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Superimposed electrical stimulation comfortably improves the endurance of maximal voluntary contractions

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***Aim*. Electrical stimulation has shown to improve muscle endurance in sub-maximal contractions but sessions were painful due to the electric stimuli parameters. Therefore, the present study tested the effects of the superimposed electrical stimulation technique using comfortable current on endurance in repetitions of maximal voluntary contraction.**

***Methods*. Seventeen young healthy subjects performed fifty maximal voluntary contractions of the triceps brachii in two conditions of contraction (voluntary vs. voluntary + superimposed electrical stimulation).**

***Results*. Peak force and force-time integral were consistently decreased in the voluntary muscular contraction condition after the 20th - 30th trials whereas they were maintained in the superimposed electrical stimulation condition (P<0.05) until the end of the fifty trials.**

***Conclusion*: The superimposition of neuromuscular electrical stimulation extends the muscle ability to repeat maximal voluntary contractions. The present results also evidenced the ability of the superimposed electrical stimulation technique to make the mechanisms of muscle central fatigue inefficient.**

Key words: Muscle contraction - Electric stimulation - Muscle strength.

The neuromuscular electrical stimulation (NMES) refers to the activation of a muscle by an electrical current for therapeutic, training or functional purposes.[1] It is currently well acknowledged that the specific motor unit recruitment [2, 3] associated with NMES imposes an exaggerated metabolic demand [4] and thus hastens the onset of muscle fatigue.[5] However, Ikai and Yabe [6] showed that endurance of a muscle was increased by the use of electrical stimulation in sub-maximal contractions. They evidenced additional electrically induced thumb adductions following exhaustion of voluntary adductions. Electrical stimulation activated the muscle directly thus making central fatigue ineffective. However, the current parameters they used made the contractions electrically induced "very painful" (pulses of 5 ms duration at a stimulation frequency of 50 Hz during 0.5 s). Whether comfortable current parameters could result in a similar endurance improvement at maximal force levels so that it could be used as a clinical method has not been yet assessed. This information could though be of interest for rehabilitative programs that aim at recovering range of motion after injury. The key factor for optimizing NMES effectiveness has been suggested to be muscle tension that is the level of evoked force with respect to maximal voluntary force,[7] which should be maximized in relation to the patient comfort, via an appropriate manipulation of the two main NMES current parameters: frequency and intensity. In order to maximize muscle tension, it is recommended to use pulses of 100-400 µs delivered at a stimulation frequency of 50-100 Hz and to apply NMES in a static loading condition, so as to strictly control the level of evoked force.[8] However, Collins [9] showed that muscular forces were inferior when the contraction was elicited by NMES alone than voluntarily alone. This result could be related to the marked visco-elastic force evidenced in electrically elicited contractions.[10] In this study, it was

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chosen to test NMES superimposed onto voluntary contractions in order to get the most effective effect of NMES on muscular force. Previous studies have already assessed the instantaneous effects (i.e. effects measured during electrical stimulation) of the superimposed electrical stimulation (SES) on the maximal voluntary contraction (MVC) and yielded divergent results. Some clinical trials supported the hypothesis of an increased maximal isometric force in SES [11] whereas other studies showed identical [12, 13] or decreased [14-17] maximal voluntary contraction with SES as compared to voluntary muscular contraction alone. It can therefore be assumed that the SES technique produces comparable maximal muscular forces as the voluntarily elicited ones.[18] These previous studies also demonstrated that the SES technique was well accepted by subjects. To determine if SES could improve endurance in maximal force repetitions, 50 maximal isometric contractions of 4 s of the M. triceps brachii were measured in two conditions of MVC with and without SES.

Materials and methods

Subjects

Seventeen right-handed adults (11 males, 6 females; age: 21±2.4 years; body weight: 61±9.2 kg; height: 171±8.0 cm; mean±SD) with no history of injury in the upper extremities participated voluntarily in the experiment. They gave their informed consent to the experimental procedure and their rights were protected as required by the Helsinki declaration (1964) and the local Ethics committee.

Experimental set-up

To collect all the components of the produced force, subjects were seated in a fixed rigid chair in front of a force platform (AMTI®, OR6-5-1 model) which was vertically positioned at the shoulders level.[19] The trunk was vertical, the right shoulder was flexed to 90 deg, arm placed on a table, elbow flexed at 95 deg, forearm in supination position, and wrist and fingers relaxed. The distal extremity of the forearm contacted the force platform. An investigator controlled the absence of trunk movement and ensured that shoulder and elbow joint angles were kept constant throughout the investigation.

Procedures

Subjects were instructed to perform elbow extension and produce maximal force against the force platform each time they were feeling the electrical stimulation. The investigators provided consistent verbal support for the subject to exert maximal voluntary force immediately following the initiation of the contraction. Subjects performed 50 trials of 4 sec with 6 sec rest between trials for a total of 500 sec in two randomized conditions of maximal voluntary contraction alone (MVC) and with SES (MVC+SES). Subjects were acquainted with the protocols and the sensation of NMES through participation in a single practice session prior to testing. A minimum of 24 hours was required between the practice session and the measurement and a minimum of one week was required between testing sessions. Before each session, a warm-up was performed through trials at infra-maximal muscular forces.

Electrical stimulation

For electrical stimulation, a portable stimulator (Danmeter®, Elpha 2000 model) was used to deliver constant current, rectangular, symmetric, biphasic pulses. In the present study, current parameters were the following: biphasic rectangular pulses of 200 µs delivered at a stimulation frequency of 40 Hz frequency and a 40% duty cycle (4 s on, 6 s off). Low stimulation frequency was preferred to high-frequency (50-100 Hz) because during pre-tests the reflexive recruitment of spinal motoneurons in high stimulation frequency [8] induced painful muscle tetanus due to the repetition of evoked contractions. Current was self-set by subjects at the highest tolerated intensity (26.9±5.8 mA) at the beginning of the session and delivered at the right arm in the SES condition.[20] Pretests showed that electrical stimulation alone produced forces that were inferior to voluntary muscular contraction alone (21% of the maximal voluntary contraction) which was consistent with the results of Collins.[9] To set the pace in the MVC condition, trains were delivered at a sensitive intensity to the left forearm. Two 5x10 cm self adhesive electrodes maintained on the skin with hook-and-loop fasteners were placed onto the left forearm posterior part and two other electrodes were placed onto the muscular body of the right M. triceps brachii.

Data analysis

Force production was analyzed during 50 trials (500 sec). Force data were sampled at 100 Hz (12-bit A/D conversion) and low pass filtered with a second-order Butterworth (10 Hz). The cut-off frequency was fixed following a spectral and residual analysis.

Two dependent variables were used to assess force performances: (1) the peak force (N) developed during a muscle action that measures the instant maximal force and (2) the force-time integral (N. s), that can be used to assess the amount of force applied during a given period of time (4 s)[21].

Statistical analysis

For the analysis of muscular force, 50 Trials (1 to 50) x 2 Conditions of contraction (MVC vs. MVC + SES) analyses of variances (ANOVAs) with repeated measures on the last factor were applied to the peak force and the force-time integral. Post-hoc analyses (Fisher LSD) were performed whenever necessary. Level of significance was set at $P<0.05$.

Results

Peak force

Analysis of the peak force showed a significant main effect of Condition of contraction ($F_{1,800}=64.21$, $P<0.0001$). The interaction of Trials x Condition of contraction was also significant ($F_{49,800}=2.66$, $P<0.0001$). As illustrated in Figure 1, post-hoc test revealed that peak force significantly decreased in the MVC condition starting for each trial after the 29th one whereas it was maintained in the MVC + SES condition ($P<0.05$).

Force-time integral

Analysis of the force-time integral showed a significant main effect of Condition of contraction ($F_{1,800}=262.71$, $P<0.0001$). The interaction of Trials x Condition of contraction was also significant ($F_{49,800}=1.58$, $P<0.001$). As illustrated in Figure 2, post-hoc test revealed that force-time integral significantly decreased in the MVC condition starting from the 20th trial whereas it was maintained in the MVC + SES condition ($P<0.05$).

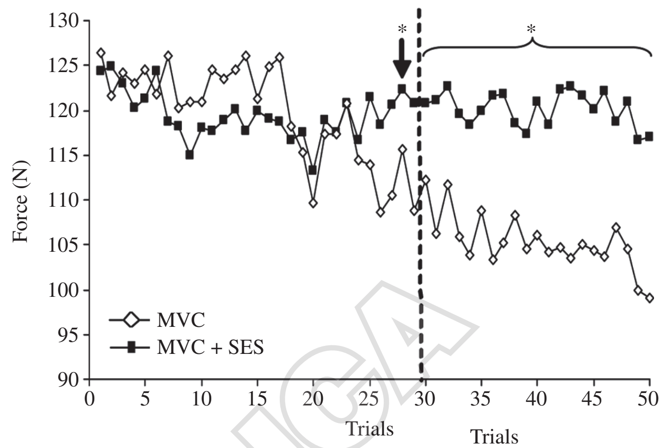

Figure 1.—Mean peak force for each trial in Newtons. Diamonds depict the voluntary muscle contraction condition (MVC) and squares depict the superimposed electrical stimulation condition (MVC + SES). Differences between conditions are significant for each trial at the right of the dotted line

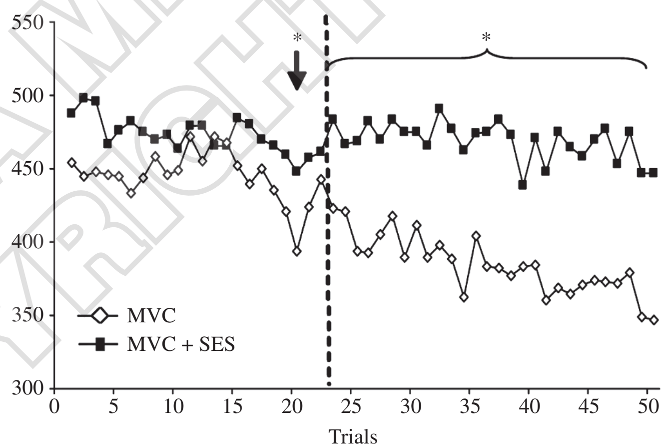

Figure 2.—Mean force-time integral for each trial in Newton x seconds (N.sec). Diamonds depict the voluntary muscle contraction condition (MVC) and squares depict the superimposed electrical stimulation condition (MVC + SES). Differences between conditions are significant for each trial at the right of the dotted line.

Conclusions

The purpose of this study was to assess the effects of SES on maximal muscular force over fifty 4 s contractions of the M. triceps brachii. When considering the 20 first contractions, no significant difference was evidenced between peak force and force-time integral in MVC and MVC + SES conditions. However, after the 20-30th trials peak force and force-time integral decreased consistently in MVC condition whereas they were maintained in MVC + SES condition. The lack of significant difference between the MVC and MVC + SES conditions in peak force and force-time integral for the 20 first trials corroborated previous studies showing that SES was unable to improve MVC.[12-17] The delayed decrease of force production observed in the MVC + SES condition supported the results of Ikai and Yabe [6] who used painful electrical stimulation.

The present findings suggested that SES extends the muscle ability to repeat MVC with the same peak force and the same amount of force. Previous studies evidenced that the decreased firing rate of motor neurons observed in prolonged MVC was related to a central inhibitory signal intending to adapt the central command to the fatigue-induced changes.[22, 23] The present results suggested that SES technique makes this central inhibition inefficient through a peripheral stimulation of motor neurons which are no longer centrally activated.

As noticed in the introduction subsection, the ability of the SES technique to extends endurance of repeated MVC is of importance in the context of orthopaedic injury. Bleeding, inflammation and immobilisation that follow the injury result in adhesions constituted by connective tissue accumulation which is randomly oriented and could impair joints' mobility.[24] When loss of mobility is due to adhesions, the rehabilitation sessions would focus on orienting, stretching, and if possible breaking the adhesions through muscle contractions in order to recover active mobility.[25] Adhesions are mainly composed of collagen which is a thyxotropic tissue whose viscosity decreases over time when strained.[26] It could therefore be assumed that the increased number of MVC allowed by SES would increase the strain on adhesions. This increased strain would facilitate stretching of adhesions and improve range of motion recovery as evidenced in previous clinical studies.[27-31]

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