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MOTOR UNITS DISTRIBUTION AND RECRUITMENT ORDER RETRIEVED FROM FORCE / M-WAVE RELATIONSHIP DURING STIMULATED CONTRACTION

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1. INTRODUCTION

Transcutaneous electrical stimulation (TES) of the peripheral nervous system is widely applied to investigate or improve muscle function. The synchronous activation of muscle fibres is most likely achieved by stimulating the motoneuron terminal branches [1]. Getting a deeper insight into the mechanisms by which the delivered current pulse induces the activation of the muscle fibres is crucial for the better exploitation of the TES. This work investigates the mechanism underlying TES using both electrical and mechanical responses (i.e., surface potential, referred to as M-wave, and torque, respectively), using simulated and experimental data from tibialis anterior (TA) muscle.

2. METHODS

Experimental data collection and processing

Eight healthy male subjects participated in the study. The dominant leg was placed in an isometric brace and the foot was fixed to a plate (Figure 1A). A load cell fixed to the plate measured the force generated during the contractions. Biphasic stimulation currents at 20 pps for 3 s were applied to the motor point of the TA muscle with different amplitudes (1.7 mA step) in different stimulation sets, with 1 minute rest (Figure 1B). Surface EMG signals were detected over the TA muscle with a linear array of 8 electrodes 5 mm apart in single differential (SD) configuration aligned to the muscle fibres. Variables of interest were average rectified value (ARV), mean frequency (MNF), conduction velocity (CV) and force.

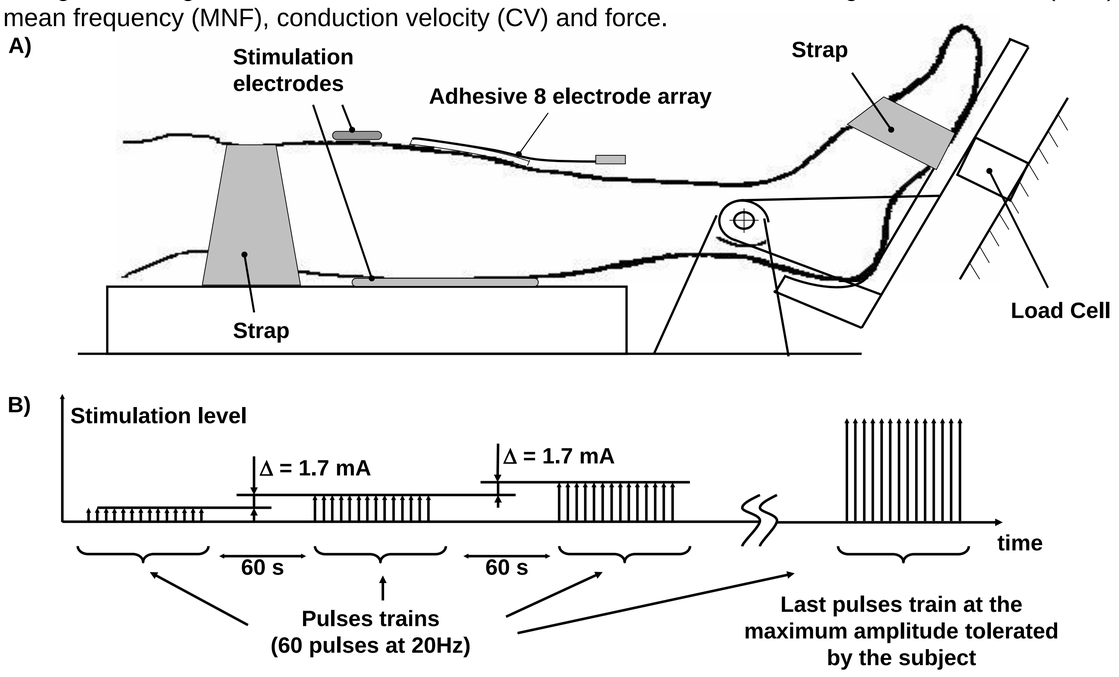
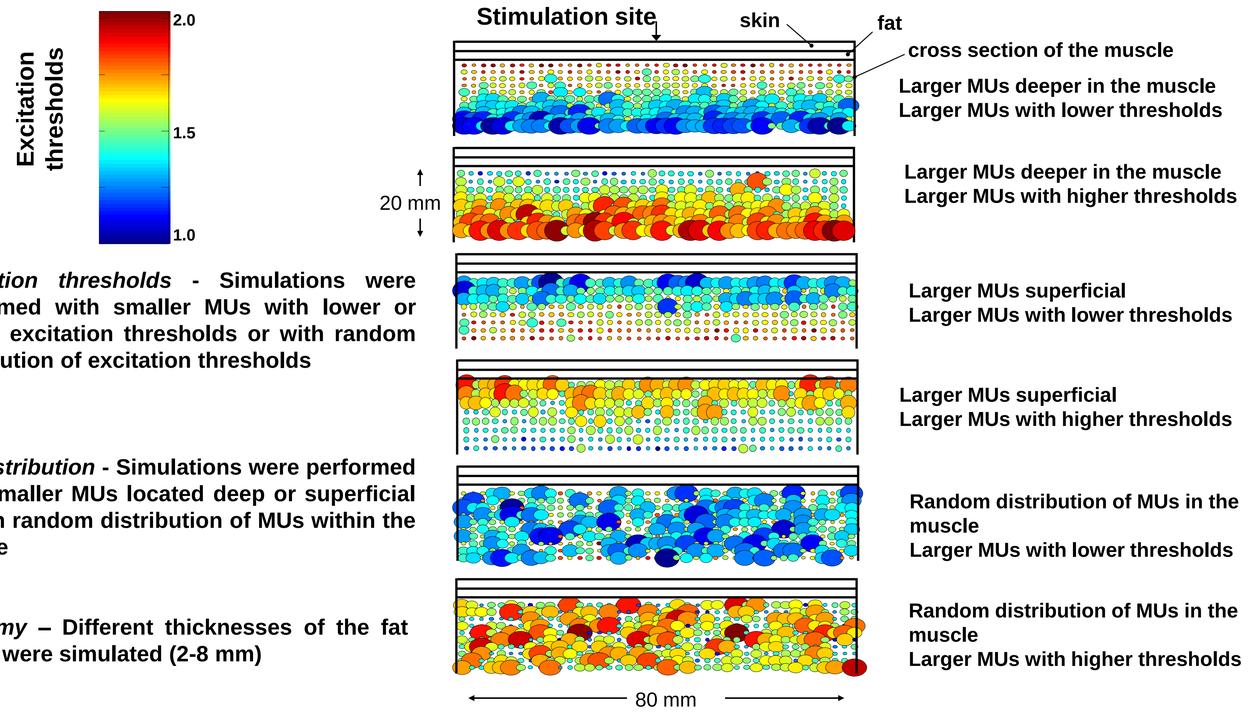


Fig.1 A) Ergometer for isometric measurement of the force produced by TA during electrical stimulation. B) Representation of the stimulation sequence used during the protocol.

Simulation of electrical and mechanical responses

M-waves were simulated by a model of electrical stimulation [2] and a simulator of surface EMG (including skin 1 mm thick, fat with thickness in the range 2-8 mm, and muscle extending to infinity). Known conductivity data were used to simulate the current distribution induced by stimulation. The selection of elicited MUs was determined considering the current density distribution in the territory of each MU and the excitation threshold characteristic of the MU. The action potentials of the elicited MUs were added up to simulate M-waves. Exerted force was simulated by adding the contribution of each of the elicited MUs, estimated on the basis of a model of muscle force in isometric conditions.



Excitation thresholds **- Simulations were performed with smaller MUs with lower or higher excitation thresholds or with random distribution of excitation thresholds**

MU distribution **- Simulations were performed with smaller MUs located deep or superficial or with random distribution of MUs within the muscle**

Anatomy **– Different thicknesses of the fat tissue were simulated (2-8 mm)**

Fig. 2 Examples of simulated distributions of MUs within the muscle and excitation thresholds.

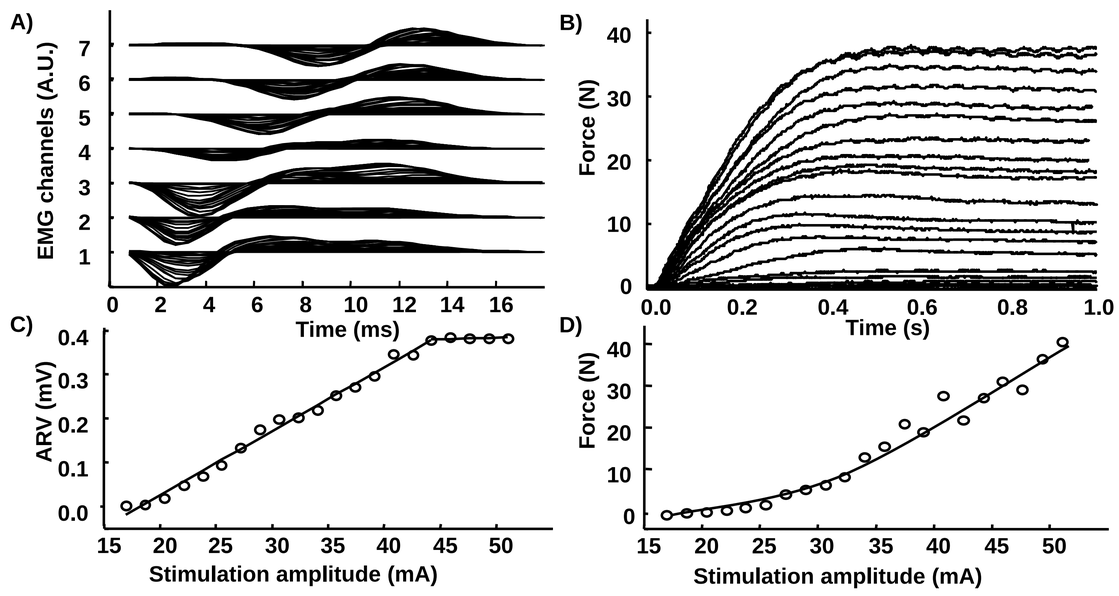


Fig. 3. M-wave, ARV and force versus stimulation amplitude of tibialis anterior muscle, during transcutaneous stimulation at different stimulation levels in a representative subject.

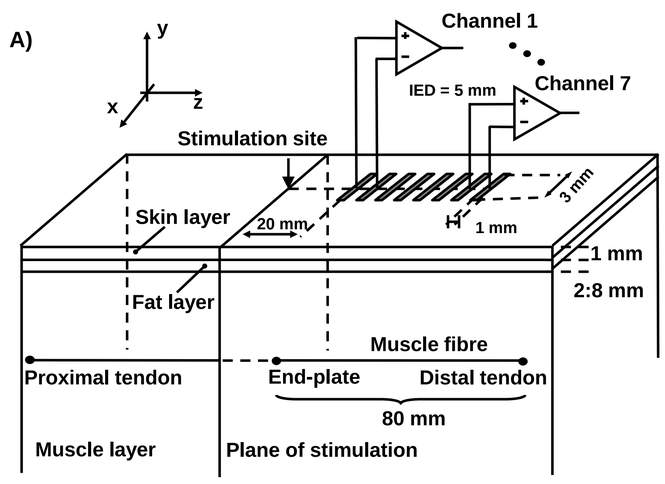
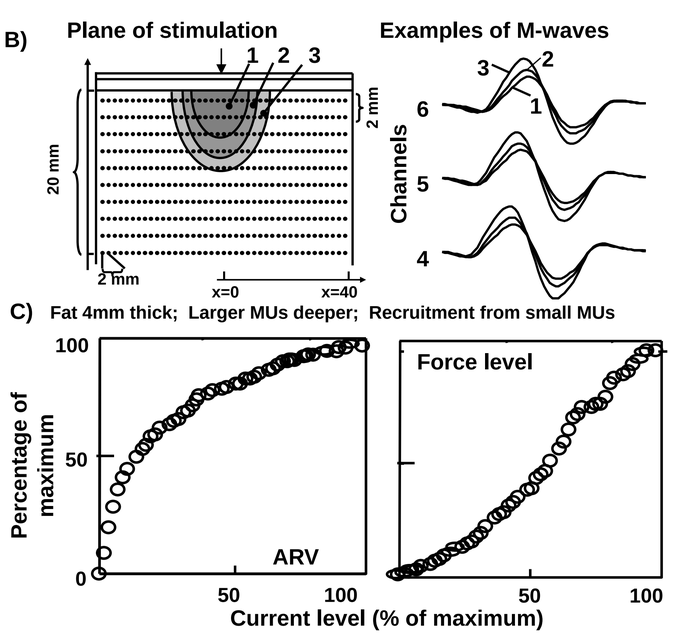


Fig. 4 A) Planar model. B) Plane of stimulation and examples of M-waves. C) Average rectified value (ARV) and force level for a representative example of simulation.



3. RESULTS

In order to compare different subjects and simulations, a normalisation procedure was applied

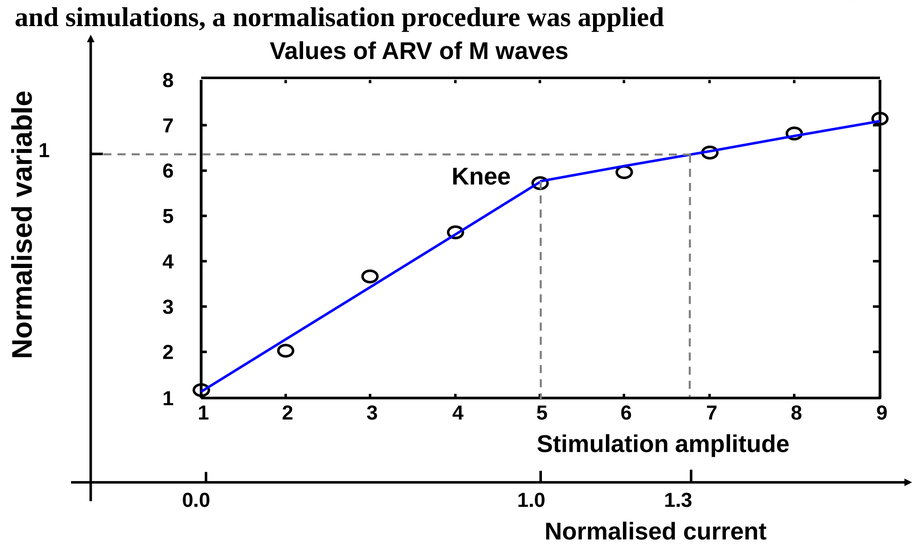


Fig. 5. Normalisation procedure illustrated on synthetic data. The circles represents values of ARV of M-waves at different stimulation amplitudes. The curve of ARV shows a knee. Current levels up to the intensity corresponding to 130% of the knee were considered. The axis of the stimulation current was scaled imposing zero value to the initial step of stimulation and unitary value to the current at which the knee appears. The value of the parameter (ARV, MNF, CV, Force) corresponding to 1.3 in the axis of normalised stimulation current was scaled to the value 1.

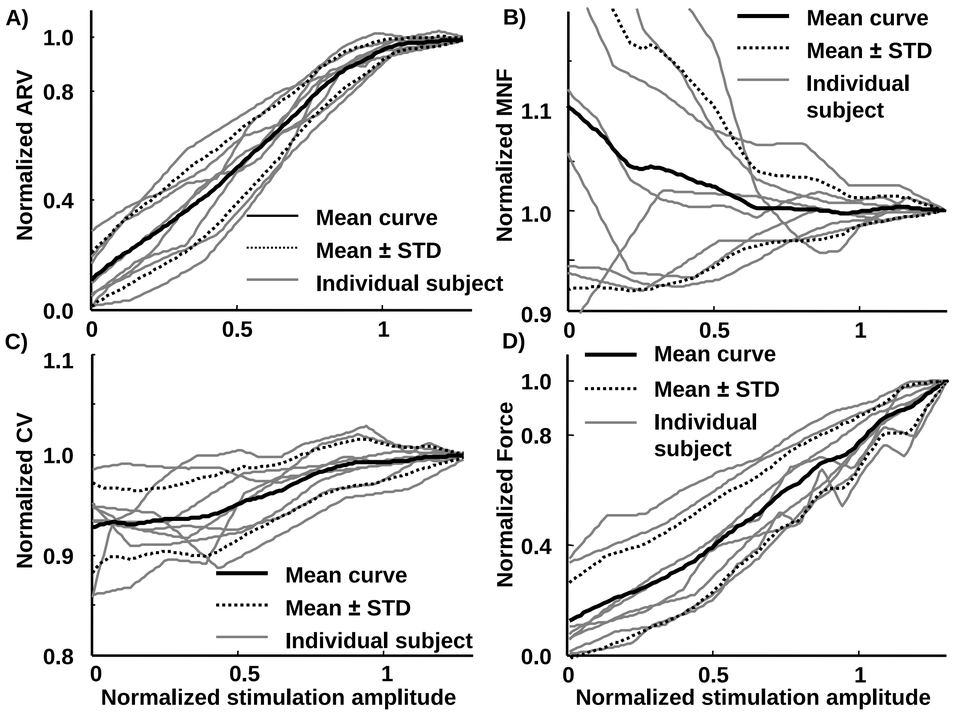


Fig. 6. A) ARV, B) MNF, C) CV and D) force obtained from the experimental protocol (normalisation described in Fig. 5).

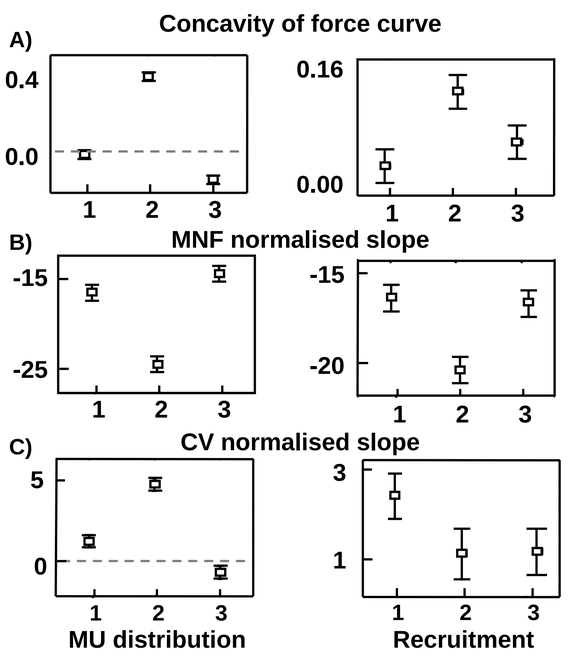


Fig. 7. Averaged parameters (mean ± standard error) extracted from simulated data. Parameters were statistically dependent on MU distribution and recruitment order and not statistically dependent on fat layer thickness.

4. CONCLUSIONS

Two variables provide important indications on MU recruitment during TES and MU distribution within the muscle: CV variation of M-waves and concavity of force curve for increasing stimulation intensity. Experimental data showed an increase of CV with increasing stimulation intensity and a positive concavity (mean across eight subjects) of the force/stimulation intensity curve. The effects of different recruitment orders (random excitation threshold, higher threshold for larger MUs or for smaller MUs) and different MU distributions in the muscle (random distribution, larger or smaller MU deeper) were tested in simulations. CV variations and concavity of force/stimulation intensity were in line with experiments only if larger MUs were distributed deep within the muscle (in line with a histochemical study [3]), regardless the distribution of MU recruitment thresholds (Figure 7). Thus, the geometrical distribution of the MUs is crucial in determining the order of recruitment of MUs during TES (it is more important than MU recruitment threshold). This provides an interpretation of the controversial results reported in the literature on MU recruitment during stimulation.

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