Muscle enhancement using closed-loop electrical stimulation: Volitional versus induced torque

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Abstract

In cases of muscle partial deficiency, force enhancement can be achieved by electrical stimulation (ES). In the present study the volitional and electrically-induced torque components are resolved under closed-loop activation. Isometric contraction of the Tibialis Anterior (TA) muscle was studied on 5 healthy subjects, using an activation protocol combining ES alone, volitional activation alone and combined activation of these two modes. Torque and EMG were measured. A computational algorithm was developed to dissociate the volitional from the overall torque, based on EMG filtering and pre-determined EMG-torque calibration curves. The results reveal that for a given overall torque, there exists a linear relationship between volitional and ES-induced torque. However, the combined effect of the two activations was found smaller than their algebraic summation, indicating that not all fibers take part in the two activation modes.

1. INTRODUCTION

Muscle force deficiency may be caused by a variety of reasons including, among others, spinal cord injury, stroke, cerebral palsy, muscle atrophy and ageing. Temporary deficiency may be the result of muscle fatigue [3].Electrical Stimulation (ES) of muscles is a well-known technique for the management of muscle force deficiency. While in complete paralysis muscle activation is the result of ES only, in other pathologies muscle activation may generally result from the combined volitional and ES-induced activations. In these latter cases ES is being used for the enhancement of muscle force.

Depending on the level of stimulation, the proportion between volitional and induced activations will vary. This question has been addressed only partly in the literature. Earlier works [5, 6] evaluated the enhancement effect without addressing the combined operation mode of the muscle. Later work assumed that the total output force of a muscle subjected to voluntary and induced activations is the simple summation of the forces that are generated by each of these components [2].

The present study mathematically resolves each of the volitional and electrically-induced torque components under closed-loop activation. Improving our knowledge will help us to achieve better controllability of muscle force enhancement by electrical stimulation.

2. METHODS

2.1. Procedure

Isometric contraction of the Tibialis Anterior (TA) muscle was studied on 5 healthy subjects. Each test was started with measurement of: (a) Maximal Voluntary Contraction (MVC), (b) Volitional torque-EMG relationship. Real-time ankle torque feedback was provided by a monitor placed in front of the subject. The subject was restricted to stay within the displayed stripe while fulfilling his task.

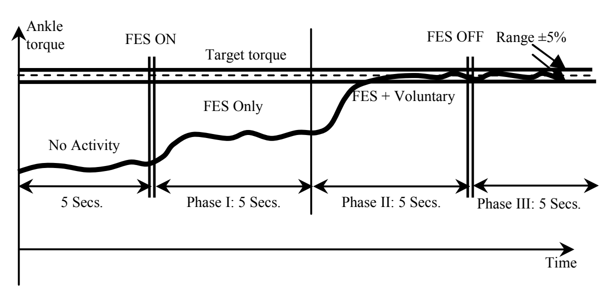

Figure 1: single trial protocol

Each trial included 3 modes of muscle activation (Fig. 1): (I) 0-5s: torque induced by ES only, (II) 5-10s: addition of a volitional torque acting together to reach an overall displayed target torque, and (III) 10-15s: Cessation of ES while maintaining the overall target torque by volitional activation only.

Normally 3 trials were conducted for repeatability and statistics. Different trials were performed by varying the induced component (ES intensity) and the target torque level. In phase II an off-line analysis was performed to evaluate the volitional torque from the overall torque.

2.2. EMG & Mechanical Measurements

The torques were measured in the sitting position by an instrumented beam attached on one side to a static structure and on the other to a plate which embraced the foot. This provided compensation of the gravitational torques. During measurement, the ankle, knee and hip angles were set at 90º.

Parallel to the torque, the subject's TA EMG was measured using three surface electrodes: 2 active electrodes were placed on the belly along the longitudinal axis of the muscle, and 1 ground electrode placed on the bony area of the knee. The impedance between each pair of electrodes was less than 5KΩ. The three electrodes were connected to a specially designed 10kHz bandwidth DC amplifier with stimulus artifact suppression. All signals were sampled at frequency of 1KHz.

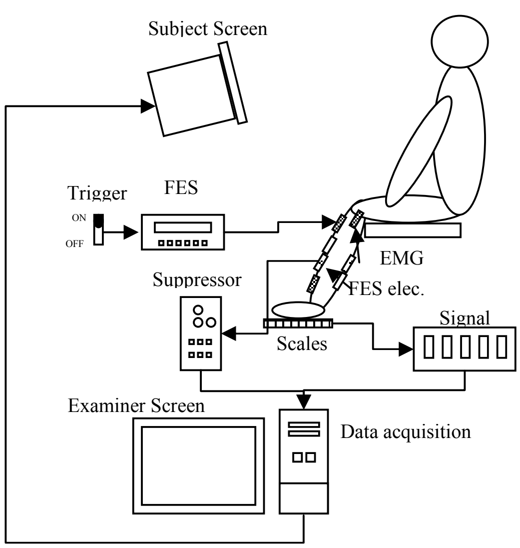

Figure 2: Experimental setup

2.3. ES Apparatus & Protocol

A programmable electrical stimulator providing constant current, rectangular, 100μs mono-phasic pulses, at frequency of 20Hz was used. The pulse intensity was varied between trials to achieve induced torques levels of 0-0.4MVC. Stimulation was delivered to the muscle using two surface electrodes: one was placed over the TA motor point, and the second, 10cm distally. The stimulation parameters were controlled by PC, and an external trigger. During each trial, the stimulator was active for 20s. Resting time between successive activations was 5min.

2.4. Signal processing

In phase II where volitional and induced activation act together, noise was first filtrated. The load cell signals were used to calculate the overall ankle torque. Using the comb-filter the volitional EMG was extracted from the raw EMG signals. Using the EMG values in the EMG-Torque calibration curve yielded the volitional part of the torque in the overall torque (Figure 3).

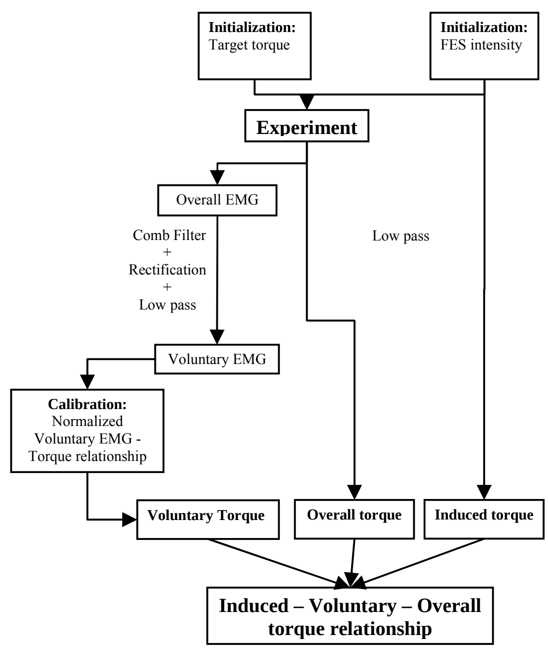

Figure 3: Computation of the volitional and induced torque components

2.5. Graphs and statistics

Linear regression was performed to describe the relationship between the induced torque (*x-axis*), voluntary torque (*y-axis*) and their combined overall torque. The difference between the regression coefficients was used to indicate significant changes between the regression lines with $\alpha < 0.05$ for significance.

3. RESULTS

The results (Figure 4) indicate existence of a systematic relationship between the three magnitudes as follows: (a) for given target torque, the volitional torque decreases as the ES-induced torque increases, (b) for a given induced torque, the volitional torque increases as the overall torque increases. This pattern is well expressed by the linear curves ($0.6 < R^2 < 0.95$)(Table1).

Applying statistical tests to the curves indicates that: (a) in 4 (out of 5) subjects for different target torques the individual curves are statistically different in their zero intersection point (b_0) but not in their slope (b_1); in one subject, though, this difference was found in both b_0, and b_1.

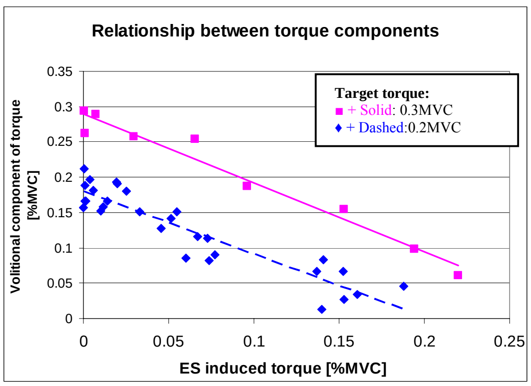

Figure 4: Typical relationship between the FES-Voluntary-Overall torques.

4. DISCUSSION AND CONCLUSIONS

Our methodology is based on deriving the volitional EMG from the overall EMG signal [2]. This EMG is then related to torque using calibration curves. This is a novel approach, which relies in part on previously published works [1], [2].

Table 1: Regression curves and statistical difference of different subjects ($y = b_1 x + b_0$).

0.2MVC			0.3MVC		
b_0	b_1	R^2	b_0	b_1	R^2
0.168	-0.62	0.57	0.28 *	-0.72	0.86
0.18	-0.88	0.85	0.29 *	-0.98	0.96
0.20	-0.51	0.58	0.28 *	-0.42	0.86
0.18	-0.62	0.44	0.28 *	-0.84	0.92
0.19	-0.30	0.23	0.31 *	-0.76 *	0.80

* Significant difference ($P<0.05$)

For a given overall torque, a linear relationship between volitional, and ES-induced torque was established. The *y-axis* intersection (= voluntary torque) value coincidences with the required target torque. The line's slope is negative, with values of (-0.3) – (-0.99), the physical interpretation of this is that with no FES the voluntary torque coincides with the target torque, however the combined effect is smaller than their algebraic sum. A possible explanation to such phenomenon is that some of the already voluntarily-activated muscle fibers are not recruited by ES as well. Likewise, ES may disrupt the volitional activation of other fibers. Thus, in situations where both volitional and ES-induced are present not all the muscle fibers are activated in these two modes. Another explanation is related to the mechanical indeterminacy of the musculo-skeletal system. When the target level and stimulation torque are set, the leg muscles are adjusted to generate the missing torque. While mostly the outcome of the monitored TA activity, part of this torque may also be produced from the other ankle joint muscles. In this case, a simple addition between the known measured volitional and ES-induced torques will not produce the overall output of the muscle, but only a major part of it.

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Acknowledgements

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