Relationship of M-wave Time Scale Variation With Motor Unit Recruitment Evaluated Using the Matched Wavelet Transform

John M Heasman, Timothy RD Scott, Ruth Y Flynn, Veronica A Vare and Claudia R Gschwind.

Quadriplegic Hand Research Unit, Spinal Cord Injuries Unit
Royal North Shore Hospital, St Leonards, NSW 2065, Australia
E-mail: jmh@ee.usyd.edu.au

Abstract

The matched wavelet transform (MWT) was used to quantify time scale variation in M-waves evoked during motor unit (MU) recruitment. Surface M-wave activity was detected from four non-fatigued paralysed hand muscles of persons with spinal cord injuries in the C5 to C6 region. Electrical stimulation was applied using implanted epimysial electrodes. Results indicated significant time scaling of the M-wave occurred during progressive MU recruitment in all the muscles studied.

Keywords: M-wave, Wavelet Transform, Recruitment, Isometric, Electrical Stimulation, Paralysed Muscle.

1. Introduction

Electrical stimulation can be applied with the aim of restoring movement to paralysed muscles of spinal cord injured persons (see [1] for a review). Electrical stimulation artificially excites the motorneurons of paralysed muscles. Each of these motorneurons innervates a group of muscle fibres distributed throughout the muscle. The motorneuron and the muscle fibres it innervates is collectively known as a motor unit (MU) [13]. When stimulation is applied proximally to a motorneuron, axons with lowest impedance (large diameter) are excited at lower stimulation intensities [2]. Since MUs with large fibers are innervated by larger axons [11], the order by which MUs are recruited is from large to small. This order is reverse to that which occurs during graded volitional recruitment which recruits MUs in the order from small to large [13]. When the electric field is applied at a distance to the motorneuron axons via transcutaneous stimulation, the order by which MUs are recruited in human skeletal muscle has been shown to vary [3]. In the case of implanted epimysial electrodes further information is required regarding the order by which they recruit MUs.

A non-invasive method of investigating MU recruitment in non-fatigued muscle is via the analysis of the surface M-wave [3,13]. The time scale properties of an M-wave detected from a non-fatigued muscle are dependant on the on the average conduction velocity of the activated muscle [13]. The average CV is subject to change with the recruitment of different sized MUs. This is because the CV of a MU increases with its respective size [12]. Therefore a time scale compression of an M-wave is likely to be the result of progressive recruitment of larger MUs with faster CVs.

To quantify time scale variation in M-waves, a time-frequency representation is required. The matched wavelet transform (MWT) produces one such representation and has been used previously to quantify such variations in M-waves detected during muscle fatigue [4]. It was proposed in this study that the MWT could be utilised for the purpose of studying MU recruitment rather than fatigue. Analysis of time scale variations could determine the relationship between M-wave time scaling and MU recruitment.

2. Method

Two men with complete lesions in the C5 to C6 spinal cord region participated in this study. In subject 1, flexor pollicis longus (FPL) and extensor digitorum communis (EDC) were studied. In subject 2, extensor pollicis longus (EPL) and extensor digitorum communis (EDC) were studied. Both recieved a fully implantable stimulator (Freehand, NeuroControl Corp.) which activated the paralysed muscles using implanted epimysial electrodes. Modulation of stimulation intensity was achieved using pulse width modulation (0-200 μs) at a constant current of 20 mA. The frequency of stimulation in all trials remained at 12 Hz.

Surface M-wave activity was detected using bipolar disposable Ag/AgCl surface electrodes (Red Dot, 3M). The active electrodes (10 mm width and 20 mm length) were placed perpendicularly to the muscle fibres, 10 mm apart, from edge to edge. A reference electrode, was placed adjacent to the elbow joint. Custom built instrumentation amplified the signal detected by the surface electrodes. The amplification stage incorporated stimulation artifact suppression. The signal was subsequently actively filtered with a bandpass of 20-500 Hz. Isometric muscle force was measured using a load cell (TEDEA model 1015, 5 gram resolution). The M-waves from the amplifier circuitry and the load cell were sampled at 2500 Hz.

At the beginning of an experimental session, maximal stimulation was applied (200 μs) and the subsequent non-

fatigued force output of the muscle was measured. In subsequent trials, the fatigue state of the muscle was monitored via comparison with this measurement. Initial experiments involved detecting M-wave and muscle force during linearly increasing stimulation recruitment trials, modulated from 0-200 μs over ten seconds, on non-fatigued muscle. These recruitment trials were applied, at intervals of 120 seconds, a time at which the force was found to recover from these short stimulation bursts, to values comparable to the original control levels.

M-waves were processed using a sliding window due to the instability of M-waves at lower stimulus intensities. The window took the average of two adjacent M-waves, each synchronised to their stimulation pulses, to produce one average M-wave. The sliding window was progressed forwards at a rate of one M-wave per step. Each average M-wave consisted of an initial negative first phase followed by a positive second phase. Subsequent to averaging, each M-wave was processed using a MWT. The mother wavelet chosen was the 'Mexican Hat' (MH) function, previously found to provide a good match to both phases of an evoked M-wave [4].

The MWT of each M-wave resulted in a two dimensional array of scale (rows) versus time (columns). Each scale is representative of correlating a version of the MH wavelet function scaled by a factor *a*, with localised sections of the M-wave. When *a* becomes large, the scaled versions of the MH wavelet are stretched, as opposed to lower values of *a* where the wavelet is compressed. The largest absolute values in the scale-time array relate where a good 'match' occurs between the scaled version of the mother wavelet shape and the M-wave signal. Since the MH wavelet matches both phases of the M-wave, the MWT produces both a maximum and minimum value in the scale-time array. These points indicate which two particular scaled versions of the MH wavelet best match the first or second phase of the M-wave. Therefore, by analysing the scale factor *a* for each M-wave phase, both the magnitude and type of M-wave time scaling (stretching or compression) can be determined via comparision to subsequent M-waves.

For each M-wave, two scale factor values, a_{Phase1} and a_{Phase2}, were extracted. These corresponded to the minimum and maximum values of the MWT for the two respective phases. As mentioned, values of *a* which increase over time, reflect progressive time scale stretching of the M-wave. Similarly, decreasing values of *a* reflect time scale compression of the M-wave. Each recruitment trial was separated into two halves. The first half corresponded to values of a_{Phase1} and a_{Phase2}, extracted during low level of stimulus intensity (0-100 μs). The second half corresponded to values of a_{Phase1} and a_{Phase2}, extracted during higher levels of stimulus intensity (100-200 μs). In each half, the net change in a_{Phase1} and a_{Phase2} relative to the initial value was calculated. Students t-test was used in all statistical evaluations.

3. Results

The mean first and second phase scale factor variation of M-waves detected from EDC of Subject 1 (trials=9) is illustrated in Fig. 1. In this case values of a_{Phase1} and a_{Phase2} decreased with increasing applied stimulation intensity. Fig. 2 contains bar plots representative of the mean net changes in a_{Phase1} and a_{Phase2}, values calculated from A) the first half of each trial (stimulation intensity 0-100 μs) and B) the second half of each trial (stimulation intensity 100-200 μs).

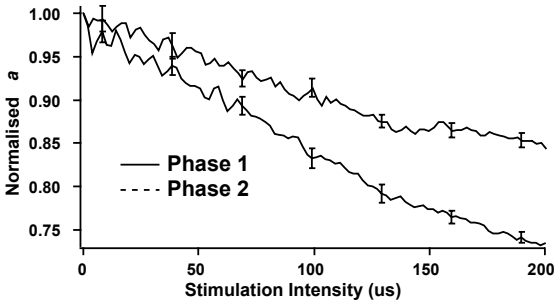
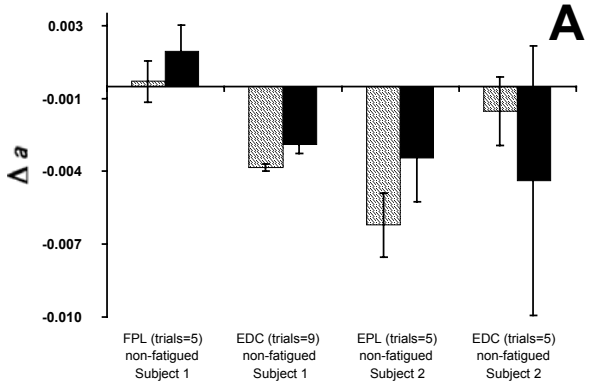


Fig. 1. Line plots of normalised mean values of a_{Phase1} and a_{Phase2}, values from recruitment trials performed on EDC of Subject 1 (trials=9).

For EDC of Subject 1 values of a_{Phase1} and a_{Phase2}, decreased significantly (P<0.001) throughout the entire recruitment trial. In EPL of Subject 2, a_{Phase2} decreased significantly (P<0.017) during the entire recruitment trial.



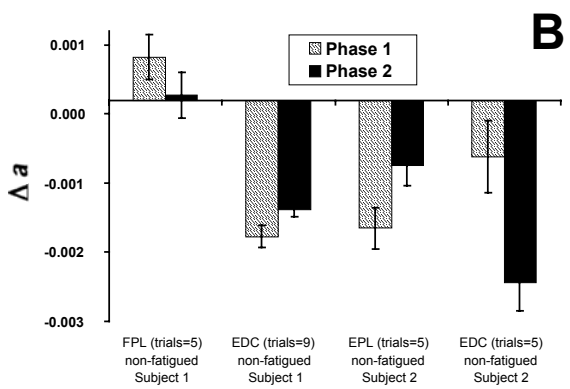


Fig. 2 : Barplots of the mean net changes in a_{Phase1} and a_{Phase2} during A) first half of recruitment trial (0-100 μs stimulation) and B) second half of recruitment trial (100-200 μs stimulation).

Variable responses in the net change of a_{Phase1} and a_{Phase2} values were expressed for FPL of Subject 1 and EDC of Subject 2 throughout the recruitment trials. For FPL of Subject 1, no significant decreases in either a_{Phase1} or a_{Phase2} occurred during the trials. In EDC of Subject 2, a_{Phase2} decreased significantly ($P<0.0037$) only during the second half of the trial. The standard error of the mean (SEM) of a_{Phase1} and a_{Phase2} values was significantly larger ($P<0.038$) during the first half of the recruitment trial (0-100 μs) than during second half of the recruitment trial (100-200 μs).

4. Discussion

The MWT was found previously to be an effective quantifier of amplitude and time scale variation in evoked M-waves during progressive muscle fatigue [4]. Results from this study indicate the MWT is equally effective in quantifying M-wave time scale variation during progressive MU recruitment. Our results demonstrated that significant time scaling of the M-wave occurred during low and high levels of applied stimulation. Interestingly, in some muscles, M-wave time scale variation at low stimulus intensities was unlike that exhibited at higher intensities. Variability of the scale factor, *a*, was reduced when higher stimulation intensities were applied. This drop in variability may be indicative of instability in M-waves detected at lower stimulation intensities.

Time scaling of the M-wave signal detected from a non-fatigued muscle is thought to be caused by a change in recruitment of muscle fibres of varying CV [5]. The CV of a muscle fibre is dependent on: 1) diameter of the fibre [6], 2) the pH of the intracellular fluids [7] and 3) the MU firing rate or stimulation frequency [9]. During this study, stimulation frequency was maintained at 12 Hz and muscle pH variation is likely to occur only during fatigue. A linear relationship exists between CV and fibre diameter [6], which means the CV of each MU will rely primarily on the distribution of muscle fibre diameters it contains. As MUs contain relatively similar muscle fibre diameters [10], it is likely then that all muscle fibres in a given MU will have relatively similar CVs [6]. Furthermore, the larger MUs contain larger diameter muscle fibres [8]. Considering these factors, the M-wave time scale compression observed in EDC and EPL of this study, suggests progressive activation of larger MUs during recruitment. This order of recruitment was also reported to occur in 72% of trials conducted on electrically stimulated tibialis anterior muscles of humans [3]. In this case the electrical stimulus was applied transcutaneously.

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