2016 CMBEC39 Conference
Calgary AB
May 24–27, 2016

MUSCLE CONDUCTION VELOCITY ESTIMATION USING HIGH DENSITY ELECTROMYOGRAPHY

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INTRODUCTION

When a muscle is activated to contract, activation signals – motor unit action potentials (MUAPs) – travel along the surface of individual muscle fibres away from the innervation zone (IZ), which is centrally located, to the terminal tendons. Conduction velocity (CV) is considered to be constant in individual motor units, and single motor unit CV is related to the state of the muscle [1]. Overall conduction velocity (CV) in a population of active motor units can be estimated from the recorded surface electromyogram (SEMG) [2].

CV estimation is affected by physiological factors – force levels, type of contraction, and muscle length [3, 4] – and non-physiological factors – the recording electrode configuration, i.e., the distance between electrodes of a bipolar pair (inter-electrode distance or IED), and the distance between two bipolar pairs used to detect conduction delay (inter-signal distance or ISD) [2]. Reported CVs are generally in the range 3.5 – 5 m/s.

The purpose of this study was to examine the effect of IED and ISD, contraction level, and muscle length, on CV estimates from high-density (HD-) SEMG data.

METHODS

Data Collection

Data were collected from five subjects (3 female and 2 male), with average age 23.8±2 years, height 171.7±11 cm, and weight 63±10 kg. All subjects provided informed consent prior to participating in the study. The experiments were conducted on the Q-Arm, a single degree-of-freedom exoskeleton testbed [ref]. The Q-Arm supports the right arm in the horizontal plane; the upper arm is held in a fixed position, with the elbow aligned with the axis of a pivoting aluminum bar. The forearm is fully supinated, and the wrist is held in a cup holder at the end of the bar. The bar can be locked at specific joint angles for isometric contraction of the elbow flexors and extensors; contraction force is measured as linear force at the wrist via a force transducer coupled to the wrist holder.

EMG data were collected using 8-electrode linear arrays (Bioelettronica ELSCH008 - Figure 1) located on the long head and short head of biceps brachii (BBL and BBS) and on the brachioradialis (BRD). Electrode arrays were oriented so that the electrode column was in-line with the direction of the underlying muscle fibres. On BBL and BBS, the electrodes were placed at the Senium recommended location and adjusted up or down to insure that the electrode array was placed over the bulk of the muscle. For BRD, the electrode was placed 2 cm distal to the elbow crease and one finger width from centre line of the forearm.

Figure 1: Linear electrode array; electrode separation is 5 mm and electrode dimensions are 2.5 mm long × 1 mm wide. Electrodes are attached to the skin by an adhesive foam pad; conductive paste is used to couple the electrodes to the skin, and skin contact area is 5 mm × 3 mm = 15 mm^2. Electrodes are numbered 1-8, as shown. Each array was positioned with the connector oriented distally.

Eight channels of monopolar EMG data per array were collected using an HD-SEMG system (OT Bioelettronica EMG-USB2). Data were sampled at 2048 Hz from four subjects and at 10240 Hz from one subject.

Initially, subjects performed two isometric maximum voluntary contractions (MVCs) in flexion at an elbow angle of 90°. Each MVC lasted 5 seconds, with a rest of 15 seconds between the two contractions, and a rest time of 2 minutes after completion of the two MVCs. Subjects were then asked to generate isometric flexion contractions to follow a force profile comprising three force levels (30, 40 and 50% maximum measured force); each contraction was 5 seconds in duration, followed by 5 seconds rest. Subjects completed four trials, at each of three joint angles: 60°, 90° and 120° (measured as the internal angle between the upper arm and forearm). The order of force levels was randomized across trials. There was a 30 second rest period after each trial at one joint angle, and a 2 minute rest period between joint angles.

Data Analysis

The monopolar SEMG data were spatially filtered by computing the bipolar (single differential) signals. CV was estimated using the cross-correlation method to find the delay time between pairs of bipolar signals. Two IED/ISD conditions were examined: IED=5 mm, ISD=10 mm; and IED=15 mm, ISD=20 mm, as shown in Figure 2. CV estimates were obtained for three pairings – D_5-1-D_5-3, D_5-3-D_5-5, D_5-5-D_5-7 – for IED/ISD=5 / 10 mm, and for one pairing for IED/ISD=15 / 20 mm. The CV data were analysed using parametric (Anova) and non-parametric (Kruskal-Wallis) tests to determine which factors significantly affected CV.

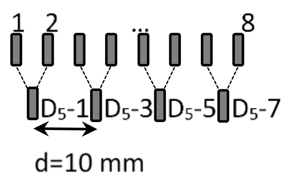

Figure 2: IED and ISD configurations: IED=5 mm and ISD=10 mm (left); IED=15 mm and ISD=20 mm (right).

RESULTS

Figure 3 shows cross-correlation plots for one trial from one subject, for IED=5 mm and ISD=10 mm. The delay, or signal propagation time, is determined from the location of the peak of the cross-correlation function. A negative peak indicates that the two signals are inverted with respect to each other, which occurs at the IZ [5]. The delay time at the IZ can be artificially small, as the signal is propagating from a point between the two differential electrodes towards each of the electrodes.

Delay times for each bipolar pair of electrodes were determined for each trial at each joint angle-force level condition resulting in 4 trials × 3 joint angles × 3 force levels = 36 values per subject. The values were reviewed and any CVs outside the range of acceptable values (less than 2.5 m/s or greater than 6.5 m/s based on previously published CV values) were rejected. There were no acceptable CV values for BBL; the number of values per condition for BBS and BRD ranged from 13 to 19, and 9 to 12, respectively. Average CV values for BBS and BRD are given in Table 1. There is an apparent increase in CV with force level for BBS, but this was not significant. There is no apparent trend in CV with joint angle.

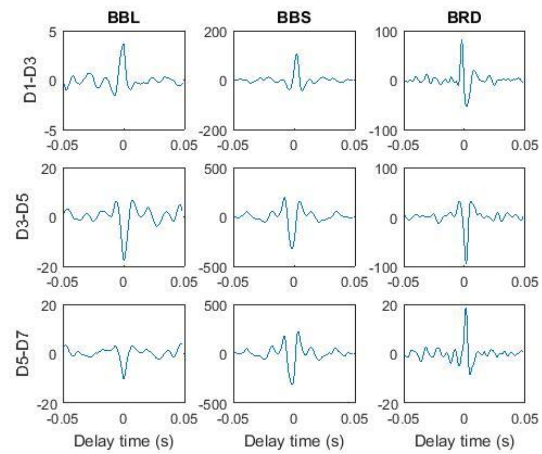

Figure 3: Cross-correlation curves for IED=5 mm, ISD = 10 mm, for one trial from one subject. Force level = 50%, joint angle = 90°.

Table 1: Average CV values in m/s for each joint angle (JA) – force level (FL) condition for IED/ISD = 5/10 mm. Standard deviations (SDs) are also given. FL-1 = 30%, FL-2 = 40% and FL-3 = 50% maximum force.

	BBS			BRD		
JA / F	FL-1	FL-2	FL-3	FL-1	FL-2	FL-3
60 Av	4.60	4.70	4.72	4.20	4.11	4.12
SD	1.23	1.01	0.77	1.06	0.73	0.92
90 Av	4.22	4.28	4.39	4.13	4.57	4.86
SD	0.47	0.58	0.8	0.78	1.02	0.73
120 Av	4.58	4.70	4.74	4.12	4.16	4.14
SD	0.76	0.65	0.67	0.69	0.6	0.55

Reasonable CV estimates were obtained for IED = 15 mm and ISD = 20 mm. Anova analysis of CV values grouped by muscle, contraction level, and joint angle revealed that contraction level had no significant effect (p-values: 0.336 to 0.774), and CV varied significantly with joint angle only for the highest contraction level in BBS ($p=0.01$). Values for all contraction levels were then grouped and Anova analysis showed that CV varied significantly with muscle ($p < 2\times10^{-5}$) for all joint angles.

Table 2: Average CV values in m/s for each JA for IED/ISD = 15 / 20 mm. Values were averaged across force levels.

	Muscle		
JA	BBL	BBS	BRD
60 Av	2.98	3.03	3.55
SD	0.55	0.64	0.9
90 Av	2.64	2.97	3.41
SD	0.56	0.50	0.90
120 Av	2.77	3.49	3.37
SD	0.61	0.87	1.03

DISCUSSION

The monopolar HD-SEMG signals were recorded with respect to a reference electrode attached over a subject's wrist. The monopolar signals comprise non-propagating far-field potentials modulated by near-field potentials, or localized SEMG signals, which are comprised of propagating MUAPs [6]. These near-field potentials are revealed by spatial filtering – or differentiating – the monopolar signals. Monopolar and bipolar (IED = 5 mm) signals are shown for one muscle (BRD) in Figure 3. The bipolar reversal potential is apparent between D-3 (monopolar CH-4–CH-3) and D-4 (monopolar CH-5–CH-4); this indicates the location of an IZ in the muscle [5, 7]. IZ location will vary from person to person and muscle to muscle, and there may be several IZs in an individual muscle [7]. Because MUAP propagation reverses across an IZ, reliable CV estimates will not be obtained for two recording sites which straddle the IZ. For IED/ISD = 5 / 10 mm, acceptable CV estimates were obtained for different electrode pairings in different subjects and different muscles. It is assumed that the pairings which gave acceptable CV values were both located on one side of the IZ.

CV values for IED/ISD = 15 / 20 mm are lower than the values obtained for IED/ISD = 5 / 10. Beck et al. [2] reported that estimated CV increased for larger IED but decreased for larger ISD. There was little change in CV when both IED and ISD increased (see Fig. 4 in [2]). It may be that the effect of larger ISD has dominated in this study, resulting in lower CV. However, it should be noted that all CV values were accepted for IED/ISD = 15 / 20 mm, where values less than 2.5 m/s were rejected for IED/ISD = 5 / 10 mm. As well, it is probable that one of the bipolar pairs (CH-1–CH-4; CH-5–CH-8) is across an IZ, contributing to inaccuracy in the CV estimate.

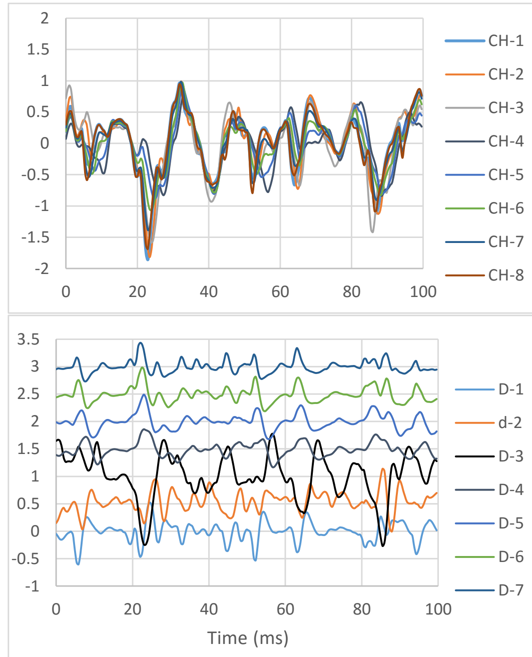

Figure 3: Monopolar (top) and bipolar (bottom) signals recorded from BRD (JA=60°; FL-1). Bipolar signals have 5 mm IED; D-1 = CH-1–CH-2, … D-7 = CH-7–CH-8. Non-zero offsets have been added to the bipolar signals to separate the individual traces.

The lack of acceptable CV values from BBL for IED/ISD = 5 / 10 mm, may be related to the presence of one or more IZ's in the data. A plot of bipolar BBL signals (IED = 5 mm) for one subject indicated the presence of an IZ at D-5 (monopolar CH6–CH5). It was also apparent that the BBL signal amplitude was substantially lower than for the BBS and BRD. This is also noticeable in the scales of the plotted cross-correlations in Figure 1. Thus, for a small IED, it may be that non-propagating, or noise, sources in the signal are significant and impact the CV estimate. A larger IED (15 mm) will detect signal activity from a larger region of the muscle [2] permitting reasonable CV estimation for the IED/ISD = 15 / 20 mm case. Note, it is known that the two heads of the biceps brachii are differentially activated, depending on the task performed, so it is not unreasonable to see a difference in SEMG amplitude [8].

It has been reported that CV increases with increasing contraction (or force) level. This is considered to be due to the size principal, where motor units of increasing size – and consequently higher CV – are recruited with increasing force. No significant increase in CV with force level was found in this study, but there is an observable trend of increasing CV with force level in the BBS for IED/ISD = 5 / 10 mm. This effect may become significant, and may be observed in other muscles, if data are collected from a larger subject pool.

No significant effect of changing elbow joint angle on estimated CV was observed. This may indicate that a consistent population of motor units is recruited under similar task performance conditions. In all cases, the task involved generating an isometric flexion contraction, albeit at different muscle lengths. It has been observed that CV varies with dynamic contraction type (concentric versus eccentric) [4], which may indicate that different recruitment strategies are used under different conditions.

It should be noted that data sampling rate affects the resolution of the delay estimates. The SEMG sampling rate in this study was 2048 Hz, corresponding to a sampling period of 0.4483 ms. Thus, the delays estimated from the cross-correlation functions will be in steps of 0.4483 ms. This adds a quantization error to the CV estimate.

CONCLUSIONS

Muscle CV has been estimated from HD-SEMG recorded over the BBL, BBS and BRD muscles during isometric, constant-force contractions, at three discrete force levels, and three elbow joint angles. Force level and joint angle did not have a significant effect on CV. Lower CV values were obtained for larger IED and ISD values, but further study is required to confirm this result, and examine underlying causes.

ACKNOWLEDGEMENTS

Ashmita De was supported by the Mitacs Globalink program to work at the BioRobotics Lab, Dept. of Electrical and Computer Engineering, Queen's University for the summer of 2015.

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