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Muscle-joint unit transfer function derived from torque and surface mechanomyogram in humans using different stimulation protocols

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ABSTRACT

Torque and laser detected surface mechanomyogram (MMG) analysis after electrical stimulation of human tibialis anterior (TA) of 14 male subjects was aimed to: (a) obtain the dynamic responses of TA muscle-joint unit from a long (LP, about 1 h) and short (SP, 12.5 s) stimulation protocol; (b) compare the resulting transfer function parameters from the two signals.

The sinusoidal amplitude modulation of a 30 Hz stimulation train (SST) changed the number of the recruited motor units, and hence the isometric torque and the TA surface position in the same fashion. Subject instrumentation and SST amplitude range definition took about 25 min. SP: seven consecutive modulation frequencies (0.4, 6.0, 1.0, 4.5, 1.8, 3.0, and 2.5 Hz). LP: fourteen 5 s long isolated frequencies (0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 4.0, 5.0, and 6.0 Hz), 5 min rest in between. Poles position (Hz) and added delay (ms) for phase correction with respect to the input sine (parameters of a critically damped II order system) were: torque 2.44 ± 0.27 Hz (SP) or 2.32 ± 0.33 Hz (LP) and 18.3 ± 2.2 ms (SP) or 17.2 ± 4.5 ms (LP); MMG 2.28 ± 0.30 Hz (SP) or 2.30 ± 0.44 Hz (LP) and 17.4 ± 5.6 ms (SP) or 17.4 ± 6.4 ms (LP). Differences were never statistically significant. Conclusion: it is possible to characterise the *in vivo* mechanics of muscle-joint unit with a short (few seconds) stimulation protocol affordable in clinical environment using both torque and MMG signals.

1. Introduction

Partridge (1965), considering the muscle as a frequency/tension converter generating a force proportional to the rate of the stimuli, was able to define the muscle-tendon unit transfer function (TF). The TF was characterised by analysing the behaviour of the force output amplitude and phase shift, when the rate of the supramaximal stimulating pulses (input to the system) was varied sinusoidally from low (fraction of Hz) to high frequencies (several Hz). Later, several papers suggested that a *force frequency dynamic response* (FFDR), useful for TF determination, was obtainable changing sinusoidally the motor units recruitment level (for a short review see Baratta and Solomonow, 1992; Baratta et al., 1998) during a constant rate stimulation of the motor nerve. Recently Orizio et al. (2007) obtained the TF of human tibialis anterior (TA) *in vivo* using a method in which the stimulation rate was kept constant while the motor units recruitment level was varied sinusoidally changing the amplitude of the stimulation train. This method avoids the problems associated with non-linear force-frequency relationship (Solomonow, 1984; Binder-Macleod and McDermond, 1992), thus obtaining a FFDR dependent only on the number of the active motor units.

During muscle contraction the force generation process is coupled with changes in the muscle geometry determining a displacement of the muscle surface. The detection and the measure of this phenomenon allow the characterisation of the mechanical activity of the muscle (Partridge and Benton, 1981). The electrical signal monitoring the muscle surface movement is named “surface mechanomyogram” (MMG) (Orizio et al., 2003a) and can be generated by a laser distance sensor. Using this transducer Orizio et al. (2000) were able to demonstrate that the MMG provides information similar to the force signal when the TF is investigated in cat medial gastrocnemius.

In both studies (2000, 2007) Orizio et al. were able to characterise the muscle TF using a long stimulation protocol (LP) with 14 separate frequencies, administered for 6 or 10 s each, that took more than 1 h. In fact the recovery periods lasted 5 min between each of the 14 stimulation frequencies (from 0.4 to 6 Hz) used to get the muscle-joint unit FFDR. It is clear that this kind of experimental procedure is not affordable in muscle function studies and/or

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in clinical investigations because of its long duration, which may trigger fatigue. Nonetheless the definition of the muscle-joint TF could be useful to provide biomechanical basic information that may contribute to explain the results of free movement analysis, to check the outcome of specific training and rehabilitation programs and finally to design functional electrical stimulation protocols to achieve muscle action in paralysed muscles.

On this basis the present study was undertaken on the tibialis anterior of human beings with two main practical aims:

- Verify, by comparison with the results from a long protocol, the validity of a short (only few seconds) stimulation protocol (SP) in which the stimulation train amplitude was sinusoidally modulated from low (0.4 Hz) to high frequencies (6 Hz) to get a reliable force frequency dynamic response.
- Compare the TFs obtained from the output torque and the MMG to verify if the laser detected muscle surface displacement can be an adjunct tool to characterise muscle mechanics.

2. Materials and methods

Fourteen male sedentary subjects (age: 20–35 years), without orthopaedic or neurological diseases, gave their informed consent to participate in the study after being given a full explanation of the purpose and procedures of the experiment according to the recommendations guiding physicians in biomedical research involving human subjects contained in the declaration of Helsinki (1964).

2.1. Experimental set-up

The experiments were carried out by eliciting isometric contractions of the dominant side Tibialis Anterior (TA) muscle. The experimental set-up is shown in Fig. 1. The leg of the subject was positioned in an anatomical device designed for isometric contraction of the ankle flexors. According to Maganaris (2001) the ankle joint angle was +30° (plantar flexion direction from neutral anatomical position) in order to elicit the maximal force output from ankle flexors. The foot was strapped to a wooden plate connected to a load cell (Interface, model SM-100 N, linear response between 0–100 N) sensing the tension produced by the portion of TA stimulated at the most proximal motor point (for details see below). The whole detection apparatus had a resonant frequency

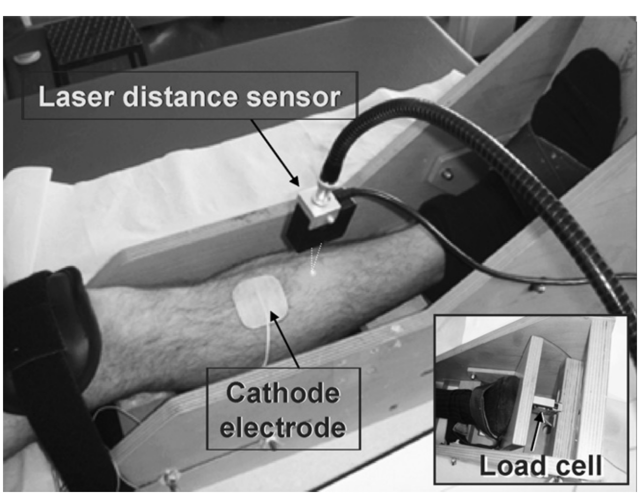

Fig. 1. Experimental set-up for mechanical signals detection during sinusoidal modulation of the 30 Hz train delivered at the most proximal motor point of tibialis anterior (TA). The laser beam for TA surface displacement recording was pointed at the muscle belly.

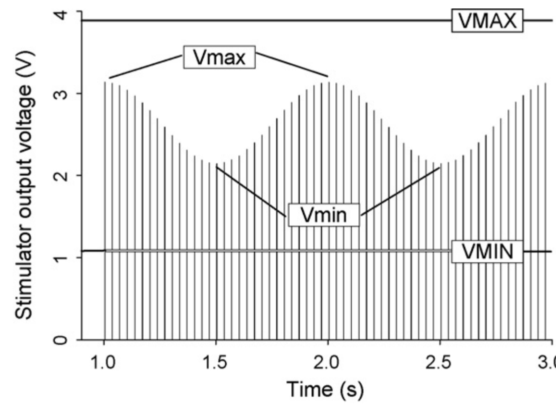

Fig. 2. The 30 Hz stimulation train whose amplitude changed sinusoidally between Vmin and Vmax. This amplitude range provided the largest sinusoidal torque and MMG oscillations at a frequency of 1 Hz with the lowest distortion. VMAX, the stimuli amplitude eliciting the maximal electrical response and the maximal output torque during 2 s 30 Hz train; VMIN, stimuli amplitude eliciting 20% of the maximal output torque during 2 s 30 Hz train.

>200 Hz. After conditioning (bandwidth DC −128 Hz) the force signal was sampled at 1024 Hz.

To measure the displacement of the TA muscle surface (MMG) an optical laser distance sensor (M5L/20, MEL Mikroelektronik, Germany, range of measurement ±10 mm, sensitivity 1 V/mm, linearity 0.6%, resolution <6 μm, bandwidth 0–10 kHz) was employed. The device provided an output DC voltage proportional to the distance between the laser-beam head emitter and the reflecting surface of the pointed object. The measure of the distance of the reflecting surface from the laser source was not affected by surface rotation within ±15 and ±30° with respect to the short and long axis of the laser head, respectively. Laser MMG was low-pass filtered at 64 Hz and sampled at 1024 samples/s.

2.2. Procedure

After skin cleaning with ethyl alcohol, the most proximal motor point (MP) of TA has been localised, according to Merletti et al. (1993), using a pen electrode as a cathode (1 cm^2 surface) to explore the muscle surface while a large positive sponge electrode (10 cm × 14 cm) was placed on the other side of the leg strictly in contact with the gastrocnemius muscle. Finally an adhesive cathode electrode (5 cm × 5 cm) was placed over the identified MP. For sake of clarity it has to be specified that the stimulation train delivered at the TA MP will be described referring to the term “rate” as the number of stimuli per second and to the term “frequency” as the reverse of the period of the sinusoidal input function modulating the train stimuli amplitude. The myoelectrical response was picked up by a surface EMG probe with 1 cm spaced 2 bar electrodes (1 cm × 1 mm × 1 mm) positioned 1 cm distally from the MP. Before the administration of the stimulation protocols three procedural steps aimed to define the stimulation train amplitude parameters were performed:

(1) Starting from 0 V the amplitude of a train of 1 Hz square pulses (having a positive and negative phase of 100 μs duration each) was increased in steps of 0.1 V every 10 events. The 10 electrical responses were averaged per each level of stimulation amplitude to follow the peak-to-peak evoked EMG increase. When no difference in EMG amplitude in the latter two levels of stimulation was found, the maximal amplitude (VMAX) of the stimuli was identified (see Fig. 2). By definition VMAX recruited all the motor units belonging to the MP. A 2 s 30 Hz stimulation train at