Comparison of Current and Voltage Control Techniques for Neuromuscular Electrical Stimulation in the Anterior Thigh

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Abstract: A comparison between current control (CC) and voltage control (VC) techniques for functional electrical stimulation (FES) with different electrodes was done. A dependency on current of the ohmic resistance of the skin-electrode interface was found. A controllability study shows that the CC offers more controllability since both amplitude and pulse width (PW) of stimulation are suitable parameters for control, unlike VC, where only the amplitude is able to control the output for PWs bigger than 200 μ s. An efficiency study shows that large PWs are electrically inefficient since not all the applied energy is use for neuromuscular or muscular excitation and up to 50% of the energy is absorbed by the tissue. Based on these, basic suggestions for parameter selection are given to minimize the risk of tissue damage and improve electric efficiency at least for our specific set-up.

Keywords: Current-control, voltage-control, skin-electrode interface impedance, efficiency

Introduction

Neuromuscular electrical stimulation is well established for rehabilitation and diagnostics. The stimulator design is in most cases based on voltage controlled (VC) or current controlled (CC) output stages. VC devices are considered to be safer than CC for transcutaneous applications, because loss electrode contact surface does not lead to dangerous high current density. On the other hand, motor unit recruitment under CC stimulation is more reliable, most likely due to the fact that the delivered current is more or less independent from electrode impedance.

However, many studies demonstrate that the skin-electrode interface impedance plays an important role in the stimulation dynamics, and several models have been proposed as equivalent circuits [1], [2]. It is aimed that this impedance variations indirectly affect both kinds of stimulation in effectiveness and controllability.

An important aim of this work was to identify the differences in the control dynamics of both stimulation control techniques and the effects of electrode selection.

Methods

Multivariable measurements were done in order to investigate the dynamics of the stimulation. CC and VC stimulation were applied to 6 subjects using two different surface electrode types of 8x13cm (self-adhesive STIMEX, Schwa-Medico GmbH and custom-made conductive rubber electrode). For the CC stimulation a Stimulette DEN2X (Schuhfried Medizintechnik GmbH, Austria) and

for VC stimulation a custom-made device were used. The neuromuscular stimulation was applied transcutaneously on the anterior thigh. The output force was measured with a custom-build dynamometer chair detecting isometric force in three dimensions. Each stimulus was monitored in both voltage and current. Finally, evoked myoelectric signals (M-wave) were recorded from rectus femoris and hamstrings. The EMG electrodes were placed in a transversal disposition instead longitudinally to reduce excessive stimulus artefacts and amplifier overdrive in the EMG recordings.

The whole protocol was divided in four stages: (1) CC with self-adhesive hydrogel electrodes (ETD), (2) VC with ETD, (3) CC with conductive rubber electrodes (ETR) and, (4) VC with ETR.

Stimulation sweeps with pulse widths (PW) modulation from 2x50 μ s to 2x1000 μ s were done. The stimulations amplitudes were varied from the sensory threshold until ± 120 mA (in steps of 5mA) and ± 60 V (in steps of 5V) for CC and VC respectively. All stimulation impulses were rectangular charge-balanced biphasic pulses.

In order to compare both stimulation techniques the electrical energy applied and the current injection during the whole pulse were considered as parameters. The detected forces were transformed to a 3D vector and only the magnitude was considered for analysis. The selected equivalent electric circuit for the skin-electrode interface is shown in Fig. 1. The impedance was estimated fitting the curves to the equations that govern this circuit. For the estimation, R_s , R_p and C were considered constant within each pulse, but not between pulses.

Figure 1: Equivalent model proposed for the skin-electrode interface.

Results

The impedance approximation was only valid for CC stimulation, since VC didn't follow the exponential behaviour of the circuit. The impedance results are shown in Fig. 2, only for CC. The recruitment curve is shown in Fig. 3, for both electrodes and techniques. A comparison between charge and energy is shown in Fig. 4, for isotonic curves (10N and 20N).

Discussion

The high dependence (up to 5 times the saturation value) of R_p to the stimulation intensity was congruent with other studies [2–4]. R_s and C variation due the stimulation amplitude were neglectable. Such dependency was addressed to the current amplitude since only CC stimulation was well-described by the proposed circuit, and system response at a given amplitude and different PWs shows no significant difference.

Figure 2: Impedance parameter estimation for CC stimulation with the ETR (upper part) and ETD (lower part) electrodes

Figure 3: Recruitment curves for a) CC with ETR, b) VC with ETR, c) CC with ETD, and d) VC with ETD

Important differences on CC and VC techniques were found by means of its controllability. Both techniques were able to reach similar output force ranges. However, CC showed better characteristics since both stimulation amplitude and PW are suitable control parameters, unlike VC, where only the amplitude affect the output force significantly on PWs bigger than 200μs. This is visible in Fig. 3 for an induced contraction force of 50N, where it is evident that CC provides more freedom in control by either PW or amplitude variation than VC, where PW related traces bigger than 200μs for ETR and 100μs for ETD overlap, and only the variation of the amplitude can lead to the desired output force.

The electric efficiency in both techniques had the same behaviour as seen in Fig. 4. Beyond differences in the magnitude between techniques, it can be observed that, in general, huge PWs require more energy and inject more charge during the stimulus than smaller PWs. This means

that energy was absorbed by mechanisms different to neuromuscular stimulation. This absorption leads to a difference of up to 50% for CC and 35% for VC on energy required for obtain the same output force. On the other hand, smaller PWs showed a tendency to require more electric energy to be delivered. For our set-up PW of 200μs showed a better performance by means of charge and electric energy delivered, it means a reduction of risk of tissue damage and an improvement in the power efficiency of the device.

Figure 4: Comparison between necessary charge and energy to generate the stimulation impulse able to induce contraction force of 10N (continuous line) and 20N (dashed line) with CC (red) and VC (blue). Triangle indicate a duration impulse of 1000μs, and the square a duration impulse of 200μs. ΔPW arrow indicates direction of PW increasing

Regardless the current dependency of the impedance, it was observed different variation ranges of it for the two different electrodes. These differences due the material and construction of the electrodes were also reflected in the recruitment curve, showing that both CC and VC are dependent on electrode configuration.

Although these results are also valid for our set-up and further research is necessary to generalize these results, the methodology may be useful to optimizing stimulation parameters in various application scenarios.

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