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Local muscle endurance is associated with fatigue-based changes in electromyographic spectral properties, but not with conduction velocity

Travis W. Beck *, Xin Ye, Nathan P. Wages

Biophysics Laboratory, University of Oklahoma, Department of Health and Exercise Science, 110 Huston Huffman Center, Norman, OK 73019-6081, United States

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ABSTRACT

The purpose of this study was to examine the associations amongst muscle fiber action potential conduction velocity (CV), spectral characteristics of the surface electromyographic (EMG) signal, and endurance time during a sustained submaximal isometric muscle action. Eleven men (mean ± SD age = 23 ± 4 yrs) performed a sustained, submaximal isometric muscle action of the dominant forearm flexors at 60% of the maximum voluntary contraction (MVC) until the designated force level could no longer be maintained. Sixteen separate bipolar surface EMG signals were detected from the biceps brachii with a linear electrode array during this contraction. Two channels from this array were used to measure CV, and one of these two channels was used for further EMG signal processing. The channels that provided the highest signal quality were used for the CV measurements and further data analysis. A wavelet analysis was then used to analyze the bipolar EMG signal, and the resulting wavelet spectrum was decomposed with a non-parametric spectral decomposition procedure. The results showed that the time to exhaustion during the sustained contraction was not correlated with the rate of decrease in CV, but it was highly correlated with both the decrease in high-frequency spectral power ($r = 0.947$) and the increase in low-frequency spectral power ($r = 0.960$). These findings are particularly interesting, considering that the decrease in traditional EMG spectral variables (e.g., mean frequency or median frequency) with fatigue is generally attributed to reductions in CV. While this may indeed be true, the present results suggested that other factors (i.e., other than CV) that can affect the shape of the EMG frequency spectrum during fatigue are more important in determining the endurance capabilities of the muscle than is CV.

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1. Introduction

The frequency spectrum of the surface electromyographic (EMG) signal is a very sensitive indicator of muscle fatigue. Piper (1907) was the first to describe a fatigue-related decrease in the frequency content of the EMG signal. Since this original investigation (Piper, 1907), numerous studies have been conducted to examine the factors affecting the EMG frequency spectrum. Lindström et al. (1970) identified the conduction velocities (CVs) of the action potentials along the active muscle fibers as one of the major (but not only) factors causing compression of the EMG power spectrum during fatiguing exercise. Other factors that can cause this fatigue-related compression are generally related to changes in motor control strategies. For example, decreases in motor unit firing rates, motor unit synchronization, and changes in the firing rate variability of the active motor units have all been proposed to play a role in the fatigue-related shift of the EMG power spectrum toward lower frequencies (Broman et al., 1985).

The fiber type composition(s) of the active muscles is the most common physiological characteristic addressed when discussing the factors that determine local muscle endurance (Bergh et al., 1978). A great deal of research has been conducted on this issue, and it has been well documented that muscles with a large percentage of slow-twitch fibers have better endurance than those with more fast-twitch fibers (Billeter et al., 1980). Other factors, such as capillary density and mitochondrial density have also been discussed (Kayar et al., 1986). However, an often overlooked aspect of muscle endurance is whether or not there are motor control strategies used by the central nervous system to reduce fatigue. Marsden et al. (1983) were the first to propose the concept of "muscle wisdom", which suggests that the central nervous system may reduce motor unit firing rates in an effort to keep them at an optimal level for force production. Specifically, as the contraction and relaxation times of the active motor units increase with fatigue, lower firing rates are needed to achieve optimal fusion of the motor unit twitches. Theoretically, firing rates that are greater

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* Corresponding author. Tel.: +1 (405) 325 1378.
E-mail address: tbeck@ou.edu (T.W. Beck).

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than this optimal level would unnecessarily fatigue the motor units, resulting in a greater force decline. Thus, the reduction in firing rates should, in theory, parallel the increased contraction and relaxation times (Marsden et al., 1983). It is important to point out that muscle wisdom will not prevent fatigue. Rather, it has been described as a strategy that could reduce the rate of fatigue. In addition, Fuglevand and Keen (2003) have provided criticism of the muscle wisdom concept, contending that the decline in motor unit firing rates is one of the causes for, rather than a consequence of, the force loss during fatigue.

Motor unit synchronization is another phenomenon that could reduce force loss during fatigue. In theory, this would allow for greater spatial summation of motor unit twitches, thereby allowing the same force to be maintained at lower firing rates and/or with fewer active motor units. Interestingly enough, however, there is very little evidence to support this contention. Contessa et al. (2009) found that during fatiguing isometric muscle actions of the leg extensors at 20% of the maximum voluntary contraction (MVC), there were no changes in motor unit synchronization for the vastus lateralis muscle. Carpentier et al. (2001) also reported no changes in motor unit synchronization during fatiguing isometric muscle actions of the first dorsal interosseous. It is important to acknowledge that these findings are from only two studies. It is certainly possible that different results could come from examining different muscles and/or using different fatigue protocols. Future research certainly needs to be done in these areas. For the time being, however, the available evidence suggests that synchronization of motor unit firings does not change significantly during fatigue.

A great deal of research has been conducted to examine how changes in firing rate parameters affect the EMG frequency spectrum (Hermens et al., 1992; Lago and Jones, 1977; Lindström and Magnusson, 1977; Blinowska et al., 1980). The results from these studies have generally shown that changes in firing rate parameters primarily affect the low-frequency (e.g., below 40 Hz) portion of the EMG frequency spectrum. Given that the surface EMG frequency spectrum can display power up to 200 Hz (De Luca, 1979; Basmajian and De Luca, 1985), or even higher, this 0–40 Hz range generally represents a small portion (e.g., 20%) of the total power in the spectrum. Thus, traditional measures of EMG center frequency (e.g., mean or median frequency) are sometimes not sensitive to changes in power in this small range. Instead, these power changes are susceptible to being "washed out" by factors that play a larger role in determining EMG frequency, such as CV. It is important to point out that this is not a fault/weakness of surface EMG. Firing rate information is contained in the EMG frequency spectrum. If researchers wish to retrieve this information, however, they must use techniques that are not susceptible to the changes in power that can occur above 40 Hz that typically dominate EMG center frequency. Fortunately, von Tscharner and Goepfert (2006) have developed a technique that is capable of retrieving this information from EMG frequency spectra. This method decomposes EMG frequency spectra onto a set of high- and low-frequency generating spectra (g_spectra). Each measured EMG spectrum can then be represented as a linear combination of the two g_spectra, weighted by the contributing weights (C_weights) (von Tscharner and Goepfert, 2006). This technique of decomposing EMG spectra is useful because it is sensitive to small changes in spectral power, yet the information it provides is simple and easy to interpret. Thus, the purpose of this study was to examine the linear associations among time to exhaustion (TTE), high-, and low-frequency C_weights, and CV during a sustained, submaximal isometric muscle action of the forearm flexors. We hypothesize that CV and the C_weights on the high-frequency g_spectrum will decrease, while the C_weights on the low-frequency g_spectrum will increase during the sustained contraction. In addition, there will be linear associations among time to exhaustion, CV, and the C_weights on the high-, and low-frequency g_spectra.

2. Methods

2.1. Subjects

Fifteen college-aged men volunteered to participate in this investigation. However, four of the 15 subjects provided EMG data that had poor signal quality. Thus, the data for these men were removed, and all subsequent calculations were made from the 11 subjects (mean ± SD age = 23 ± 4 yrs; height = 178.9 ± 9.0 cm; body weight = 84.5 ± 12.8 kg) that provided very high quality EMG signals. All 11 subjects were healthy and reported no current or recent neuromuscular or musculoskeletal disorders that could have affected the results from the study. The investigation was approved by the University Institutional Review Board for Human Subjects, and all subjects signed an informed consent form and completed a health history questionnaire prior to testing.

2.2. Isometric testing

The first visit to the laboratory was to familiarize the subjects with the equipment and procedures used for the isometric testing. The subjects were first placed in a custom-built isometric testing chair in which the dominant arm (based on throwing preference) was extended in front of the body, and the elbow was placed in a padded cuff. The forearm was then flexed in a position that allowed for a 90° elbow joint angle, and the subjects held onto a padded handle that was fixed to an S-Beam load cell (Interface, Model SSM-AJ-500, Scottsdale, Arizona). The other end of the load cell was attached to the isometric testing chair. Once positioned in the isometric testing chair, the subjects performed a warm-up of five separate 6-s submaximal isometric muscle actions of the forearm flexors at approximately 50% of the subject's maximum voluntary contraction (MVC). Following these warm-up muscle actions, the subjects performed two separate 6-s maximal isometric muscle actions. Two minutes of rest were allowed between these maximal muscle actions, and the highest force output from the two muscle actions was designated as the MVC. Upon completion of the two maximal muscle actions, the subjects were allowed to rest for 2 min, during which, 60% of the MVC force was calculated. The subjects then performed a sustained, 15-s isometric muscle action of the forearm flexors to become familiarized with the fatiguing muscle action that they would be required to perform in the subsequent visit. The subjects were provided with visual feedback of their real-time force output during the sustained 60% MVC muscle action. This real-time force output was overlaid onto a target force template, and the subjects were encouraged to match the template force as closely as possible.

At least 48 h after the familiarization visit, the subjects returned to the laboratory to perform the isometric testing. During this visit, the subjects were positioned into the isometric testing chair in exactly the same manner as during the familiarization visit. They also performed the warm-up and maximal muscle actions just as they had done previously. Following the maximal muscle actions, the subjects performed the sustained 60% MVC isometric muscle action to exhaustion. The subjects were verbally encouraged to match their real-time force with the target force template for as long as possible. The sustained 60% MVC muscle action ended when the subject's voluntary force

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