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Concentric and eccentric isokinetic muscle activity separated by paired pattern classification of wavelet transformed mechanomyograms

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ABSTRACT

It was hypothesized that concentric and eccentric isokinetic muscle actions should yield detectable differences in the mechanomyograms, which may reflect properties of the contraction and relaxation phases of the muscles. A paired pattern classification technique was adapted to determine whether wavelet transformed mechanomyograms from the three superficial quadriceps muscles were different during maximal concentric and eccentric isokinetic muscle actions. Mechanomyograms for this study were recorded from eleven healthy men (mean ± SD age = 20.1 ± 1.1 yrs) who performed maximal concentric and eccentric isokinetic muscle actions of the dominant leg extensors at a velocity of $30^{\circ}\ s^{-1}$. The results indicated that the paired pattern classification accurately classified the MMG intensity patterns in approximately 94% of the cases as being from a concentric or eccentric movement. Thus, it can be concluded that the differences in the intensity patterns recorded from concentric and eccentric muscle actions were significant. These findings indicated that the combined MMG wavelet analysis and pattern classification techniques could potentially be useful in situations where muscle activity during concentric muscle actions must be distinguished from that during eccentric muscle actions.

1. Introduction

Surface mechanomyography (MMG) has become a fairly common technique for examining the mechanical aspects of muscle function. Most previous studies have focused on the responses for MMG amplitude and mean or median frequency of the power spectra during isometric muscle actions [1–6]. These investigations have made important contributions regarding the potential applications of MMG for examining the motor control strategies that are used to increase isometric force production [7], the dissociation between the electrical and mechanical events that occurs with fatigue [8], and the characteristics of various neuromuscular disorders, including cerebral palsy [9], myotonic dystrophy [10], cranio-mandibular disorders [11], chronic and severe low back pain [12], diaphragmatic fatigue [13], and skeletal muscle atrophy [14]. Stokes ([15], p. 7), however, indicated that "If AMG [MMG] is to be used as a means of monitoring force during functional activities, then its relationship with force during dynamic activation must be considered." Examination of the MMG amplitude and frequency responses during dynamic muscle actions has implications not only for monitoring functional and/or sporting activities, but also in clinical applications such as controlling external prostheses [16], assessing low back pain that can be exacerbated during movement [12], monitoring rehabilitation following injury [17,18], and examining masseter muscle function in association with cranio-mandibular disorders [11].

A particularly important issue when analyzing MMG signals recorded during dynamic muscle actions is selection of the appropriate signal processing technique. Specifically, during a dynamic muscle action, changes in muscle length, the number of active motor units, and the thickness of the tissue between the muscle and MMG sensor can affect MMG amplitude and frequency, resulting in a nonstationary signal [19–22]. Several recent studies have used wavelet-based methods to process MMG signals recorded during dynamic muscle actions, since these techniques do not assume signal stationarity like Fourier-based techniques [22–24]. In addition, we have recently proposed a new wavelet analysis that was designed specifically for processing MMG signals [25]. The MMG wavelet analysis uses a filter bank of eleven nonlinearly scaled wavelets that maintain the optimal relationship between time and frequency resolution for MMG signals [25]. In addition, the MMG wavelet analysis provides comprehensive information regarding the time-dependent changes in intensity (which is analogous to power) and frequency of the input signal. This information is contained in a matrix which is displayed as an intensity pattern. The intensity pattern can be further processed to examine specific features of the MMG signal using statistical pattern recognition methods [26,27]. Von Tscharner [28] and von

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Tscharner and Goepfert [29] recently introduced the concept of pattern space for decomposing the intensity patterns of surface electromyographic (EMG) signals. Pattern space is a multidimensional space spanned by orthogonal coordinates. In this space each intensity pattern is represented by a point. Intensity patterns with similar characteristics form tight clusters of points in pattern space, and those with dissimilar traits are clearly separated [28,29]. Pattern classification methods have been used primarily in the classification of surface EMG signals for the control of externally powered prostheses [30–32]. In these cases, the subjects were asked to produce significantly different EMG signals that are likely classifiable. In the cases described by von Tscharner and Goepfert [29] the classification problem is more difficult because the subjects try to keep their muscle activation as constant as possible. For example, von Tscharner and Goepfert [29] reported that when surface EMG signals were recorded from the gastrocnemius, tibialis anterior, hamstring, rectus femoris (RF), and vastus medialis (VM) muscles during running, the resulting intensity patterns could be correctly classified as belonging to either a male or a female subject in at least 95% of the cases, although both groups showed very similar patterns. The method may therefore have the potential to identify patterns resulting from concentric and eccentric muscle actions.

Several previous investigations have suggested that eccentric muscle actions may require a unique motor control strategy when compared to those used during concentric and isometric muscle actions [33,34]. Specifically, eccentric muscle actions are characterized by decreased levels of muscle activation [35], reduced recruitment thresholds [36,37], and lower motor unit firing rates [38] when compared to concentric and/or isometric muscle actions. Previous studies [39,40] have also found that the normal order of motor unit recruitment (i.e., low-threshold to high-threshold) was reversed during eccentric muscle actions. Despite the discrepancies in muscle activation patterns during concentric and eccentric muscle actions, no previous studies have used pattern classification methods to examine differences in the resulting MMG intensity patterns. This information could be useful not only for identifying differences in the mechanical aspects of concentric and eccentric muscle actions, but also for using MMG as a control signal for an externally powered prosthesis [16]. Thus, the purpose of this study was to use pattern classification techniques to determine whether there were significant differences between the MMG intensity patterns recorded from the vastus lateralis (VL), RF, and VM during maximal concentric and eccentric isokinetic muscle actions of the leg extensors.

2. Methods

2.1. Subjects

Eleven healthy men (mean ± SD age = 20.1 ± 1.1 yrs; body weight = 81.8 ± 11.2 kg) volunteered to participate in this investigation. The training status of the subjects ranged from untrained to moderately trained (approximately 4–5 resistance training or aerobic training sessions per week). The study was approved by the University Institutional Review Board for Human Subjects, and all subjects completed a health history questionnaire and signed a written informed consent document before testing.

2.2. Isokinetic testing

For the isokinetic testing, the subjects performed maximal concentric and eccentric isokinetic muscle actions of the leg extensors at a velocity of $30^\circ\ \mathrm{s}^{-1}$ on two occasions separated by at least 48 h. The concentric isokinetic muscle actions were always performed during the first testing session to avoid the potential effects of delayed-onset muscle soreness following the eccentric isokinetic muscle actions. Both testing sessions began with a warm-up of five submaximal isokinetic muscle actions (either concentric or eccentric isokinetic) of the dominant leg extensors (based on kicking preference) on a calibrated isokinetic dynamometer. During each warm-up muscle action, the subjects were instructed to contract their leg extensors at approximately 50% of their subjectively rated maximum possible contraction force. The concentric isokinetic muscle actions were performed on a Cybex II isokinetic dynamometer, while the eccentric isokinetic muscle actions were done on a Cybex 6000 isokinetic dynamometer, since the Cybex II does not allow for measurement of eccentric torque production. Following the warm-up muscle actions, the subjects performed four maximal isokinetic muscle actions (concentric or eccentric isokinetic), all of which were separated by two minutes of rest. The subjects were verbally encouraged to produce as much torque as possible during each muscle action, and the isokinetic peak torque values were calculated without compensating for the acceleration due to gravity.

2.3. MMG measurements

During all muscle actions, surface MMG signals were recorded from the VL, RF, and VM muscles of the dominant thigh with miniature accelerometers (Entran EGAS FT 10, bandwidth 0–200 Hz, dimensions $1.0\ \mathrm{cm} \times 1.0\ \mathrm{cm} \times 0.5\ \mathrm{cm}$, mass 1.0 g). The accelerometers were placed over each muscle in accordance with the procedures described by Cramer et al. [41] and were fixed to the skin using double-sided adhesive tape.

2.4. Data acquisition and signal processing

The MMG signals from each muscle were amplified (gain 200), discretized by a 12-bit analog-to-digital converter (Model MP100, Biopac Systems, Inc.), and stored in a personal computer (Macintosh 7100/80 AV Power PC, Apple Computer, Inc., Cupertino, CA) for subsequent analyses. The conversion factors to obtain the acceleration were $66.28\ \mathrm{mV\ m\ s^{-2}}$ for the VL, $66.31\ \mathrm{mV\ m\ s^{-2}}$ for the RF, and $69.94\ \mathrm{mV\ m\ s^{-2}}$ for the VM. The signals were sampled at a rate of 2000 samples/second. All signal processing was performed using custom programs written with LabVIEW programming software (version 7.1, National Instruments, Austin TX). The concentric movement started at full leg flexion (90°) and ended at maximal extension (full extension = 180°). During the concentric isokinetic muscle actions, the MMG signals were measured between 120 and 150° of leg extension to avoid the acceleration and deceleration phases. The MMG signals during the eccentric isokinetic muscle actions were subsequently measured throughout the same range of motion (150 to 120° of leg flexion). Thus, at the set angular velocity of $30^\circ\ \mathrm{s}^{-1}$, there was a 1-s recording time. The MMG signals for each muscle were band-pass filtered (zero-lag, fourth order Butterworth with cutoff frequencies of 5 and 100 Hz) and processed with the wavelet analysis described by Beck et al. [25]. This wavelet analysis is designed specifically for MMG signals and results in an intensity pattern that describes the time locations and frequency distributions of the events that generate nonstationary MMG signals. The abscissa of the MMG intensity pattern was set to represent the leg extension angle. Thus, time progresses from low to high knee joint angles for the concentric movement and from high to low knee joint angles for the eccentric movement.

2.5. Statistical analyses

The MMG intensity patterns for the VL, RF, and VM during both the concentric and eccentric isokinetic muscle actions were