Journal of Electromyography and Kinesiology 25 (2015) 565–570

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Effects of the innervation zone on the time and frequency domain parameters of the surface electromyographic signal ☆

Cory M. Smith [a,*], Terry J. Housh [a], Trent J. Herda [b], Jorge M. Zuniga [c], Eric D. Ryan [d], Clayton L. Camic [e], Haley C. Bergstrom [f], Doug B. Smith [g], Joseph P. Weir [b], Joel T. Cramer [a], Ethan C. Hill [a], Kristen C. Cochrane [a], Nathaniel D.M. Jenkins [a], Richard J. Schmidt [a], Glen O. Johnson [a]

[a] University of Nebraska – Lincoln, Lincoln, NE, United States
[b] University of Kansas, Lawrence, KS, United States
[c] Creighton University, Omaha, NE, United States
[d] University of North Carolina – Chapel Hill, Chapel Hill, NC, United States
[e] University of Wisconsin – La Crosse, La Crosse, WI, United States
[f] University of Kentucky, Lexington, KY, United States
[g] Oklahoma State University – Stillwater, Stillwater, OK, United States

A R T I C L E I N F O

Article history:
Received 20 February 2015
Received in revised form 26 March 2015
Accepted 27 April 2015

Keywords:
Electromyography
Patterns of responses
IZ
Linear array
Amplitude
MPF
RMS
Vastus lateralis

A B S T R A C T

The purposes of the present study were to examine the effects of electrode placements over, proximal, and distal to the innervation zone (IZ) on electromyographic (EMG) amplitude (RMS) and frequency (MPF) responses during: (1) a maximal voluntary isometric contraction (MVIC), and; (2) a sustained, submaximal isometric muscle action. A linear array was used to record EMG signals from the vastus lateralis over the IZ, 30 mm proximal, and 30 mm distal to the IZ during an MVIC and a sustained isometric muscle action of the leg extensors at 50% MVIC. During the MVIC, lower EMG RMS ($p > 0.05$) and greater EMG MPF ($p < 0.05$) values were recorded over the IZ compared to away from the IZ, however, no differences in slope coefficients for the EMG RMS and MPF versus time relationships over, proximal, and distal to the IZ occurred. Thus, the results of the present study indicated that during an MVIC, EMG RMS and MPF values recorded over the IZ are not comparable to those away from the IZ. However, the rates of fatigue-induced changes in EMG RMS and MPF during sustained, submaximal isometric muscle actions of the leg extensors were the same regardless of the electrode placement locations relative to the IZ.

1. Introduction

The linear array allows for the simultaneous recording of surface electromyographic (EMG) signals from an inline series of electrodes at multiple locations along the muscle (Merletti et al., 2003) and has many applications including identifying the location of the connection between nerve terminals and muscle fibers called the innervation zone (IZ) (Basmajian and De Luca, 1985). Recently, the SENIAM project and other authors (Hermens et al., 1999, 2000; Merletti et al., 2003; Rainoldi et al., 2000, 2004) have developed electrode placement guidelines which recommend avoiding the IZ due to the large EMG signal variations that occur over the IZ. Typically, electrode arrangements over the IZ result in lower EMG amplitude (root mean square: RMS) and greater EMG frequency (mean power frequency: MPF) values than when recorded away from the IZ (Rainoldi et al., 2004; Beck et al., 2008) The lower EMG RMS values recorded over the IZ result from signal cancellation. That is, bipolar electrode arrangements placed over the IZ detect motor unit action potentials (MUAP) propagating in opposite directions and therefore, result in greater signal cancellation. The greater EMG MPF values recorded over the IZ are due to the presence of non-propagating MUAPs. Thus, the variations in EMG signals allow for the identification of the IZ by using a linear array to locate the channel with minimal amplitude and phase reversal.

The effects of the IZ on EMG signals have been shown (Beck et al., 2008; Rainoldi et al., 2004) to occur during discrete measurements such as a maximal voluntary isometric contraction (MVIC),

☆ Each co-author was directly and substantially involved in the development of this manuscript in one or more of the following: (1) Development of the concept, (2) Subject Recruitment, (3) Data Collection, or (4) Manuscript Preparation.

* Corresponding author at: Department of Nutrition and Health Sciences, 110 Ruth Leverton Hall, University of Nebraska – Lincoln, Lincoln, NE 68583-0806, United States. Tel.: +1 402 472 2690.

E-mail address: CSmith@unl.edu (C.M. Smith).

http://dx.doi.org/10.1016/j.jelekin.2015.04.014
1050-6411/

but Roy et al. (1986) and Hogrel et al. (1998) suggested that the IZ does not affect the EMG MPF versus time relationship during sustained submaximal isometric muscle actions at 80% MVIC. These findings (Hogrel et al., 1998; Roy et al., 1986) suggested that EMG MPF patterns of responses and rate of fatigue-induced changes occur at a similar rate over and away from the IZ. Little is known, however, regarding the effects of electrode placement over the IZ on the EMG RMS versus time relationships during fatiguing isometric muscle actions. Thus, differences in electrode placements among previous studies can make it difficult to interpret the conflicting findings (Hermens et al., 2000; Hogrel et al., 1998; Roy et al., 1986) regarding the effect of the IZ on the time and frequency domain parameters of the EMG signal.

The placements of electrodes relative to the IZ have often gone unreported. For example, Hermens et al. (2000) found that in 144 studies there were over 352 different descriptions of electrode placements, and many only reported the muscle involved. Differences in electrode placement influence a number of factors that contribute to variations in the EMG signal including: (1) the alignment of electrodes relative to the pennation angle of the muscle; (2) the magnitude of cross-talk from nearby muscles; (3) the effect of electrodes placed near the tendonous region of the muscle; and (4) placement of electrodes over the IZ (Farina et al., 2004; Hermens et al., 2000). Due to these influences on the EMG signal, it has been suggested (Hermens et al., 2000) that "wrong estimations" (p. 368) of the EMG RMS and MPF values occur when recorded over the IZ and that "... the SEMG [Surface EMG] pattern near or over the motor endplate zone is not very 'typical' for the muscle: it is not very stable or reproducible since relatively small displacements of the sensor will shift it to a place next to or over the innervation zone." (p. 368). Thus, it has been suggested that EMG electrodes should be placed "far away from the IZ" (p. 368) to avoid the effects the IZ has on EMG RMS and MPF values (Hermens et al., 2000). Therefore, the purposes of the present study were to examine the effects of electrode placements over, proximal, and distal to the IZ of the vastus lateralis (VL) on surface EMG RMS and MPF responses during: (1) an MVIC, and; (2) a sustained, submaximal isometric muscle actions EMG RMS and MPF patterns of responses.

2. Methods

2.1. Subjects

Nine adults (7 men and 2 women, mean ± SD age = 22.0 ± 1.2 yrs; body mass = 81.3 ± 14.2 kg; height = 179.7 ± 10.4 cm) volunteered to participate in the investigation. The subjects regularly participated in physical activities such as running, bicycling, and resistance training. The study was approved by the University Institutional Review Board for Human Subjects, and all subjects completed a health history questionnaire and signed an informed consent document prior to testing.

2.2. Orientation session

The orientation session was used to determine the location of the IZ and the pennation angle of the muscle fibers of the VL. The subjects were dry shaven and cleaned with a damp cloth prior to applying a probe of 8 silver bar electrodes (5 mm × 1 mm, 10 mm interelectrode distance, Ottino Bioelectronica, Torino, Italy) on the muscle belly of the VL, orientated at a 20° angle related to the reference line between the anterior superior iliac spine and the superior border of the patella to approximate the pennation angle (Abe et al., 2000). The reference electrodes were placed around the subject's wrist according to the procedures described by the EMG 16 User's Manual (2006). The subjects were instructed to perform a submaximal isometric contraction of their leg extensors to identify their IZ. The location of the IZ was identified by the EMG channel with the minimal amplitude and phase reversal (Merletti et al., 2003). The probe was then moved along the muscle until the IZ was in the center of the electrode array. Once the IZ was centered, the probe was aligned with the long axis of the muscle fibers by rotating the probe around the IZ until the slopes of the two lines connecting the EMG waveforms from the channels above and below the IZ were as equal as possible. The outline of the probe was then traced with a non-washable marker before removing the probe so the same electrode position could be obtained in the subsequent session.

2.3. Warm-up

All isometric testing was performed by the subject's dominant leg extensors on a calibrated Cybex II dynamometer (Cybex International Inc., Medway, MA), with a knee joint angle of 120° (Kulig et al., 1984). Prior to the isometric testing, each subject performed a warm-up of 5, 6-s submaximal isometric muscle actions, followed by a 2-min rest period. The subjects were instructed to provide an effort corresponding to approximately 50% of their maximum during each warm-up muscle action.

2.4. Maximum voluntary isometric contraction (MVIC)

After completing the warm-up, each subject performed two, 6-s MVICs. A 2-min rest was allowed between trials. Strong verbal encouragement was provided for all subjects. The MVIC was calculated for a 2-s time period, corresponding to the middle 33% of each 6-s trial. The highest torque value of the two MVIC trials was used to calculate each subjects 50% MVIC torque value for the subsequent sustained isometric task.

2.5. Sustained isometric task

Each subject was instructed to perform a sustained isometric muscle action to exhaustion at 50% MVIC. Exhaustion was operationally defined as the subject being unable to maintain a torque value within ±5% of their 50% MVIC despite strong verbal encouragement. The subjects tracked their torque production on a computer monitor placed in front of them that displayed the real-time, digitalized torque signal overlayed onto a programmed template identifying their target torque value. The isometric template and real-time torque signal overlay was programmed using LabVIEW 7.1 software (National Instruments, Austin, TX).

2.6. EMG measurements and signal processing

Surface EMG signals were recorded from the VL muscle of the dominant thigh with an 8-channel linear electrode array and EMG 16 data acquisition system (EMG 16, LISiN-Prima Biomedical & Sport, Treviso, Italy). The skin over the VL was carefully abraded and cleaned with rubbing alcohol prior to placing the array. The 8-channel linear electrode array was secured to the VL using a double-sided adhesive strip. The adhesive strip had small holes that were cut for each silver bar electrode, and each hole was filled with 30 μl of conductive gel with a gel dispenser (AG22331, Eppendorf, Hamburg, Germany) (EMG 16, 2006).

The raw EMG signals from each electrode of the probe were recorded in a monopolar signal acquisition mode (gain × 500) and analog filtered (fourth-order Bessel, bandwidth = 10–500 Hz) with the surface EMG 16 data acquisition system. Channel 1 corresponded to the most proximal and channel 8 to the most distal electrode. The monopolar EMG signals were converted to a digital