Quantitative Measure of Fatigue in Isometrically Activated Paralysed Muscles

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Abstract

The aim of this study was to test a proposed fatigue which provides a quantitative assessment of muscle fatigue in isometrically activated paralysed muscle. The extensor digitorum communis (EDC), extensor pollicis longus (EPL) and flexor pollicis longus (FPL) muscles of two C5/C6 tetraplegic men were studied. Stimulation ramps (0-200 μs pulse width) were applied before and during 20 minutes of maximal stimulation (200 μs). Muscle force correlated to the M-wave parameter, second phase area (SPA), with a mean correlation coefficient of 0.90 +/- 0.022 (n=40) for the pooled stimulation ramp tests from both subjects. During the 20 minute maximal stimulation tests, an initial steep decline in muscle force was present in all the muscles studied. Subsequent to this force decline, the M-wave quantitative descriptor, SPA, demonstrated little relative change whilst muscle force further declined in this remaining interval. The proposed fatigue index, correlating muscle force with the detected M-wave, successfully differentiated between a reduction in force caused by either fatigue or an alteration in the applied level of stimulation.

Keywords: Fatigue, M-wave, Isometric, Stimulation, Paralysed

1. Introduction

Functional electrical stimulation is a technique whereby paralysed muscles are electrically stimulated, in a coordinated manner, to provide functional movement. Functional applications of FES for persons with spinal cord injuries include hand grasp, standing, bowel and bladder control. Sensory information pertaining to the detection of muscle fatigue is often impaired due to the spinal cord injury of the FES system user. Therefore, the user of a FES hand grasp system, relies primarily on visual feedback to assess the fatigue state of the stimulated grasp. The safety and robustness of future FES systems will rely upon their ability to detect the onset of muscle fatigue. Such a system would warn the user that the activated muscles are approaching a fatigued state and are no longer functional. Previous stimulated muscle fatigue detection schemes relied upon the presumption that stimulus intensity will remain unchanged during use. This is not the case in most practical applications of FES systems. Furthermore, past studies experimental times, ie duration of electrical stimulation, are not comparable to those required for completing functional tasks such as using a fork to eat.

An accurate assessment of electrically activated muscle fatigue cannot be made by measuring force output alone. The muscle force output may modulate not only due to fatigue, but also with a change in the level of recruited motor units. Such a variation in motor unit recruitment is caused by the user of a FES system altering the level of applied stimulation. The M-wave resultant from each stimulus pulse provides a means of detecting such a change. The amplitude of the motor unit action potentials (MUAPs) contributing to the M-wave, reflects the size and number of the currently active motor units [1]. A descriptor of the M-wave can be utilised to provide a quantitative estimation of the current level of motor unit recruitment. The aim of this study is to establish a fatigue index which provides a quantitative assessment of fatigue in isometrically activated muscles where the level of applied stimulation is subject to change. The proposed fatigue index correlates the individual muscle force output with a suitable quantitative descriptor of the M-wave. The fatigue measure is thus capable of compensating for non-fatigue related changes in muscle force that result from an alteration in the level of applied stimulation.

2. Method

Electrical stimulation was applied to the paralysed muscles of two men with spinal cord injuries at the C5/C6 level. A fully implantable stimulator (Freehand, NeuroControl Corp.) activated peripheral nerves using epimysial electrodes. The applied stimulus was pulse width modulated from 0 to 200 µs with a constant current of 20 mA and constant frequency of 12 Hz. In subject 1, extensor digitorum communis (EDC) and flexor pollicis longus (FPL) were studied. In subject 2, extensor pollicis longus (EPL) and EDC were studied. The M-wave was detected using a bipolar surface

Ag/AgCl electrodes (Red Dot, 3M) with the active electrodes having dimensions of 10 mm width and 20 mm length. The active electrodes were placed perpendicularly to the muscle fibers, ten millimeters apart as described in other work [1] and a reference electrode, 20 mm by 20 mm, was placed superior to the olecranon bone, just above the elbow joint. The skin was cleaned using 70 % isopropyl alcohol prior to electrode application. Initially, the muscle was maximally stimulated and the active electrodes were positioned according to the location of the particular muscle's motor point [2] and subsequently adjusted until a maximal M-wave was evoked. Signals from the surface electrodes were passed through amplification circuitry, using instrumentation amplifiers (AD620, Analog Devices), with an adjustable gain of 500 to 2000. The signal was subsequently actively filtered with a bandpass of 20 to 500 Hz. The amplifier stage incorporated stimulus artifact removal circuitry, similar to that utilised in other work [5].

A load cell (TEDEA model 1015, 5 gram resolution) was used to measure isometric muscle force at the fingers or thumb, receiving the distal insertion of the muscle's tendon. An adjustable forearm splint was used in all the fatigue tests to stabilise and secure the forearm and wrist during the experiments (Fig. 1). During tests involving FPL and EPL, the wrist, fingers and the head of the first metacarpal bone of the thumb, were secured in a custom moulded thermoplastic wrist / hand splint. The thumb was in full extension during all FPL experiments, via the use of a Zimmer splint across the interphalangeal (IP) joint. During EPL experiments the thumb IP joint was positioned in a fully flexed position. For EDC experiments, the arm was fully pronated and the wrist was splinted parallel to the forearm. The fingers of the hand were splinted across the interphalangeal joints and were flexed at an angle of 45 degrees at the head of the metacarpal bones of the fingers.

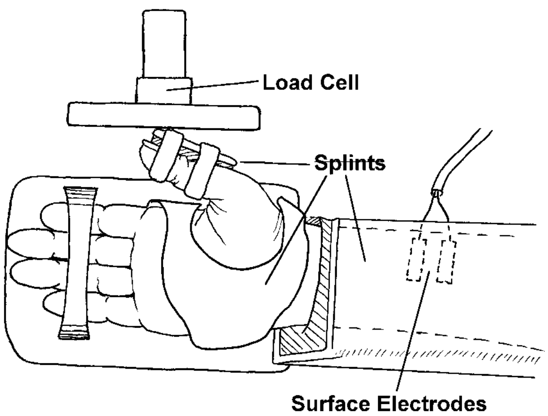

Fig. 1: Illustration of the experimental setup.

At the beginning of each experimental session, maximal stimulation was applied and the subsequent force output of the muscle was measured. This provided a control value of the muscle's maximal non-fatigued force output. In subsequent tests, the fatigue state of the muscle was estimated by comparison to the control value. Initially, the M-wave and muscle force output were measured during linear stimulation ramps, 0 to 200 µs applied over ten seconds, on non-fatigued muscle. These ramps were applied five times at intervals of 120s, a time at which the muscle recovered to values comparable to control force values. Subsequent to the stimulation ramps, maximal stimulation was applied briefly. The output force was again compared with that of the initial control force. When the force recovered to a value comparable to that of the control value, the muscle was stimulated maximally (200 µs) for a period of twenty minutes. In this period the measurement of muscle force and the M-wave was undertaken concurrently. On one separate occasion for FPL and EDC of Subject 1, the 20 minute stimulation was interrupted with stimulus ramps (0 to 200 µs over ten seconds) at each 120 s interval.

The M-wave from the amplifier circuitry and the load cell were sampled at 2500 Hz. An acquisition board (National Instruments PCI-MIO50XE) was used to perform the data sampling, controlled by LabView software (National Instruments) running on a personal computer (Macintosh 9500/200). Muscle force data was processed by taking the average of each of the one second rectangular windows taken from the data. M-waves were processed in one second rectangular windows synchronised to the stimulation pulses. The twelve enclosed M-waves in each one second window were extracted by their respective stimulus pulses to yield one average M-wave. Various quantitative descriptors were calculated from each windows resultant average M-wave. First phase area (FPA) and second phase area (SPA) and Peak to Peak (PTP) voltage are shown in Fig. 3A. Tcross and T_{P-P} are shown in Fig. 3B.

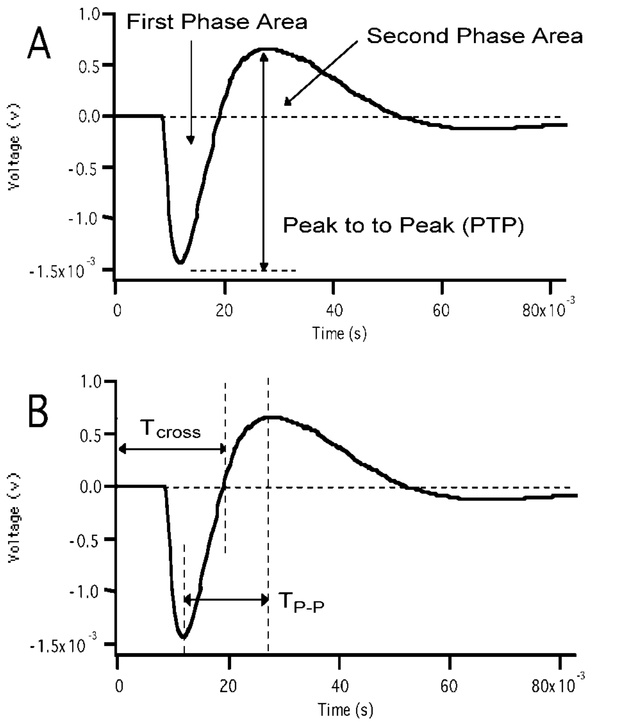

Fig. 2: Quantitative descriptors of M-wave. A) First Phase Area , Second Phase Area, Net Area = First + Second Phase Area. B) Tcross and $T_{P\text{-}P}$.

In addition, the root mean square (RMS) and average rectified value (ARV) were also calculated. The single spectral parameter, MNF (Mean Frequency), was calculated by zero filling the averaged M-wave and applying a fast fourier transform (FFT). Tenth order polynomials approximations (IGOR Pro Ver 3.0, Wavemetrics Inc.) were performed on the averaged force data recorded during 20 minutes of maximal stimulation. The polynomial approximations permitted the extraction of the first order differential's inflection points. These points could possibly be used to indicate a shift towards a higher proportion of recruited motor units that are slow twitch in nature. Sampled force and M-wave descriptors were processed using a non-regressive index developed by Merletti et al [4]. The resultant data was divided into two intervals delineated by each experiments respective first inflection point. Rates of change were calculated using linear regression for the interval up to and after the first inflection point for force and M-wave data. All values expressed as mean ± SEM.

3. Results

Second phase area and RMS both correlated to force for the pooled data (n=40) from both subjects, with mean correlation coefficients of greater than 0.88. The SPA correlated more closely to the muscle force when compared to that of stimulus pulse width, for the stimulation ramps performed during muscle fatigue. A non-linear relationship between muscle force and stimulus intensity was evident for both FPL and EDC of Subject 1. The net percentage changes for the 20 minute constant maximal stimulation experiments were calculated for muscle force and M-wave descriptors. For the pooled data for both subjects the mean percentage decrease of muscle force was 90.5 % (n=14), whilst the mean percentage decrease of either second phase area or RMS was under 28 % (n=14).

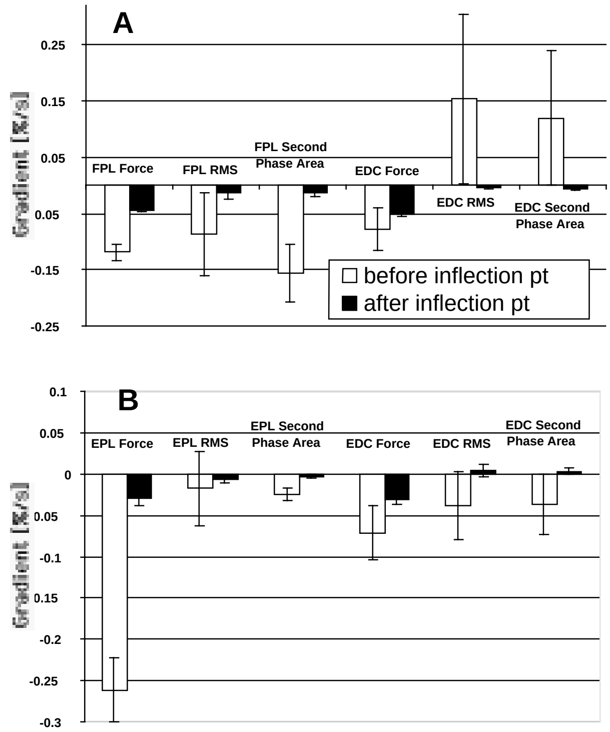

Fig. 3. Gradients of linear regression of the two data intervals processed by the Merletti index for A) FPL and EDC of Subject 1 and B) EPL and EDC of Subject 2.

The resultant fatigue index is plotted in Fig. 4 for FPL of Subject 1 from a 20 minute maximal stimulation experiment periodically interrupted by stimulation ramps. The proposed fatigue index successfully compensated for the non-fatigue related fluctuations in force caused by an alteration in stimulation intensity.

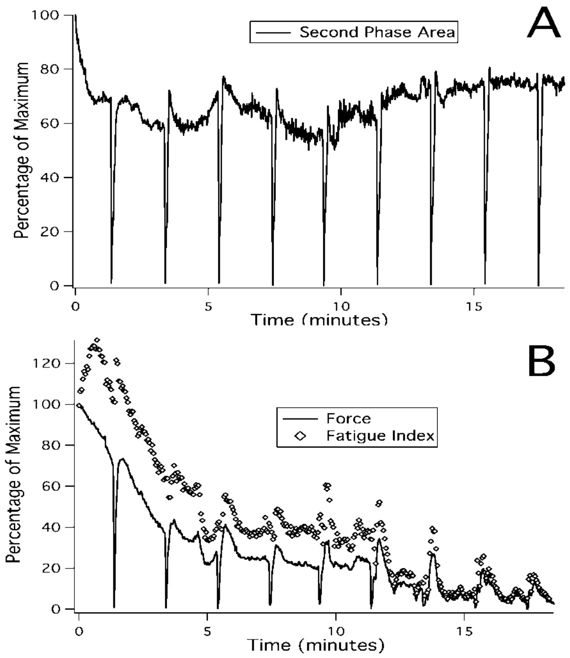

Fig. 4: Plots of A) the M-wave parameter Second Phase Area and B) muscle force output and Fatigue Index, versus time recorded during 20 minutes of maximal stimulation which was periodically interrupted with recruitment ramps on FPL of Subject 1.

4. Discussion

The robustness and safety of future FES systems will be improved through the addition of an on-line assessment of muscle fatigue. The peripheral nervous system is often unable to supply such information to a user of a FES system due to the spinal cord injury. This paper has investigated a proposed fatigue index that provides a quantitative measure of fatigue, which is intolerant to fluctuations in the applied level of stimulation. An alteration in applied stimulus may consequently lead to a variation in the number of recruited fibers and consequently cause a non-fatigue related change in force output. To detect such a change, the proposed fatigue index correlates the muscle force output with a quantitative descriptor of the M-wave. A suitably chosen descriptor of the M-wave permits detection of a modulation in the number of actively recruited motor units, thus enabling detection of non-fatigue changes in force.

The study found that SPA of the M-wave closely correlated to muscle force when the muscle was in either a fatigued or non-fatigued state. The current level of motor unit recruitment can be estimated by monitoring the value of SAP. The extraction of the first inflection point from the polynomial approximations of the force data enabled the creation of two data intervals for force and M-wave data. The first inflection point, could provide a simple mathematical approximation to when fast twitch motor units begin to fatigue [6]. The fast twitch type motor units, fast glycolytic (FG) and fast oxidative glycolytic (FOG) motor units, produce the majority of the initial force output decrease and M-wave amplitude change during an electrically induced contraction [3]. The study found that SPA for all the muscles studied, exhibited significantly less change relative to force output in the second interval when it was probable that the some of the fast twitch units had fatigued. SPA's ability to both estimate the level of motor unit recruitment and stability in the second interval made it a suitable estimator of motor unit recruitment for the proposed fatigue index. The fatigue index successfully compensated for non-fatigue related fluctuations in muscle force when the applied stimulation was modulated.

5. Conclusion

The study found that SPA of the evoked M-wave correlated closely to muscle force output during stimulation pulse width ramps applied to both non-fatigued and fatiguing muscle. Such a quantitative descriptor of the M-wave can provide an estimation of the current level of motor unit recruitment and thus enable the detection of an alteration in applied stimulation. The proposed fatigued index successfully compensated for non-fatigue related changes in muscle force caused by alterations to the applied stimulation level. The fatigue index is an effective method of assessing muscle fatigue in conditions where the user of an FES systems is liable to modulate the stimulus intensity during functional use of the device.

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