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Insights gained into the interpretation of surface electromyograms from the gastrocnemius muscles: A simulation study

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ABSTRACT

Interpretation of surface electromyograms (EMG) is usually based on the assumption that the surface representation of action potentials does not change during their propagation. This assumption does not hold for muscles whose fibers are oblique to the skin. Consequently, the interpretation of surface EMGs recorded from pinnate muscles unlikely prompts from current knowledge. Here we present a complete analytical model that supports the interpretation of experimental EMGs detected from muscles with oblique architecture. EMGs were recorded from the medial gastrocnemius muscle during voluntary and electrically elicited contractions. Preliminary indications obtained from simulated and experimental signals concern the spatial localization of surface potentials and the myoelectric fatigue. Specifically, the spatial distribution of surface EMGs was localized about the fibers superficial extremity. Strikingly, this localization increased with the pinnation angle, both for the simulated EMGs and the recorded M-waves. Moreover, the average rectified value (ARV) and the mean frequency (MNF) of interference EMGs increased and decreased with simulated fatigue, respectively. The degree of variation in ARV and MNF did not depend on the pinnation angle simulated. Similar variations were observed for the experimental EMGs, although being less evident for a higher fiber inclination. These results are discussed on a physiological context, highlighting the relevance of the model proposed here for the interpretation of gastrocnemius EMGs and for conceiving future experiments on muscles with pinnate geometry.

1. Introduction

The modeling of surface electromyograms (EMGs) has been sought for the interpretation of experimental data (Dimitrova and Dimitrov, 2003; Merletti et al., 1999b; Roeleveld et al., 1997), for the development of algorithms aimed at information extraction (Duchene and Hogrel, 2000; Mesin et al., 2009), and for didactic purposes (Merletti et al., 1999a). Available models for the generation of surface EMGs rely both on numerical (Lowery et al., 2004; Mesin et al., 2006) and analytical (Blok et al., 2002; Farina et al., 2004b; Gootzen et al., 1991; Mesin, 2006) approaches.

The assumption that the volume conductor is invariant in the direction of propagation of intracellular action potentials allowed for the development of fast analytical models for the simulation of surface EMGs (Farina and Merletti, 2001; Farina et al., 2004a). If a volume conductor is space invariant, the surface representation of motor unit action potentials does not change with propagation. Such a space invariance is frequently assumed when simulating, processing and interpreting experimental EMGs (Lindstrom and Magnusson, 1977; Reucher et al., 1987). Therefore, much of the insights gained into the interpretations of surface EMGs from the use of mathematical models are valid, exclusively, for muscles whose geometry fits in the assumption of space invariance.

Some of the muscles investigated by surface EMG cannot be approximated assuming the muscle fibers to be parallel to the skin. The fibers of the gastrocnemius muscle, for example, are inclined with respect to the skin surface and extend from the deep to the superficial aponeurosis (Kawakami et al., 1998; Narici et al., 1996). Surface electrodes positioned on the calf are, thus, located above the superficial aponeurosis, where muscle fibers attach. Considering that action potentials propagate along the muscle fibers, their propagation along the oblique gastrocnemius fibers contributes to the surface EMGs with a component toward muscle extremities and another toward the skin/tibia. Therefore, the area on the skin surface upon which the action potential of a single muscle fiber distributes likely depends on how inclined the muscle fibers are (i.e. its pinnation angle) (Vieira et al., 2011). Currently existing models do not provide indications of how the surface EMG relates to the pinnation angle. Which physiologically relevant information might be extracted from surface EMGs in the pinnate gastrocnemius muscle is unknown.

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In this study we simulate a pinnate muscle, with fibers inclined in depth direction, to interpret surface EMGs detected from the gastrocnemius muscles. A complete mathematical model, which includes muscle fibers with finite length and three layers of tissues, is presented here for the generation of single fiber action potentials (SFAPs). In particular, we simulate the distribution of motor unit action potentials (MUAPs) on the skin and the interference EMG for different degrees of fibers inclination. Implications for the interpretation of how action potentials distribute on the skin and for the estimation of muscle fatigue are addressed as well. Ultrasound images and experimental EMGs are recorded from the human medial gastrocnemius (MG) muscle to investigate how much theoretical and empirical data correspond.

2. Methods

2.1. Mathematical model

The simulation model was developed by extending our previous work (Mesin and Farina, 2004), which considered the impulse response of a two-layers volume conductor. Three layers were considered here (skin, fat and muscle; Fig. 1). Moreover a complete model (including finite-length fibers) was implemented to generate each SFAP.

Libraries of MUAPs were generated from the simulated SFAPs. These libraries were used with a model of spatial and temporal recruitment of motor units (MUs) to simulate interference EMGs during fatiguing contractions.

Full details on the model and the simulated EMGs are described in the Appendix.

2.2. Experimental signals

Single-differential EMGs were recorded from the medial gastrocnemius (MG) muscle to test for the correctness of the information gained from simulated signals. In particular, we investigated how the amplitude of surface potentials varies with the pinnation angle. This variation likely provides information of how localized the gastrocnemius activity might be. Furthermore, we were interested in understanding whether experimental and simulated EMGs in pinnate muscles are comparable during fatiguing contractions.

Three male subjects (age: 33, 29, 27 years; body mass: 78, 80, 75 kg; height: 182, 178, 180 cm) participated in two protocols designed to compare experimental and simulated signals.

Protocol 1: Sixteen surface electrodes (10 mm interelectrode distance—IED) were used to record EMGs during electrical stimulation. Two ankle angles were considered; foot in neutral position ($\sim 20^{\circ}$ pinnation angle) and plantar flexed ($\sim 35^{\circ}$ pinnation angle). With an adhesive pre-gelled electrode (cathode; Fig. 6a) placed carefully on the leg, bipolar current pulses were delivered at 2 pps and for 20 s to the tibial posterior nerve. The anode electrode (80 mm × 50 mm; soaked cloth) was positioned immediately above the patella with elastic Velcro straps. Stimulation amplitude was as minimal as possible to allow for the detection of the firstly observable M-wave. Low stimulation amplitude was chosen to recruit the least number of MUs and, thus, to better isolate the effect of ankle angle on the surface distribution of M-waves amplitude. Averaged M-waves were obtained after triggering the 15 single-differential EMGs.

Protocol 2: EMGs were recorded with an array of eight electrodes (5 mm IED) when the subjects exerted isometric plantar flexion at 60% MVC. The contraction lasted for 30 s to ensure the occurrence of myoelectric manifestation of fatigue. Fatigue plots were created from the average rectified value (ARV) and the mean frequency (MNF), calculated on 500 ms epochs (i.e. both descriptors are plotted with respect to their initial values). ARV and MNF indices were calculated as indicated in Merletti et al. (1990). This protocol was applied once with the foot dorsal flexed (pinnation angle $\sim 10^{\circ}$) and once in neutral position (pinnation angle $\sim 20^{\circ}$), with 5 min interval between trials. Plantar flexion torque was measured and displayed to the subjects. Subjects were in prone position and their feet were firmly secured to a footplate, with the lateral malleolus being coaxial to the center of rotation of the torque meter. MVC values were determined for each pinnation angle as the maximum torque measured across three attempts separated by 5 min.

EMGs were amplified by 1–5 k (EMG-USB amplifier, LISiN and OTBioelettronica, Turin), and sampled at 2048 Hz with a 12bit A/D converter (± 2.5 V dynamic range). Ultrasound images were taken with a linear probe (3.86 cm long; Fukuda Denshi, UF 4000, 7.5 MHz) and pinnation angles were estimated with one degree precision. A custom-made neuromuscular stimulator (LISiN, Turin), equipped with a hybrid output stage, was used in the first protocol. In the second protocol, load cells output was amplified (150 Nm full-scale amplifier; MISOII, OTBioelettronica, Turin) and then converted to ankle torque values. After cleaning the skin with abrasive paste and water, ultrasound scanning was used to assist in positioning the electrodes. Specifically, electrodes were positioned above the superficial

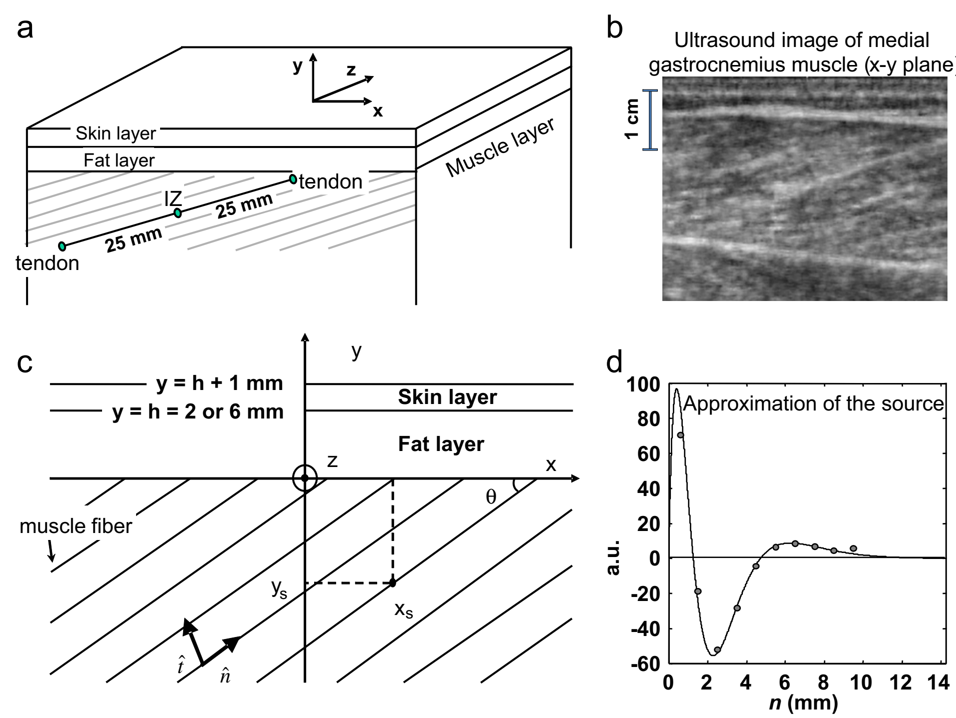

Fig. 1. (a) Schematic representation of the volume conductor model, including the definition of the coordinate system and the geometry of the simulated muscle fibers. The muscle layer is considered as homogeneous and anisotropic, with fibers inclined with respect to the skin surface. Fat and skin layers are homogeneous and isotropic. (b) Ultrasound image of the gastrocnemius, showing the pinnation of muscle fibers. (c) Longitudinal section of the simulated volume conductor, indicating the notation used for determining the analytical solution. (d) Sampling of the phenomenological model of the transmembrane current proposed in Rosenfalck (1969), using 10 impulse sources.