, the stimulator's compliance meter and the hand-written logbook were also recorded. After the second 6 weeks of training, the training dose and compliance data were each recorded again.

Volitional Strength Training

Children with CP who were in the volitional training group were taught to perform 1 set of 15 MVICs 3 times per week for 12 weeks for the quadriceps and triceps surae muscles. The children in the volitional training group performed the isometric contractions on a custom-built exercise board as described above for the children in the NMES group. Contractions were performed to mimic NMES training, with each contraction lasting 15 seconds in duration. Contractions were timed by the child, parent, or guardian on an electronic timer. The parents or guardians were also trained to provide verbal encouragement for maximum effort during the length of each contraction. Additionally, parents/guardians and children were instructed in the setup procedures and were given a logbook to document their training along with written and illustrated instructions for volitional strength training. After 6 weeks of training, children were brought back to record their logbooks and to allow one of the investigators to observe a strength-training session to ensure that training was being performed properly.

MVIC Force and Voluntary Muscle Activation Testing

All MVIC force and voluntary activation testing was performed on a computer-controlled dynamometer (Kin-Com II, Chattecx Corp, Chattanooga, TN, USA) and performed in the same test. Patients were encouraged to perform MVICs, and when force reached a plateau, a maximal brief electrical stimulus was superimposed on the volitional effort to assess the extent of motor unit recruitment (Figure 2). For the quadriceps femoris, patients were seated with their right leg, thigh, pelvis, and shoulders stabilized with inelastic straps and seat belts. Hips were flexed to approximately 85 degrees, knees flexed to 60 degrees, and participants were instructed to keep their arms folded across their chest or lap. The axis of the dynamometer was aligned to the lateral femoral condyle, and the force transducer pad was 2 finger widths (~3.5 cm) above the apex of the lateral malleolus. For the triceps surae, patients were supine with their right foot placed in the dynamometer's foot apparatus with the axis of the dynamometer aligned bisecting the lateral and medial malleoli. The patient's heel was secured in the heel counter with athletic tape, and the foot, heel, and lower leg were additionally stabilized with Velcro straps. The ankle was flexed to neutral for isometric testing. Each patient's position while on the dynamometer was measured and recorded for future testing.

MVIC force and voluntary muscle activation testing was performed immediately before and after the 12-week strength-training program. For all patients, voluntary muscle activation testing used surface electrical stimulation with self-adhesive electrodes covering the width of the muscle. Depending on the size of the individual, electrodes ranged from 3.8 × 6.35 cm to 7.6 × 12.7 cm (Axelgaard Manufacturing Company, LTD, Fallbrook, CA, USA; ConMed Corporation, Utica, NY, USA). Two hours before testing was to begin, the electrode size was selected and an area slightly larger than the electrode was marked with a permanent marker. An anesthetic cream (EMLA, Astra-Zeneca Pharmaceuticals, LP, Wilmington, DE, USA) was applied to the area and covered with a self-adhesive occlusive dressing. This cream was used to reduce the cutaneous sensation during the electrical stimulation and to reduce the possibility of reflex responses due to the electrical stimulation. The cream was left on the skin for approximately 2 hours, after which the cream was removed and the skin cleansed with alcohol before electrode placement. For the quadriceps, electrodes were placed across the width of the proximal and distal musculature. For the triceps surae, electrodes were placed across the width of the proximal portion of the medial and lateral gastrocnemius muscles just below the knee joint line and longitudinally across the distal portion of the soleus superior to the Achilles tendon. The quadriceps and triceps surae muscles were stimulated with a Grass Instruments S88 stimulator with a Grass model SIU8T stimulus isolation unit (Astromed, Inc, West Warwick, RI, USA). Force data during MVIC testing were sampled at 2000 Hz and analyzed with custom written software (Labview, 4.0.1, National Instruments, Austin, TX, USA).

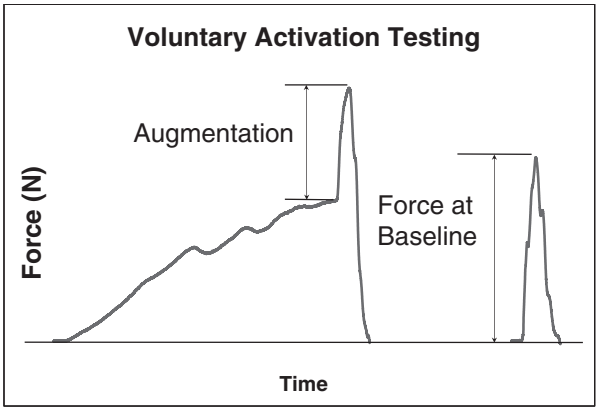

Figure 2. Raw force trace during maximum voluntary isometric contraction (MVIC) and voluntary activation testing. A maximal burst of electrical stimulation is delivered during the MVIC when the force plateaus (force augmentation from maximum burst) and again when the force returns to baseline and the patient is at rest (force of maximum burst at baseline).

Once positioned on the dynamometer, patients performed a submaximal knee extension or ankle plantarflexion isometric contraction and then performed a practice MVIC after approximately 2 minutes of rest. Next, the electrical stimulation intensity used for testing voluntary muscle activation was set by gradually increasing the voltage output in 5- to 10-volt increments, until a force plateau was achieved using a 13-pulse, 100-pps electrical train in which each pulse was 600 μs in duration. We termed this stimulus the *maximum burst*. On the dynamometer's feedback monitor, visual force targets were set approximately 10% higher than the force produced during the practice MVIC trial. After a 5-minute rest, 2 to 3 attempts at knee extension or ankle plantarflexion MVICs were performed to quantify peak voluntary force production and volitional activation. A 5-minute rest was allowed between each attempt. Peak forces were normalized to each participant's body weight. Voluntary activation of the quadriceps and triceps surae muscles was assessed by delivering the maximum burst during an MVIC and again immediately after the MVIC attempt when the force returned to baseline.[2] A ratio that represents the degree of voluntary activation was calculated as follows:

$$\text{Vol. Activation} = 1 - \frac{\text{Force Augmentation from Maximum Burst}}{\text{Force of Maximum Burst at Baseline}}$$

where 1.0 represents full voluntary activation and anything < 1.0 represents incomplete activation.[2]

MRI of Quadriceps Femoris and Triceps Surae Muscle Morphology

Magnetic resonance imaging (MRI) was used to assess changes in muscle morphology quantitatively and to determine the interaction between changes in muscle cross-sectional area (CSA) and gains in muscle strength over the 12-week training program. Patients went through an MRI training program in which a recreational therapist from Shriners Hospitals for Children instructed the child on what to expect during an MRI. The MRI scan was simulated by having the patient don earplugs and lie supine inside a "play tunnel." Patients listened to an audiotape of an actual MRI scan and were instructed to lie still for the duration of the recording. Patients were also given the opportunity to tour the MRI facility and observe a scan in progress. If a child became severely anxious about having the MRI, the child and parent/guardian were given the option to schedule the MRI session with light sedation from an anesthesiologist from Temple University Hospital (Philadelphia, PA). The anesthesiologist obtained separate parental/guardian consent and child assent if sedation was chosen.

All imaging procedures were performed in a clinical 1.5 Tesla magnet (GE Medical Systems, Waukesha, WI, USA) located at Temple University Hospital. Prior to initiating any images of study patients, MRI personnel reviewed provided safety documentation regarding MRI imaging with internal Memberg electrode implants. The proposed procedures were determined safe, and the documentation was kept on file. Images of the right leg were acquired using a standard thoracic coil. Patients were placed supine, and padded supports were used to help maintain the leg in a fixed and relaxed position. Sequential scans acquired 3D data from the most proximal to the most distal part of the quadriceps femoris or triceps surae muscles, using a standard spoiled gradient-echo sequence. The imaging protocol was conducted as follows: (1) Coronal T1-weighted (TR/TE = 500/20) spin-echo localizing scans were obtained with a field of view of 24 cm and a slice thickness of 5 mm and (2) transverse 3D spoiled gradient-echo images (flip angle = 30) were obtained with a TR of 22.5 ms, and minimum TE was automatically determined by the imaging software (typically 1.7 ms). The images were acquired with an encoding matrix of 256 × 256 × 28. A field of view of 12 to 27 cm was used depending on the size of the patient's leg, and slice thickness was 7 mm. Chemically selective fat suppression was used to enhance definition between muscle groups. The image slice that contained maximum fat-free CSA of the quadriceps and triceps surae muscles was determined using an interactive computer program, EXTRACTOR, and a correction algorithm.[34]

Instrumented gait analysis. Gait data were collected using a 7-camera motion analysis system and processed using Vicon Clinical Manager software (Vicon, Oxford Metrics, Lake Forest, CA, USA). The participants walked barefoot along a 6-m walkway at a self-selected walking speed with their usual assistive device if they used one. Walking speed was calculated from the average of 3 gait cycles. Gait cycles were obtained after the participant reached a steady-state walking speed.

Statistical Analysis

All raw data files were gathered by the lead investigator (SL) and assigned randomly generated, nonrepetitive numerical filenames for analysis. Using this method, the data analyzers were blinded to whom the data belonged (SL did not participate in data analysis). The mean difference scores between baseline and post-12-week strength-training measures of MVIC peak force normalized to body weight, voluntary muscle activation, and maximum CSA for the quadriceps and triceps surae muscles of the right lower extremity were each compared between NMES and volitional groups using independent *t* tests with alpha set to .10. An alpha level of .10 was chosen because this report represents preliminary data from an ongoing study, and we wanted to guard against committing a type II error.[35] If no between-group differences were found, within-group *t* tests (alpha set to .10) were used to examine for pre-post training differences. Because all of our hypotheses were directional, all *t* tests were 1-tailed. For each treatment group (NMES and volitional), the data for the quadriceps femoris and triceps surae muscles were combined and linear regressions were performed to determine which variables (percentage change in voluntary muscle activation or maximum CSA) were most important in determining the degree of change in force production. Lastly, the relationship between the NMES training dose and the percentage change in CSA area was examined across muscle groups using linear regression.

RESULTS

Five out of 6 patients completed strength training as prescribed for the NMES group. All 5 patients completed

Table 1. Neuromuscular Electrical Stimulation Training Doses (% maximum voluntary isometric contraction force)

	Right Quadriceps			Right Triceps Surae		
Subject	Pre	6 Weeks	Post	Pre	6 Weeks	Post
1	152.0	157.0	160.9	64.7	57.4	66.2
2	98.4	154.0	143.6	53.0	51.2	67.9
3	53.4	60.5	—	74.5	32.1	—
4	61.5	128.0	112.4	57.6	62.6	74.3
5	43.5	95.1	105.1	33.8	38.7	35.0
Mean (SD)	81.8 (39.7)	118.9 (36.7)	130.5 (22.7)	56.7 (13.6)	48.4 (11.4)	60.9 (15.2)

training as prescribed in the volitional group. The data from 1 NMES patient were excluded from final analysis because of a localized irritation at the lead passing site of the left medial gastrocnemius electrode; this patient did not complete the NMES strength training as structured on the training calendar. This patient, on multiple occasions during the last week, performed 2 sets of 15 repetitions for each muscle group to obtain the goal number of training sessions. This made the patient sore and most likely impaired her force-generating ability.

There were no differences in initial body mass (NMES = 40.12 [SD, 10.68] kg, volitional = 34.04 [SD, 8.88] kg; $t = 0.88$; $P = .20$) or change in body mass between the 2 groups over the 12-week intervention (NMES = 0.48 [SD, 1.24] kg, volitional = 0.74 [SD, 1.93] kg; $t = –0.22$; $P = .414$). The quadriceps and triceps surae NMES training dose was measured relative to the patient's MVIC obtained at 3 time points: pretraining, after 6 weeks of training, and posttraining. The quadriceps NMES training dose increased from 81.8% to 118.9% of the MVIC after 6 weeks of training (Table 1). We were not, however, on average able to increase the NMES training dose for the triceps surae muscles at the 6-week time point owing to suboptimal electrode placement at implantation or owing to patient tolerance (Table 1).

The quadriceps femoris MVIC force normalized to body weight increased more over the 12-week strength-training intervention for the NMES group compared to the volitional group (Figure 3A; NMES +1.61 N/kg, volitional +0.52 N/kg; $t = 1.69$; $P = .065$). A similar pattern of change in normalized force production occurred for the triceps surae muscles with the NMES group increasing force generation more than the volitional group (Figure 3B; NMES +0.80 N/kg, volitional –0.29 N/kg; $t = 1.88$; $P = .049$).

In an attempt to explain the changes in force production, we examined the changes in voluntary muscle activation and muscle CSA. We had hypothesized that the volitional group would experience a greater increase in voluntary muscle activation because of a practice effect from their training; however, no between-group differences were observed for the quadriceps (Figure 3C; $t = 1.20$; $P = .13$) or triceps surae (Figure 3D; $t = –1.25$; $P = .12$). Both groups, however, had significant gains in voluntary activation of the quadriceps (NMES +0.057, $t = –1.678$, $P = .084$; volitional +0.134, $t = –2.478$, $P = .034$) but not in voluntary activation of the triceps surae (NMES +0.104, $t = –1.136$, $P = .160$; volitional –0.098, $t = 0.732$, $P = .252$). For muscle CSA, we had hypothesized that the NMES group would show greater increases in CSA than the volitional group because we predicted that we would produce greater training forces with NMES. We found that training with NMES produced greater changes in quadriceps CSA than volitional training (Figure 3E; NMES +4.42 cm^2, volitional +2.36 cm^2; $t = 2.52$, $P = .023$), but not in triceps surae CSA (Figure 3F; NMES +1.28 cm^2, volitional +0.35 cm^2; $t = .77$, $P = .232$). For the triceps surae, neither group showed significant muscle hypertrophy following training (NMES $t = –1.223$, $P = .144$; volitional $t = –1.368$, $P = .132$).

To gain a better sense of the contribution that voluntary activation and muscle CSA made toward changes in force production, linear regressions were used to compare the percentage change in voluntary activation or muscle CSA to the percentage change in MVIC force pooled across both muscle groups for each treatment group. The variability in voluntary activation of the agonists explained approximately 67% of the variability in the MVIC force for the NMES group (Figure 4A; $r^2 = .67$; $F = 15.944$; $P = .004$) and approximately 37% of the variability in MVIC force in the volitional group (Figure 4B; $r^2 = .37$, $F = 4.737$, $P = .061$). No relationship was seen, however, between the percent change in maximum CSA and the percentage change in MVIC force for either the NMES ($r^2 = .001$, $F = 0.007$, $P = .933$) or volitional groups ($r^2 = .074$, $F = 0.481$, $P = .514$).

Walking speed was used to examine if either NMES or volitional training had an impact on gait performance

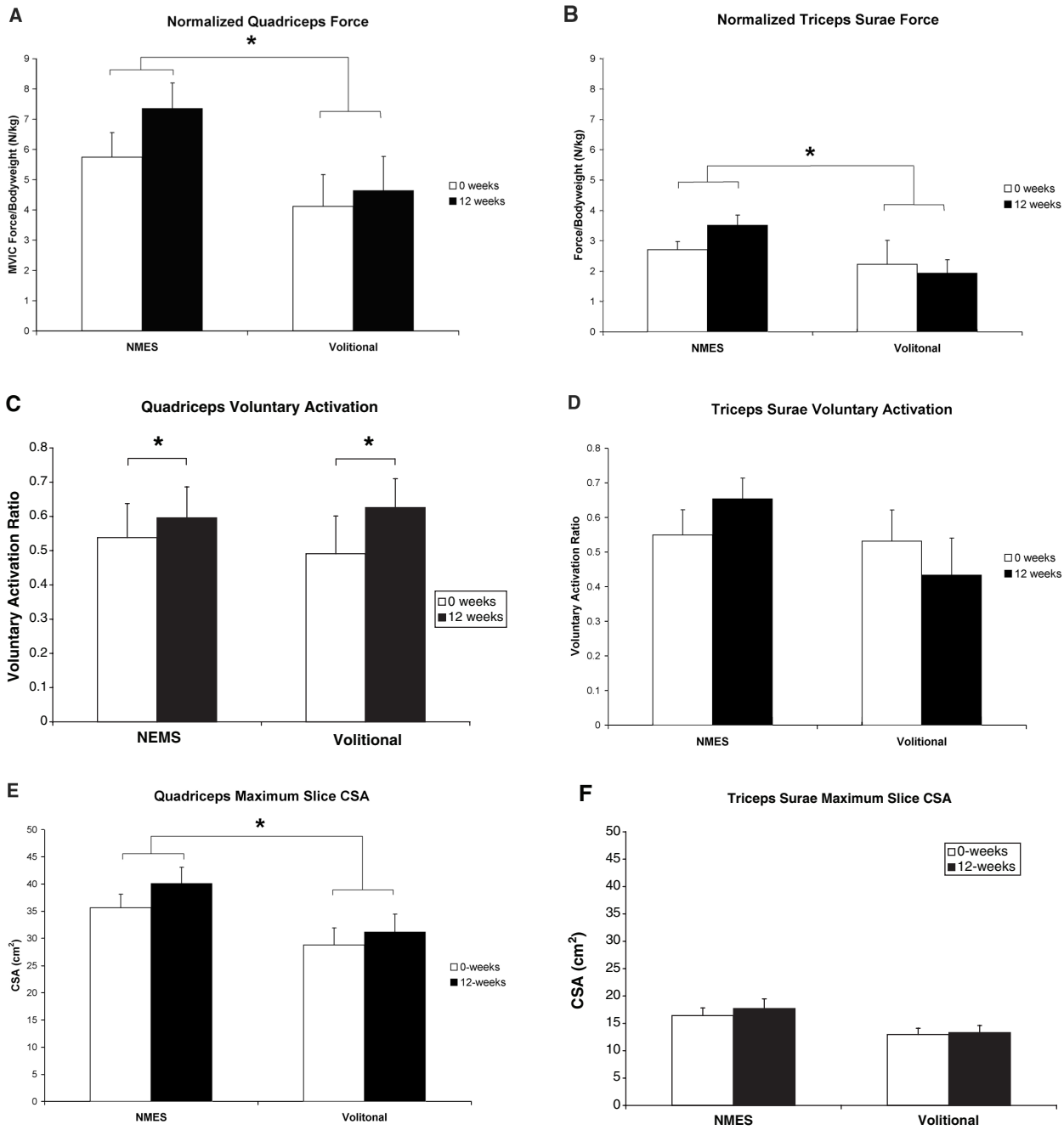

Figure 3. Quadriceps femoris (A) and triceps surae (B) force production normalized to body weight (N/kg) before (open bars) and after (solid bars) neuromuscular electrical stimulation (NMES; n = 5) and volitional (n = 5) 12-week strength-training programs in children with spastic diplegic cerebral palsy. The amount of voluntary muscle activation before (open bars) and after (solid bars) NMES and volitional strength training in the (C) quadriceps femoris and (D) triceps surae muscles. The maximum cross-sectional area (CSA) before (open bars) and after (solid bars) strength training using NMES or volitional exercise in the (E) quadriceps femoris and (F) triceps surae muscles. MVIC = maximum voluntary isometric contraction. *$P < .1$.

(Figure 5). There was no pre-post intervention difference between the NMES and volitional groups ($t = 1.149$; $P = .142$). The NMES group, however, showed a within-group increase in walking speed from 80.47 (SD, 16.80) cm/s at baseline to 96.37 (SD, 25.78) cm/s after 12 weeks of training ($t = 2.671$; $P = .028$), whereas the volitional group did not (85.57 [SD, 27.85] cm/s to 89.99 [SD, 23.14] cm/s; $t = 0.551$; $P = .306$).

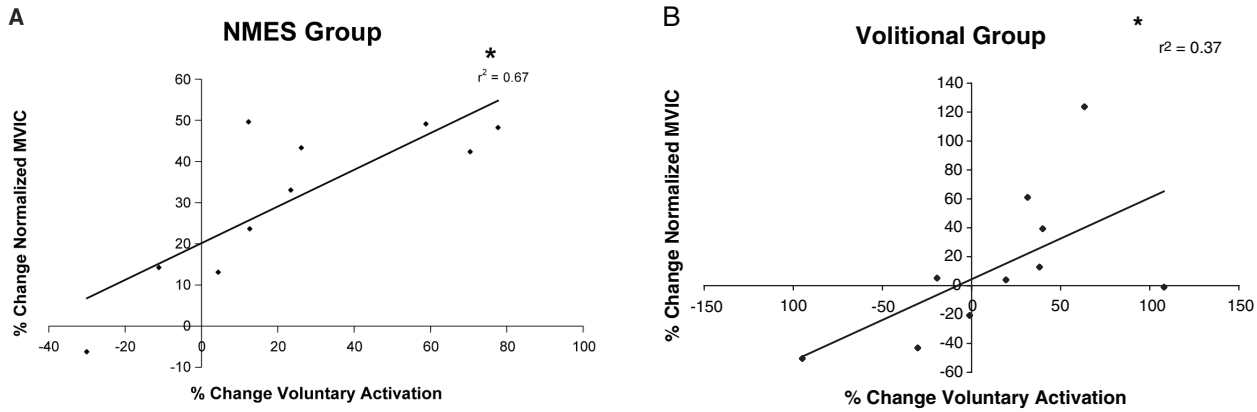

Figure 4. The relationship between the percentage change in voluntary activation and the percentage change in maximum voluntary isometric contraction force in the (A) neuromuscular electrical stimulation (NMES) and (B) volitional strength-training groups after pooling the data for the quadriceps and triceps surae. MVIC = maximum voluntary isometric contraction. * indicates a significant positive linear relationship, $P < .1$.

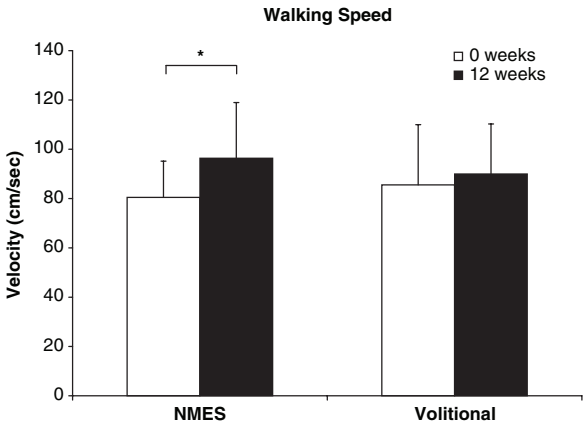

Figure 5. Self-selected walking speed before (open bars) and after (solid bars) a 12-week strength-training program that uses either neuromuscular electrical stimulation (NMES) or volitional isometric contractions. *$P < .1$.

DISCUSSION

The results of this preliminary study support the concept that children with spastic diplegic CP can use percutaneously implanted electrodes for NMES strength training of the quadriceps femoris and triceps surae. To our knowledge, this is the first use of high-force, low-repetition NMES strength training in these children. High training doses for the quadriceps (~130% of MVIC) and triceps surae (~60% of MVIC) were achieved by using a percutaneously implanted electrode system that was well tolerated, in part because the implanted electrodes avoided the sensory receptors in the skin and subcutaneous tissue.[36]

Force production improved by approximately 32% and 33% in the NMES group for the quadriceps femoris and triceps surae muscles, respectively (Figure 4A and B). These percentage gains in force production are very similar in magnitude to the 13.1% to 47.8% gains in knee extensor force reported after resistance training in healthy, prepubescent children[37-41] and to the 16.5% to 48.5% gains reported for children with CP.[14,15,18,42,43] High-force strength training in children can be performed safely and effectively under the proper supervision where good technique is emphasized.[37,38,40,44] Despite having the children train at home with very high contraction intensities (up to 160% MVIC), none of the children experienced any negative responses other than short-term muscular soreness lasting several days after the initiation of training and after the dose was increased at midtraining. We believe that we were able to train safely because we made sure that the contraction was not causing any joint pain (eg, anterior knee pain) and we trained the parents or guardians to stabilize their child appropriately on the customized exercise boards so that the contractions would be isometric.

Several possibilities may explain why we observed greater increases in normalized force production for the NMES compared to the volitional trained group. One reason may be related to the NMES group training at force levels beyond what they were able to produce volitionally from the quadriceps femoris (~118% of MVIC). Thus, the NMES group loaded the musculotendon unit to a greater degree than the children training with MVICs. This higher loading may have exceeded the threshold required to induce a training response. This theory seems especially plausible because we previously demonstrated that children with CP are not able to activate their muscles fully and, therefore, might not be able to attain training forces that are sufficient to induce an effect.[2] When the dose-response relationship was examined for the NMES group, however, we saw no clear relationship ($r^2 = .139$; $P > .05$). Other possibilities may be that the NMES may

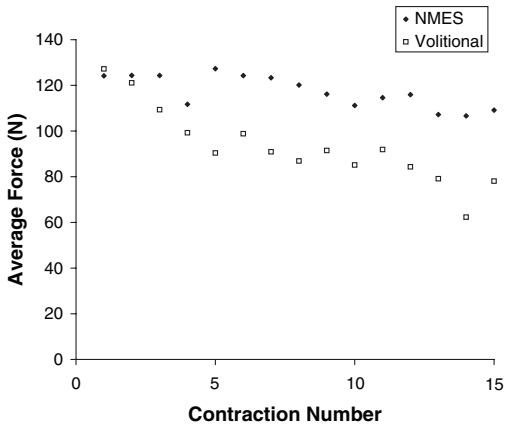

Figure 6. Example of the average forces of one child with cerebral palsy performing knee extension training using only neuromuscular electrical stimulation (NMES; solid symbols) or volitional contractions (open symbols) while being recorded on a dynamometer. This child was in the volitional training group and later had electrodes implanted for NMES strength training (NMES data not included in this report).

provide a more consistent training force because each contraction is not susceptible to variations in voluntary activation (Figure 6). Additionally, NMES may be facilitating neural factors that are associated with early changes in force production during strength training.[45-48]

Mechanistically, our results indicate that voluntary muscle activation is the primary factor that accounts for changes in force production in children with spastic diplegia after 12 weeks of training (Figure 3A and B). This finding is supported in the strength-training literature for typically developing preadolescent children.[39,40] Ozmun and colleagues[39] studied the neuromuscular adaptations to an 8-week volitional training program for the elbow flexors using integrated EMG amplitudes. Children in the trained group experienced a 27.8% increase in force production and a 16.8% increase in integrated EMG amplitude. Ramsay and colleagues[40] assessed voluntary activation using twitch-interpolation, a technique similar to what we described in this study, during which a single stimuli is delivered during the contraction and again while at rest. Training was performed for 20 weeks for the elbow flexors and knee extensors. Voluntary muscle activation increased by 13.2% and 17.4% in the elbow flexors and knee extensors after training, respectively, but these increases only represented a trend due to high variability in the data.

We hypothesized that we would see a larger increase in voluntary activation in the group that trained with volitional contractions because they would have practiced MVICs for 12 weeks. Our preliminary study shows that both NMES and volitional groups increased their quadriceps femoris volitional activation, but there was no difference in magnitude between the groups. We, however, observed no significant increases in triceps surae volitional activation, but 4 out of 5 patients in the NMES group increased their volitional activation, whereas increased volitional activation was evident for only 2 out of 5 patients in the volitional group. Our combined volitional activation data from the quadriceps femoris and triceps surae demonstrate a linear relationship between the change in force and the change in voluntary activation that was nearly twice as strong in the NMES group ($r^2 = .67$ vs .37). In case studies, people poststroke were able to volitionally perform ankle dorsiflexion immediately after electrical stimulation was delivered to the tibialis anterior.[49] More recently, increases in voluntary activation[50] and fMRI voxel intensity of the involved motor cortex[51] after several weeks of treatment with NMES were found in patients with stroke compared to a control group.

Another mechanism for increasing force generation that we examined was muscle hypertrophy. We measured the maximum fat-free CSA of the quadriceps femoris and triceps surae muscles using MRI and found a significant increase in CSA in the quadriceps femoris muscles in the NMES group (10.87%) and a nonsignificant change in the volitional group (4.34%). No differences were observed in hypertrophy for the triceps surae muscles. The average percentage increase in quadriceps maximum CSA in the NMES group is within the reported range of 4.9% to 19.3% increases for young adults following strength training.[52-57] The increase in quadriceps maximum CSA seen in the volitional group was at the low end of the reported range for young adults.[52-57] The more robust increase in CSA seen in the quadriceps of the NMES group could have resulted from the substantially higher relative forces produced versus the triceps surae (Table 1). However, we did not see a relationship between the percentage change in MVIC force and the percentage change in CSA. The lack of a linear relationship between the percentage change in MVIC force and percentage change in CSA could be the result of only a modest increase in CSA and limited variability in the data. Therefore, more patients will be necessary to make any conclusions regarding the relationship between changes in muscle CSA and MVIC force.

Our inability to achieve equivalent forces when stimulating the triceps surae was due to either electrode placement or discomfort. Of the 5 individuals on whom we report dosing information, 2 patients only had 1 electrode placed to activate the entire triceps surae. Subsequent to finding out that the triceps surae stimulation doses were not as high as the quadriceps femoris, we changed our implantation procedure to include electrodes in both the medial and lateral heads of the gastrocnemius. This change helped to produce greater forces; however, we

found for this smaller muscle group, subject tolerance is lower than for quadriceps femoris muscle stimulation. Another important clinical difference between the 2 muscle groups is that children in this study wore molded ankle foot orthoses for ambulation, which discouraged their use of the triceps surae muscles during weight bearing. Thus, the use of orthoses may have blunted any potential hypertrophic effect of the stimulation training.

In this preliminary study, we did not observe group differences in the magnitude of pre-post intervention walking speed. However, a within-group increase in speed was observed for the NMES group. This gain in walking speed was approximately twice the magnitude observed by another strength-training study in children with spastic diplegia.[13] We believe, therefore, that NMES has great potential for use in conjunction with volitional strength training and motor learning therapies to achieve the goal of increased function for children with CP.

To our knowledge, this is the first study to show strength gains using electrically elicited high-force, low-repetition contractions of the quadriceps femoris and triceps surae muscles for strength training in children with CP. These preliminary findings will be further tested in the course of the larger randomized clinical trial involving nonexercised control, NMES, and volitional groups with spastic diplegia from CP.

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