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Automatic analysis of EMG during clonus

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ABSTRACT

Clonus can disrupt daily activities after spinal cord injury. Here an algorithm was developed to automatically detect contractions during clonus in 24 h electromyographic (EMG) records. Filters were created by non-linearly scaling a Mother (Morlet) wavelet to envelope the EMG using different frequency bands. The envelope for the intermediate band followed the EMG best (74.8–193.9 Hz). Threshold and time constraints were used to reduce the envelope peaks to one per contraction. Energy in the EMG was measured 50 ms either side of each envelope (contraction) peak. Energy values at 5% and 95% maximal defined EMG start and end time, respectively. The algorithm was as good as a person at identifying contractions during clonus ($p = 0.946$, $n = 31$ spasms, 7 subjects with cervical spinal cord injury), and marking start and end times to determine clonus frequency (intra class correlation coefficient, α: 0.949), contraction intensity using root mean square EMG (α: 0.997) and EMG duration (α: 0.852). On average the algorithm was 574 times faster than manual analysis performed independently by two people ($p \leq 0.001$). This algorithm is an important tool for characterization of clonus in long-term EMG records.

1. Introduction

Clonus is one kind of involuntary muscle contraction (spasm) often seen in muscles paralyzed by spinal cord injury (SCI; Beres-Jones et al., 2003; Little et al., 1989; Wallace et al., 2005). It involves repetitive contractions followed by periods of relative muscle silence (Cook, 1967; Dimitrijevic et al., 1980; Rack et al., 1984; Walsh, 1976). Some individuals describe clonus as manageable, whereas others consider it extremely distracting because it interferes with daily activities (Adams and Hicks, 2005; Little et al., 1989; Sheean, 2002). Only a few studies have focused on quantifying clonus in the controlled environment of a laboratory or a clinic by measuring overall clonus duration, contraction frequency or duration (Dimitrijevic et al., 1980; Iansek, 1984; Rack et al., 1984; Rossi et al., 1990; Wallace et al., 2005; Walsh, 1976). Whether these observations provide a representative view of the clonus that occurs throughout the day in muscles paralyzed by SCI is unclear. Furthermore, the magnitude of the EMG has not been evaluated systematically in these previous studies but could provide valuable information about the intensity of the muscle contractions. The prevalence of clonus is also unknown.

We have made long-term (24 h) electromyographic (EMG) recordings from paralyzed leg muscles to quantify the prevalence and characteristics of involuntary muscle contractions after cervical SCI. For the clonus identified in these records, it is possible to measure the magnitude and the duration of the EMG in each contraction, the frequency of the contractions, and the total duration of the clonus. Manual analysis is laborious and time consuming, particularly for 24 h records. Thus, the main aims of this study were to develop an algorithm that automatically: (1) identifies when the bursts of EMG occur during clonus, and (2) marks the start and end of these contractions. The timing of these events can be used to calculate the duration, frequency and intensity of the contractions during the entire spasm. To be effective, this algorithm must be capable of accurately identifying the occurrence of the repeated bursts of EMG during clonus, while at the same ignoring any motor unit activity between these contractions. The start and end of each contraction must be determined irrespective of the size (magnitude or duration) of the contractions or the overall duration of the clonus. While the start and end of EMG are often measured manually in laboratory-based studies, the number of contractions is usually limited. Isometric or constant velocity contractions are often performed. These constraints make manual analysis feasible. In contrast, we are monitoring clonus as it occurs naturally during the day-to-day activities of people with SCI who have no voluntary control of leg muscles. Thus, our algorithm needs to be flexible

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enough to analyze data gathered under a variety of conditions, from different muscles, and individuals.

Only a few algorithms have been developed to identify the onset of EMG. Data have been scanned using single or double windows, a technique that does not suppress intra-burst maxima (Di Fabio, 1987; Marple-Horvat and Gilbey, 1992). Polynomial regression is another approach but this requires calculation of steady state parameters and equations for each EMG pattern (Takada and Yashiro, 1995). EMG onset has also been defined as the time when a specified number of sample points exceed an established baseline (Di Fabio, 1987; Hodges and Bui, 1996). Statistical approaches have used dual thresholds to detect muscle activation (Bonato et al., 1998) or a generalized likelihood ratio to estimate EMG onset (Micera et al., 1998). Recent approaches have included use of wavelet transforms to either identify motor unit action potentials at contraction onset (Merlo et al., 2003) or to detect the sudden changes in EMG that occur at the start and end of a contraction (Vannozzi et al., 2010).

The algorithm developed in this study to automate the analysis of EMG during clonus also used wavelets for event-oriented analysis. Wavelets were scaled non-linearly to create a bank of filters which were used to extract time–frequency information from the EMG (von Tscharner, 2000). To aid identification of the bursts of EMG during clonus, the algorithm was constrained using criteria we developed from our knowledge of clonus. Signal energy rules were then applied to the globally processed EMG signals to extract the duration of each burst of EMG, clonus frequency and intensity. To evaluate the reliability of the algorithm, its outputs were compared to the results produced independently by two experts with years of experience in EMG recognition. The total amount of time taken by each person to manually mark the start and end of each burst of EMG during clonus was also compared to the time taken by the algorithm to perform the same task. An accurate algorithm that can automatically analyze EMG during clonus in long records is important to understand the nature of these involuntary muscle contractions, and the prevalence of clonus.

2. Materials and methods

2.1. Subjects

Seven subjects (5 male, 2 female, median age: 36 yr, range: 27–52 yr) with a chronic (>1 yr) cervical SCI were studied (median time since injury: 14 yr, range: 4–33 yr). These injuries were caused by diving mishaps ($n = 4$), motor vehicle accidents ($n = 2$), or a sports event ($n = 1$). The injuries were at C4 ($n = 1$), C6 ($n = 5$) or C7 ($n = 1$) and were complete (AIS A) according to American Spinal Injury Association criteria (Maynard et al., 1997). The subjects had no voluntary control of any leg muscles, indicated by an inability to generate any voluntary EMG. Subjects took no medication to mitigate muscle spasms. All of the procedures were approved by the Institutional Review Board of the University of Miami. All subjects gave informed, written consent before participating in this study.

2.2. Muscles

Surface EMG signals were recorded simultaneously from 8 leg muscles over 24 h: vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA) and medial gastrocnemius (MG) bilaterally using a bipolar configuration (Klein et al., 2010). Three self adhesive electrodes (Superior Silver Electrodes, Uni-patch, MN) were cut to 2.5 cm × 1.0 cm for each muscle. The distal electrode for TA and MG was placed just proximal to the respective tendon-muscle interface. The distal electrode for vastus lateralis was placed 12 cm proximal to the patella. The other two electrodes for each muscle were placed proximally with an inter-electrode spacing of 4 cm. Electrodes for biceps femoris were aligned with the vastus lateralis electrodes but on the midline of the posterior surface of the leg. The electrodes were secured to the skin with Hypafix tape (Smith & Nephew, Andover, MA) then wrapped with Co-flex bandage (Andover Healthcare, Andover, MA) to ensure that the electrodes stayed in the same position during the entire experiment. The two distal electrodes on each muscle served as the active and reference electrodes. The proximal electrode was the ground. The electrodes from each muscle were connected to the inputs of a preamplifier (Model Z03, Motion Labs Systems, Baton Rouge, LA) via soldered cables. These cables allowed custom electrode spacing, and placement of the preamplifiers on the limb close to the target muscle. Each preamplifier was wrapped in foam to provide comfortable contact with the skin over 24 h and to avoid skin breakdown.

2.3. Protocol

Each experiment consisted of a 24 h EMG recording, and laboratory measurements before and after this recording. In the laboratory, maximal compound muscle action potentials (M-waves) were recorded from VL, TA and MG muscles in response to supramaximal stimulation of the femoral, common peroneal and tibial nerves, respectively. These EMG data were sampled online (3000 Hz) using a SC/Zoom system (Physiology section, Umeå University, Sweden). For each muscle, the area of the maximal M-waves were similar before and after the 24 h recording (Mean ± SE area for MG: 10.2 ± 1.3 μVs versus 10.4 ± 1.6 μVs; TA: 6.9 ± 1.0 μVs versus 6.5 ± 0.9 μVs; VL: 9.0 ± 1.1 μVs versus 9.6 ± 1.1 μVs). These results indicate that the electrodes remained in place during the entire recording and that the changes in EMG activity over 24 h were recorded faithfully from each muscle (Klein et al., 2010). No M-waves were recorded from BF because the sciatic nerve is too deep to stimulate reliably. Subjects were also asked to perform 3 brief (5 s) maximal voluntary contractions (MVCs) with each muscle. The absence of EMG activity during all MVCs confirmed the muscle paralysis.

The 24 h EMG recording was initiated after the laboratory measurements using a portable, battery powered data processing and logging system (Tepavac et al., 2003). The electrodes from each muscle were connected to a preamplifier (Motion Labs Systems, Baton Rouge, LA). The outputs from the four preamplifiers for each leg were connected to a custom-built preprocessing unit which was responsible for filtering (10–500 Hz) and amplifying the input signal to fit the input range (0–4.096 V; gain: ∼400) of a custom-built battery-operated, data logging device with a 12-bit analog to digital converter (Tattletale 8 Logger, Onset Computer Corporation, Bourne, MA). This logger was driven by custom software written using Metrowerks Code Warrior (a C based software development tool; Metrowerks Corporation, Austin, TX). The sampling rate was 1000 Hz per channel. The data were written to a 1 GB compact flash card in compressed format.

The subject was advised to maintain his/her normal routines during the 24 h recording to ensure a representative view of daily activities, which they documented on paper. The data logging system was stored in a hip pack that was carried on the wheelchair or the lap of the subject. The subject returned after 24 h to repeat the laboratory recordings, as described above.

2.4. Global data processing

Standard data processing procedures were implemented on all 24 h EMG recordings to enable data comparisons across muscles and experiments. This global processing occurred before the application of the algorithm. Using software developed in Matlab (The Mathworks Inc., Natick, MA) and DADiSP (DSP Development