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Time and frequency domain responses of the mechanomyogram and electromyogram during isometric ramp contractions: A comparison of the short-time Fourier and continuous wavelet transforms

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Abstract

The purposes of this study were to examine the mechanomyographic (MMG) and electromyographic (EMG) time and frequency domain responses of the vastus lateralis (VL) and rectus femoris (RF) muscles during isometric ramp contractions and compare the time–frequency of the MMG and EMG signals generated by the short-time Fourier transform (STFT) and continuous wavelet transform (CWT). Nineteen healthy subjects (mean $\pm$ SD age $= 24 \pm 4$ years) performed two isometric maximal voluntary contractions (MVCs) before and after completing 2–3, 6-s isometric ramp contractions from 5% to 100% MVC with the right leg extensors. MMG and surface EMG signals were recorded from the VL and RF muscles. Time domains were represented as root mean squared amplitude values, and time–frequency representations were generated using the STFT and CWT. Polynomial regression analyses indicated cubic increases in MMG amplitude, MMG frequency, and EMG frequency, whereas EMG amplitude increased quadratically. From 5% to 24–28% MVC, MMG amplitude remained stable while MMG frequency increased. From 24–28% to 76–78% MVC, MMG amplitude increased rapidly while MMG frequency plateaued. From 76–78% to 100% MVC, MMG amplitude plateaued (VL) or decreased (RF) while MMG frequency increased. EMG amplitude increased while EMG frequency changed only marginally across the force spectrum with no clear deflection points. Overall, these findings suggested that MMG may offer more unique information regarding the interactions between motor unit recruitment and firing rate that control muscle force production during ramp contractions than traditional surface EMG. In addition, although the STFT frequency patterns were more pronounced than the CWT, both algorithms produced similar time–frequency representations for tracking changes in MMG or EMG frequency.

Keywords: MMG; EMG; Motor unit recruitment; Motor unit firing rate; Rate coding

1. Introduction

The mechanomyogram (MMG) is commonly defined as the recording of the low-frequency lateral oscillations of active skeletal muscle fibers (Orizio, 1993) and is considered to be the "mechanical counterpart" of motor unit electrical activity measured by the surface electromyogram (EMG). Barry and Cole (1990) and Orizio (1993) have suggested that the lateral oscillations recorded by MMG are a function of: (a) gross lateral movements of the muscle at the onset of contraction due to non-simultaneous activation of muscle–fibers, (b) smaller subsequent lateral oscillations occurring at the resonant frequency of the muscle, and (c) dimensional changes of the active muscle fibers (Barry and Cole, 1990; Orizio, 1993; Orizio et al., 2003).

Like surface EMG, the MMG signal represents a summation of the mechanical activity from individual motor units (Orizio et al., 2003). During voluntary contractions, it has been suggested that the time and frequency domain parameters of the MMG reflect motor unit recruitment and firing rate, respectively (Beck et al., 2006b; Orizio, 1993; Orizio et al., 2003). This is in contrast with the time and frequency domain parameters of the surface EMG

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signal, which are thought to reflect muscle activation (a combination of motor unit recruitment and firing rate) and motor unit action potential conduction velocity, respectively (Stulen and DeLuca, 1981). Therefore, due to their unique and complimentary capabilities, simultaneous measurements of MMG and EMG have been used to identify the dissociation between the electrical and mechanical events (excitation–contraction coupling) that occur with fatigue (Stokes and Dalton, 1991) and to examine factors related to electromechanical and phonomechanical delay (Petitjean et al., 1992).

Several previous studies have also utilized MMG and EMG to characterize the motor control strategies that modulate muscle force production. Most of these investigations have performed isometric "step" contractions (Beck et al., 2005c, 2004; Bilodeau et al., 1991; Coburn et al., 2005, 2004; Dalton and Stokes, 1993; Ebersole et al., 1998, 1999; Lariviere et al., 2001; Maton et al., 1990), which involve separate isometric contractions performed at specific force increments from submaximal to maximal levels of force production (i.e., 20%, 40%, 60%, 80%, 100% MVC, etc.). The same step contraction principle has also been applied to dynamic muscle actions (Beck et al., 2004; Beck et al., 2004; Coburn et al., 2005; Coburn et al., 2004), which may employ different motor control strategies (Kossev and Christova, 1998). Fewer studies have utilized isometric "ramp" contractions (Akasaka et al., 1997, 2004, 2002, 2001, 2003; Bilodeau et al., 1991; Lariviere et al., 2001), which consist of a single, non-fatiguing, linearly increasing, force-varying contraction over a 5–7 second period (Akasaka et al., 1997; Akataki et al., 2004, 2002, 2001, 2003; Bilodeau et al., 1991; Lariviere et al., 2001). Akataki and coworkers Akataki et al., 2004; Akataki et al., 2001; Akataki et al., 2003) and Orizio et al. (2003) have suggested that isometric ramp contractions may provide higher resolution throughout the force spectrum, shorter time taken for data acquisition, and less susceptibility to fatigue than step contractions. It is possible, however, that ramp and step contractions that characterize the force spectrum may incorporate different motor control strategies, much like the comparisons between isometric and dynamic isokinetic step contractions (Beck et al., 2004,; Coburn et al., 2005, 2004). To our knowledge, only two studies have examined the simultaneous measurement of MMG and EMG during isometric ramp contractions in the biceps brachii (BB) (Akataki et al., 2004; Orizio et al., 2003), and no studies have examined these relationships for the superficial quadriceps femoris muscles during leg extension muscle actions.

Bilodeau et al. (1991, 1997) have examined the issues surrounding the use of traditional Fourier-based procedures for determining the center frequency of discrete EMG signal portions extracted from a non-stationary isometric ramp contraction. It has been suggested that the EMG signal epoch being analyzed with a Fourier transform must remain stationary (or at least quasi-stationary) in the time and frequency domains in order to extract meaningful frequency information from the power spectrum (Bonato et al., 1996). Bonato et al. (1996) have proposed that a surface EMG signal epoch can be considered quasi-stationary if it is recorded during a constant–force contraction and is 0.5–2.0 s in duration. Unfortunately, at least one, if not both, conditions are not met during an isometric ramp contraction. Despite the force-varying non-stationarity of ramp contractions, Bilodeau et al. (1997) suggested that local stationarity exists for portions of the ramp contraction selected over small force increments during slow force increment rates. However, to our knowledge, no previous studies have compared the EMG or MMG frequency patterns of response during ramp contractions computed by traditional Fourier procedures, such as the short-time Fourier transform (STFT), and more computer-intensive time–frequency analyses, such as the continuous wavelet transform (CWT), which was proposed to be superior to the STFT (Karlsson et al., 1999, 2000). Therefore, the purposes of the present study were two-fold: (a) to extend the findings of Akataki and colleagues (Akataki et al., 2004; Akataki et al., 2002; Akataki et al., 2001; Akataki et al., 2003) and Orizio et al. (2003) and examine the MMG and EMG time and frequency domain responses of the vastus lateralis (VL) and rectus femoris (RF) muscles during isometric ramp contractions of the leg extensors and (b) to compare the time–frequency representations of the MMG and EMG signals generated by the STFT and CWT procedures during isometric ramp contractions.

2. Methods

2.1. Participants

Nineteen healthy subjects (mean ± SD age = 24 ± 4 years; height = 173 ± 9 cm; mass = 75 ± 13 kg) volunteered for this investigation. None of the participants reported any current or ongoing neuromuscular diseases or musculoskeletal problems specific to the ankle, knee, or hip joints. Each participant completed a pre-exercise health and exercise status questionnaire and signed a written informed consent document. Fifteen of 19 participants reported engaging in 1.5–7 h of aerobic exercise, 12 of 19 reported 1.5–7 h of resistance exercise, and 7 of 19 reported 1–4 h of recreational sports per week, however, none of the participants were competitive athletes. This study was approved by the University Institutional Review Board for Human Subjects Research.

2.2. Isometric assessments

Isometric torque for the right leg extensor muscles was measured using a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY). The participants were seated with restraining straps over the pelvis, trunk, and contralateral thigh, and the lateral condyle of the femur was aligned with the input axis of the dynamometer in accordance with the Biodex User's Guide