

Superimposed electrical stimulation decreases maximal grip force

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Aim. The purpose of this study was to assess maximal grip force in two conditions of voluntary muscular contraction (MVC) and electrical stimulation superimposed on voluntary muscular contraction (SES) to better understand mechanisms and effectiveness of electrical stimulation of the hand. There is conflicting evidence regarding the effectiveness of electrical stimulation superimposed on voluntary muscular contraction on improving maximal force. Increased knowledge of the physiologic and mechanical effects of electrical stimulation applied during voluntary muscular contraction can lead to refinement of its clinical application.

Methods. Twenty subjects (36±13 years; 17 males and 3 females) participated in this study. All subjects were undergoing physical therapy within a hand rehabilitation center. They were instructed to randomly perform three grip determinations in both voluntary muscular contraction and superimposed electrical stimulation conditions to elicit maximal grip force of the unaffected hand. Force was assessed using a handheld dynamometer. Subjective force and contraction were assessed just after sessions as well as pain and discomfort using a visual analogue scale.

Results. The mean force values were 22±7 kg and 30±1 kg for the superimposed electrical stimulation and voluntary muscular contraction conditions, respectively. Analyses of the force measures showed that force was weaker in the superimposed electrical stimulation condition ($P<0.001$). Patients rated their pain and discomfort at 0±0 mm and 4±2.9 mm, respectively.

Conclusion. Maximal grip force is reduced when electrical

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stimulation is superimposed to voluntary muscular contraction. This result could be explained by unbalanced muscular synergies at the hand due to SES, confirming these synergies as essential to produce maximal grip force.

KEY WORDS: Hand strength - Muscles - Electric stimulation.

Transcutaneous neuromuscular electrical stimulation (NMES) uses current to activate – with surface electrodes – muscle and nerve cells by generating a depolarization that involves muscular contraction. In innervated muscles, as the nerves' threshold is twenty times lower than the threshold of muscular fibers, depolarization always activates nerves first.¹

In rehabilitation, NMES protocols are widely accepted and routinely shown as beneficial in research studies as well as in clinical practice for the management of muscle dysfunction following surgery,^{2,3} spinal cord injury⁴ or stroke.⁵ Among the benefits resulting from NMES protocols, a recent study⁶ demonstrates that a maximal NMES intensity superimposed on vol-

untary muscular contraction⁷ (Superimposed Electrical Stimulation, SES) applied during rehabilitation sessions allowed greater range of motion (ROM) recovery after finger sprain than an active ROM protocol alone. In this study, the differential benefit of SES *versus* ROM alone yielded up to a mean of 18° per rehabilitation session. One possible explanation for this added benefit with SES is that the SES protocol allowed greater contraction intensities resulting in greater grip force as well as a greater stress on adhesions and thus greater recovery of ROM.

Maximal hand grip has already been assessed in patients and healthy subjects.⁸⁻¹¹ However, motor unit recruitment is different in maximal voluntary muscular contraction (MVC) and in muscular contraction electrically induced and could therefore yield different results. During MVC, motor units are recruited alternately, thus holding some units at rest, in reserve at any time.¹² In NMES, this alternated pattern is replaced with an artificially elicited muscle contraction. Indeed, electrically induced spikes raise maximal fiber activation by recruiting motor units in a non-selective, spatially fixed, and temporally synchronous pattern.¹³

Despite the greater fiber recruitment illustrated in some clinical trials that support the hypothesis of an increased maximal isometric force in SES,¹⁴⁻¹⁶ other studies show identical^{14, 17} or decreased^{14, 18, 19} force in SES compared to force in MVC. However, these studies focused on lower limb applications and analytical movements mainly involving a single joint and/or a single muscle. None of these studies addressed a global movement involving multiple muscles and joints as with hand grip. The purpose of this study was to examine performances of maximal grip force in MVC and SES conditions in order to better understand mechanisms and effectiveness of this latter technique in hand range of motion recovery after injury.

Materials and methods

Subjects

Twenty right-handed individuals (mean age: 36±13 years; 17 males and 3 females) with various hand injuries participated in this study. All subjects were undergoing rehabilitation which included NMES at the time of the study; however, the uninjured hand was used for measurement. Patients provided informed consent and their rights were protected as required by

the Helsinki declaration (1964) and the local Ethics Committee. All subjects were treated using SES for more than three weeks (5±2 weeks) in order to recover range of motion and they were therefore accustomed to this technique at the injured hand. In our investigation, measures were performed on the patient's uninvolved hand (9 rights and 11 lefts) because electrical stimulation had to be maximal.

Force measurement

Isometric force measures were assessed using a Jamar dynamometer (Asimow engr. Co. 21591). To provide consistency in reporting of clinical and research data,⁸ and in accordance with the guidelines established by the Clinical Assessment recommendations of the American Society of hand therapists,²⁰ we recorded three successive grip determinations in kg. Handheld dynamometer was set at the third handle position when evaluating grip force.

Stimulator

For electrical stimulation, a portable stimulator (Danmeter®, Elpha 2000 model)⁶ was used to deliver constant current. This device produces up to 60 mA contingent upon the maximum intensity tolerated by the patient of symmetrical biphasic rectangular pulses, which have shown to provide the greatest current intensity with the least discomfort while permitting the greatest peak torque scores.¹⁴ With biphasic currents, both electrodes are alternatively positive and negative. Thus, biphasic currents have no polar effect and do not fatigue muscles as fast. Train characteristics were modulated to 40 Hz frequency and 200 µs pulse duration to produce the greater muscle tension with least discomfort.^{21, 22} The contraction duration was 5 s with a 1 s ramp on time and a 1 s ramp off time for a total duration of the electrical stimulation of 7 s. The output was ramped over 1 s at the beginning and end of each contraction for comfort and also to attempt to prevent stretch reflexes in the antagonist muscles in response to sudden movements.

Stimulator intensity must never be increased during off-time in order to avoid unpleasant intense muscle tetanisation occurring at the following on-time. As soon as contraction intensity is reached, a slight rotation of potentiometer will increase muscle contraction intensity even in the off-time. Thus, stimulation was adjusted when the current was on. The goal inten-

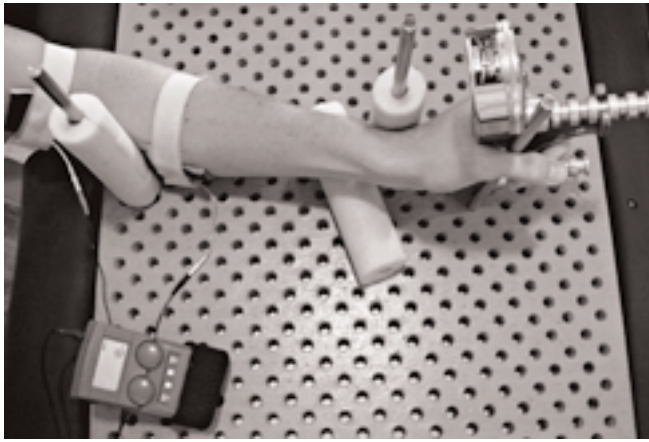


Figure 1.—Superimposed electrical stimulation technique set up for fingers flexion.

sity of the electrical stimulation in this study was the maximal intensity the patient could sustain.

Electrodes

Two stainless steel electrodes (8 × 4.5 cm) covered with a wet sponge and maintained on the skin with a hook-and-loop fastener were placed onto the subject. Sponge electrodes were preferred to adhesive ones to easily adjust positioning to get the best fingers flexion. The proximal electrode was positioned medially to the biceps brachii tendon. This electrode, therefore, covered the medial part of the elbow flexion crease and the medio-posterior aspect of the elbow, where the median and ulnar nerves are closer to skin, respectively (Figure 1). This nerve stimulation allows contraction of extrinsic (flexor digitorum profundus, flexor digitorum superficialis) and intrinsic flexor muscles. The distal electrode was positioned at the forearm along the Ulna medial edge on the flexor digitorum profundus muscular body through the flexor carpi ulnaris which is a thin layer of muscle at this site (Figure 1). Exact positioning choice of the muscular electrode varied from individual to individual based on which position allowed the best finger flexion. The electrodes and the subject's hand remained in the same position during all testing conditions.

Proximal joint blocking

In MVC, the Central Nervous System commands muscle contractions along an exact timing and mus-

cular contraction intensity according to a central pattern. This allows proximal muscle-crossed joints blocking and balance between muscle contractions.²³ In NMES, muscle contraction is peripherally engaged by an electronic device which is unable to perform such a sophisticated pattern as the Central Nervous System. NMES applied onto flexor digitorum profundus products digits flexion, wrist flexion, ulnar inclination and leads to a short muscle positioning. Thus, wrist joint has to be blocked to substitute for the normal control of its flexion. When wrist is blocked, finger flexors force is devoted to the flexion of metacarpophalangeal joints and proximal and distal interphalangeal joints. In hand rehabilitation, this blocking is performed with a hand rehabilitation pegboard (Figure 1) that compensates for the absence of central motor patterns and focuses muscle actions on target joints.

Patient set up

Because the position of the upper extremity directly influences grip measurements, patient positioning was standardised. He was seated with his shoulder adducted and neutrally rotated, the forearm in a neutral position²⁰ and 35° of wrist extension which is the self-selected wrist position to produce optimal grip.²⁴ Elbow was flexed at 110° to make proximal electrode positioning possible.

Subjects were acquainted with the protocols, the sensation of NMES in the uninvolved hand and with the dynamometer through participation in a single practice session prior to testing. A minimum of 48 hours was required between the practice session and the measurement. The two testing conditions (MVC and SES) were randomly performed in this study design, as outlined in Figure 2.

In both testing conditions, subjects were instructed to perform three grip determinations with maximal force. Each trial lasted 5 s with a 1 min rest period between trials and a 5 min rest period between conditions. In the MVC condition, grip determinations were performed without electrical stimulation. In the SES condition, grip determinations were performed with maximal NMES intensity superimposed to MVC. During testing, the subject was not permitted to see his force measures. The investigators provided consistent verbal support (*i.e.*, “grip it!”) for the subject to exert maximal voluntary force immediately following the initiation of the contraction.

Immediately following each SES condition, pain

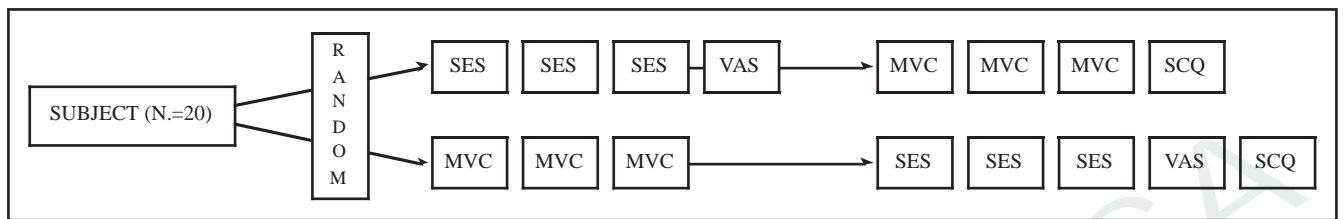


Figure 2.—Study design. SES: superimposed electrical stimulation; MVC: maximal voluntary contraction; VAS: visual analogue scale; SCQ: strength and contraction questionnaire.

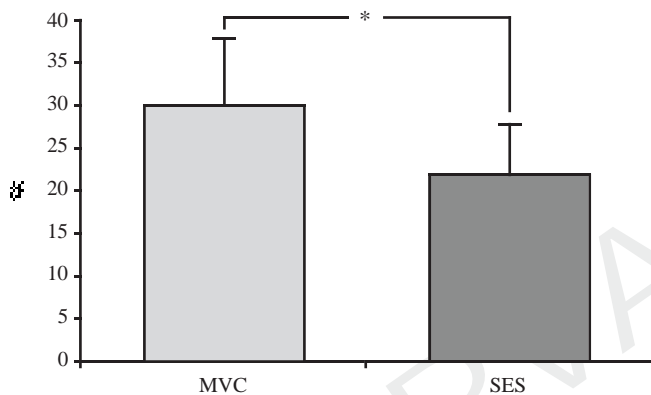


Figure 3.—Mean grip force (kg) in MVC and SES conditions. MVC: maximal voluntary contraction; SES: superimposed electrical stimulation.

and discomfort were assessed using a visual analogue scale (VAS).²⁵ Side of the VAS instrument presented to the patient had a broad unmarked line, 100 mm in length. At the left extreme of the line was the text “no pain” and, at the right extreme, the text “worst imaginable pain.” Patients were instructed to estimate the degree of discomfort and the degree of pain caused by electrical stimulation and to slide the cursor along the line to rate their estimation. Pain and discomfort using the VAS were assessed after each estimation by recording the cursor’s placement. At no time during the estimation of pain and discomfort were the patients informed of their VAS pain and discomfort scores.

Just after each session, patients were asked two questions concerning their subjective assessment of the exerted force scores and the muscle contraction intensity.

Statistical analysis

All data are summarized by mean \pm SD unless otherwise specified. The results obtained in the two test-

ing conditions (MVC and SES) were averaged across the three trials. Due to the paired nature of the data, we used the t test for paired samples and the Wilcoxon signed-ranks two-sided test for matched paired samples. Resulting P-values <0.05 were considered statistically significant. All analyses were performed using SPSS V17.0.

Results

As illustrated in Figure 3, analyses of the data showed that grip force was significantly greater in the MVC condition ($P<0.05$) for both t test and Wilcoxon test with estimated mean force values of 22 kg (95% CI: 20.5~23.5) and 30 kg (95% CI: 28~32) for the SES and MVC conditions, respectively. Of note, the mean force was inferior in the SES conditions for all patients.

During the SES condition, the intensity of applied NMES was 29 ± 70 mA and all patients rated their pain VAS at 0 mm. The discomfort VAS was rated at 4 ± 2.9 mm.

Whereas objective force values are all superior during the MVC protocol, patient’s perception of maximal force was more often associated with the SES condition. Furthermore, subjective maximal muscle contraction was felt to be greater during SES for all patients as shown in Table I.

Discussion

The aim of this study was to examine the effects of SES on maximal grip force. To address this objective, 20 subjects participated voluntarily in this study. Force was measured 3 times in each condition (MVC and SES) in random order and then averaged. The main result was that force was weaker in SES than in MVC condition.

TABLE I.—Subjective and objective assessment of exerted force and muscle contraction intensity.

Stronger	Weaker
“Based solely on your sensation at the hand, did you feel electrical stimulation produced a stronger or weaker force than maximal voluntary contraction alone?”	
14	6
“Based solely on the sensation within the muscles, did you feel electrical stimulation produced a stronger, equal or weaker contraction than maximal voluntary contraction alone?”	
20	
Based on the Jamar Dynamometer measurements, SES grip force was superior to MVC	
	20

Compared to normative data,^{9, 10, 26} the voluntary grip force results of subjects in this study are weaker (Table II). These results could be linked to the difference in hand dynamometer position setting. Indeed, literature reports a decreased maximal grip force in the third position compared to the second position.^{27, 28} The present study support these results since the Jamar dynamometer was set at the third position whereas in the other studies setting was the second position. We chose the third position of the Jamar dynamometer in order to enable the joint blocking essential to allow maximal current intensity during SES.

The maximal NMES intensity tolerance in this study (29 ± 7 mA and 26 ± 9 mA for men and women respectively) was similar to the intensity reported by Locicero¹⁵ for knee extensors (32 ± 6 mA and 26 ± 4 mA) but superior to the intensity reported by Hortobagyi *et al.*¹⁸ for elbow flexors (22 mA for men). The higher NMES intensity tolerated by subjects in this trial compared to those from Hortobagyi's study¹⁸ could be due to the fact that our subjects were using NMES for more than three weeks prior to the initiation of the study and were therefore more accustomed to it. In addition, exposure to NMES may account for the low discomfort levels reported by our subjects (40 ± 29 mm). The discomfort levels reported by subjects in this trial correspond to moderate discomfort (mean of 50 mm)²⁹ and is similar to data reported in previous studies (41 ± 19 mm and 37 ± 19 mm for older and younger subjects respectively).³⁰ Finally, all subjects reported a pain level of zero indicating that the decrease in force was not related to pain.

TABLE II.—Study and normative data for volitional grip force in kg.

Patient	Schmidt and Toews ^{10*}	Mathiowetz <i>et al.</i> ^{9**†}	Hanten <i>et al.</i> ^{26*}	Boisgontier <i>et al.</i> [‡]
1	56	55	53	30
2	47	46	49	30
3	53	55	53	37
4	54	55	52	31
5	—	32	34	25
6	46	35	39	37
7	51	50	49	49
8	50	51	50	35
9	49	47	—	18
10	53	50	49	37
11	53	50	49	44
12	52	54	54	30
13	—	26	30	10
14	—	32	31	21
15	51	50	49	32
16	51	51	50	32
17	51	50	49	28
18	48	50	55	23
19	51	54	—	26
20	—	41	—	32
Mean	51	47	47	30
SD	2.6	8.8	8.0	8.8

* Jamar dynamometer hand position setting 2; † Elbow at 90°, arm at the side of the body; ‡ Jamar dynamometer hand position setting 3, elbow at 110°.

In this study, subjective force and contraction perception were distinguished and assessed. The data collected with the questionnaire indicate that force was perceived as superior in the SES condition (Table I). These results are consistent with data reported by Kramer *et al.*¹⁴ Subjects also perceived greater contractions in the SES condition despite the decrease in objective force measures, suggesting that while more motor units are recruited during SES at a local level this motor unit recruitment does not translate into greater global force output (*e.g.*, grip force). It is also possible that the added sensation that accompanies electrical stimulation was involved in the greater contraction perception.

Indeed, the primary outcome of this trial is a statistical ($P<0.05$) and clinical (8 kg) decrease in maximal grip force with SES. In the uninvolved hand, muscle coordination patterns result in balance between intrinsic and extrinsic activations regulating produced force at the hand.³¹ A previously validated model based on these coordinations assesses the maximal possible biomechanical fingertip forces.³² In this study, the authors highlighted the fact that every maximal magnitude is produced by a unique muscle

coordination pattern, whereas submaximal fingertip force coordinations are redundant. As the fingertip and the grip forces both involve intrinsic and extrinsic muscles, we can assume that a similar model takes place for grip force. Also, the twitch interpolation technique evidenced that single impulse of SES artificially enabled to produce the true muscle strength that is superior to the MVC.³³ Therefore, it could be assumed that the application of SES would likely break the intrinsic-extrinsic balance by overcontracting extrinsics and thus preventing the application of the maximal force magnitude pattern.

Furthermore, at the hand, a single muscle may be a member of more than one synergy in order to allow accuracy of movement and hand shape adaptation to objects. Thus, single motor units receive a variety of motor commands, and the net result may be that the neighbouring units in the same muscle are preferentially recruited to produce forces in different static postures. Producing a force in a new direction would then entail derecruitment of the current group of motoneurons and recruitment of a new group, which may or may not contain some of the same members as the old group.²³ By eliciting contraction of all motor units reached by the current regardless of their function, muscle contraction in SES makes these fine recruitments impossible.

Due to the complexity of the hand motor units recruitment and its muscle coordinations, a gross contraction like the one elicited by electrical stimulation is unable to produce greater force than a voluntary one. Indeed, even if more motor units are recruited or greater recruited by superimposed electrical stimulation, they do not work in synergy with the ones recruited by voluntary muscular contraction and would rather resist one another, thus decreasing global force.

The coordination and motor unit recruitment hypotheses can account for the results of superior¹⁴⁻¹⁶ or equal^{14, 17} maximal force in SES protocol in knee extension. Indeed, compared to hand grip, knee extension is a far less complex movement that mainly involves only one muscle, only one joint and only one plan. Thus, SES has no synergies to perturb and can involve a greater force if it is able to induce contraction of more motor units as in MVC. Those hypotheses can also account for the results of decreased force in SES protocol for elbow flexion,¹⁸ which is a poly-joint complex and a poly-muscles movement like hand grip.

Conclusions

In summary, the current data showed mean grip force that was only 64% of the normative value. Interestingly, SES; reduced maximal grip force by 27% of MVC. Therefore, effectiveness of SES in recovering range of motion of the hand after injury cannot be explained by a greater maximal force of the finger flexor muscles. The decrease of MVC when electrical stimulation is superimposed could be explained by unbalanced muscular synergies of the hand due to SES, confirming these synergies as essential to produce maximal grip force.

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