A SPIKE TRIGGERED AVERAGING TECHNIQUE FOR HIGH RESOLUTION ASSESSMENT OF SINGLE MOTOR UNIT CONDUCTION VELOCITY CHANGES DURING FATIGUING VOLUNTARY CONTRACTIONS

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Abstract- **In this paper we propose an improved spike triggered averaging technique for the assessment of control properties and conduction velocity (CV) of single motor units (MUs) during voluntary sub-maximal muscle contractions. The method is based on the detection of multi-channel surface EMG signals (with linear electrode arrays) and intramuscular recorded single MU action potentials (MUAPs). Intramuscular electrodes are inserted taking into account the MU structural properties (innervation zone and tendon locations, length of the fibers), assessed by the linear array surface EMG detection. A technique for intramuscular EMG signal decomposition is used to identify single MUAP trains. The MUAPs obtained from the intramuscular EMG decomposition algorithm are used to trigger and average the multi-channel EMG signals. CV of single averaged surface MUAPs is estimated by the use of advanced signal processing methods based on multi-channel recordings which allow to consistently reduce the variance of CV estimates with respect to traditional two channel delay estimators. The number of averaged potentials can thus be reduced, improving temporal resolution. The technique proposed is tested with recordings from the tibialis anterior muscle of 11 volunteers. It is shown that the method allows the assessment of CV changes (fatigue) of single MUs as small as 0.1 m/s with a limited number of averages (temporal resolution of 1-2 seconds), leading to a consistent improvement with respect to traditional surface EMG spike triggered averaging techniques. The method has potential usefulness in a number of basic and applied research fields.**

Keywords **- electromyography, single motor unit conduction velocity, fatigue, spike triggered averaging, maximum likelihood delay estimators**

I. INTRODUCTION

Intramuscular electromyographic (iEMG) signal decomposition allows to extract information about single motor unit (MU) firing rate and recruitment threshold. Nevertheless, many physiological and anatomical properties of the detected MUs cannot directly be assessed by iEMG analysis. Indications about physiological properties of single MUs during muscle activity could however clarify the relationships between central motor control strategies, fatigue and mechanical properties of the MUs.

The concomitant recording of iEMG and sEMG would permit estimation of single MU control properties (recruitment threshold, firing rate) as well as physiological (CV and fatigability) and structural (location of the innervation zone, length of the fibers, location of the tendon regions) properties of single MUs. The conduction velocity (CV) with which action potentials propagate along the muscle fibers is an important physiological parameter, which indicates muscle fatigue [2][10] and reflects the mechanical properties of the MUs [1]. Usually CV is estimated non-invasively from the surface EMG (sEMG) signal without the separation of the contributions of the single MUs (a global CV value is obtained). To extract single MUAPs from the surface recordings, a spike triggered approach based on intramuscular detected MUAPs can be used. A high number of averaged potentials is, however, needed to obtain the high signal to noise ratio required for estimating the CV of the detected MUAPs with low variance. Moreover, the estimation of single MUAP CV implies careful placement of the electrodes since different locations along the muscle fibers and/or different inclinations with respect to the muscle fibers may determine large differences in the estimates [6].

The aim of this work was to develop a system for improving surface EMG spike triggered averaging techniques in order to reliably detect single MU CV and CV changes during time with high temporal resolution. The method proposed is based on the detection of multi-channel surface EMG signals and the applications of low variance multi-channel CV estimation algorithms. In particular the technique consists of the following steps (Fig. 1), described below in detail: 1) recording of iEMG (with a multi-wire system) and sEMG signals (with a multi-electrode system), 2) decomposition of the iEMG signal into the constituent motor unit action potential (MUAP) trains, 3) sliding window spike triggered averaging of the multi-channel sEMG with iEMG potentials as triggers, and 4) low variance multi-channel single MU CV estimation.

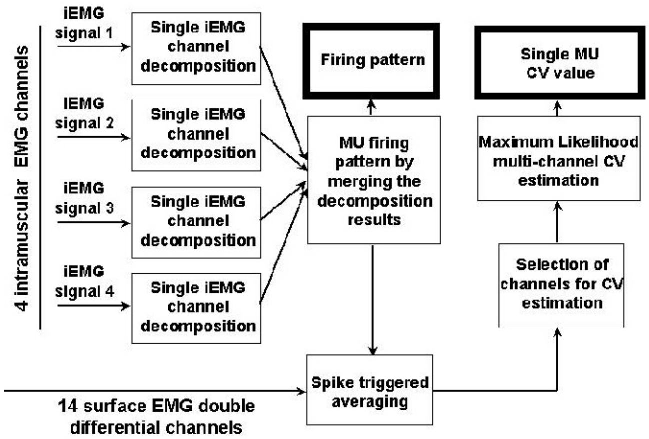

Fig. 1. Schematic representation of the detection and processing techniques. Four intramuscular EMG signals are detected, decomposed into the constituent MUAP trains and used to generate trigger signals for averaging 14 double differential surface EMG signals using a 30 ms time window. Conduction velocity is estimated from a subset of surface averaged EMG signals using the maximum likelihood multi-channel delay estimator.

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II. Methodology

A. Detection of intramuscular and surface EMG signals

Intramuscular signals have been recorded with the use of four wire electrodes made of Teflon coated stainless steel (A-M Systems, Carlsborg, WA, USA) inserted in the muscle via one needle (23 G). Surface EMG signals were collected by the use of a linear array of 16 electrodes (bar electrodes 5 mm long, 1 mm diameter, 5 mm interelectrode distance) [8][11]. Structural properties of the MUs (innervation zone, tendon location, length of the fibers) were assessed by a preliminary visual analysis of the multi-channel surface EMG signal characteristics. In order to detect common MU activities with the two recording systems the surface electrodes were placed between the most distal innervation zone (IZ) and the distal tendon while the wires were inserted between the most distal IZ and the proximal tendon region; in this way the array covered the distal part of the fiber corresponding to propagating MUAPs. The inclination of the array was selected by visual inspection of the multi-channel signals in order to obtain minimal shape changes of the MUAPs during their propagation along the muscle fibers.

B. Decomposition of the intramuscular signals

A simple technique for intramuscular EMG signal decomposition was developed. Each channel is decomposed independently and the results from the different channels are then compared in order to merge MU firings detected by more than one channel. Each channel is decomposed by a segmentation phase based on amplitude threshold and a classification phase based on high resolution alignment by spectral matching [9]. The developed decomposition technique was tested with methods described in the literature [5][7] and provided results comparable with those obtained with other techniques [7] when the signal to noise ratio was sufficiently high (> 8 dB) and the number of superimposed MUAPs limited.

C. Spike triggered average of the surface EMG signals

The firings of the individual MUs estimated by iEMG signal decomposition were used as triggers for the multi-channel surface detected MUAPs. A window of 30 ms was used for the average of the surface EMG signals. Overlapping epochs have been used, so that the step in the averaging process was of a single firing (sliding window spike-triggered averaging).

D. Low variance multi-channel single MU CV estimation

The CV estimation using multi-channel techniques is implemented by high resolution fast algorithms [5][6]. Double differential signals were used for CV estimation. CV is estimated from the channels of the array corresponding to unidirectional potential propagation (propagation between IZ and tendon region) with minimal shape distortion. The channels used for CV estimation were selected automatically as the set of channels with shape difference [12] lower than a given threshold.

E. Experimental protocol and data analysis

Eleven healthy subjects (3 females, 8 males) with ages ranging from 21 to 28 years (mean age ±standard deviation: 23.4 ±2.2 years) participated in the study. No subject had symptoms of neuromuscular disorders or ligament problems. The study was conducted in accordance with the Declaration of Helsinki, approved by the Local Ethics Committee, and written informed consent was obtained from all subjects prior to inclusion.

The subject sat comfortably on a chair with the foot of the dominant leg fixed in an isometric force brace incorporating a torque transducer (Aalborg University, Aalborg, Denmark). Invasive and surface electrodes for EMG signal detection were placed on the tibialis anterior muscle as described above. Three measures of the maximal voluntary contraction (MVC) force were done. The highest of the three estimated maximal forces was considered as the reference MVC. After the MVC assessment and 5 min rest, the subject performed an isometric contraction at 25% MVC for 60 s. Before and after the fatiguing contraction, 10 s recordings were performed at rest in order to estimate the noise level.

All the data collected were analyzed with the method described above. Twenty potentials were averaged to obtain each single surface potential. MU CV over time has been estimated with the multi-channel maximum likelihood estimator and, for comparison, with a traditional two channel estimator [9]. Linear regressions of CV versus time have been computed in order to assess changes of CV over time. The slope of the regression line of CV has been used as fatigue index and the initial value of CV of the single MUs has been defined as the value of the regression line at the initial time instant [10]. Finally, the global CV has been also computed from the surface EMG signal by the spectral matching method [9]. For this purpose, the signal has been divided in epochs of 0.5 s without overlapping and only two channels were used.

The hypothesis that the CV slope was different from zero was tested (at $p = 0.05$) by linear regression analysis for each MU and the standard deviation of estimation (standard deviation of the prediction error) has been computed in all the cases. The statistical analysis has been performed for the entire contraction length (60 s) and also for half of the contraction length (30 s).

III. Results

The estimated CV over time for a single MU is shown in Fig. 2. Two to six channels for CV estimation corresponding to unidirectional propagation with minimal shape distortion of the potential were selected in this case. In all the cases the surface averaged potentials have been obtained from 20 averages. The improvement in CV estimation quality obtained by increasing the number of channels is evident. The large difference in the information obtained by the traditional two-channel technique and the multi-channel algorithm should be noted. Using a two-channel approach it is possible to obtain a variance of estimation comparable to that obtained by using six channels but it is necessary to increase considerably the number of potentials being averaged, thereby decreasing the temporal resolution.

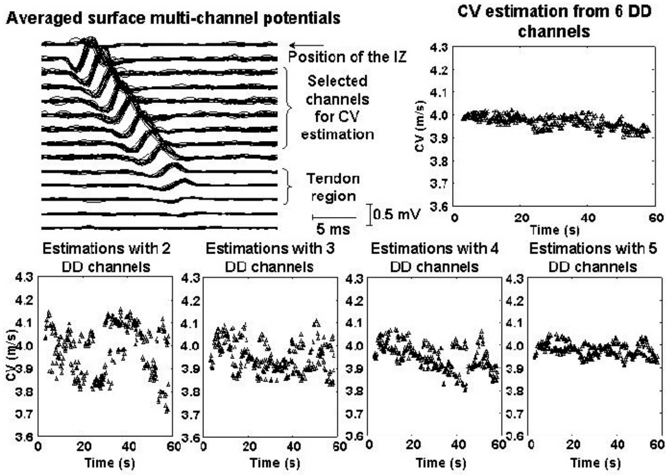

Fig. 2. Example of estimation of single MU CV from averaged surface MUAPs. The surface averaged potentials obtained by 20 averages each are shown. With six channels clear fatigue pattern is evident (correlation coefficient between CV and time statistically different from zero). The CV estimation obtained using two to five channels is also shown.

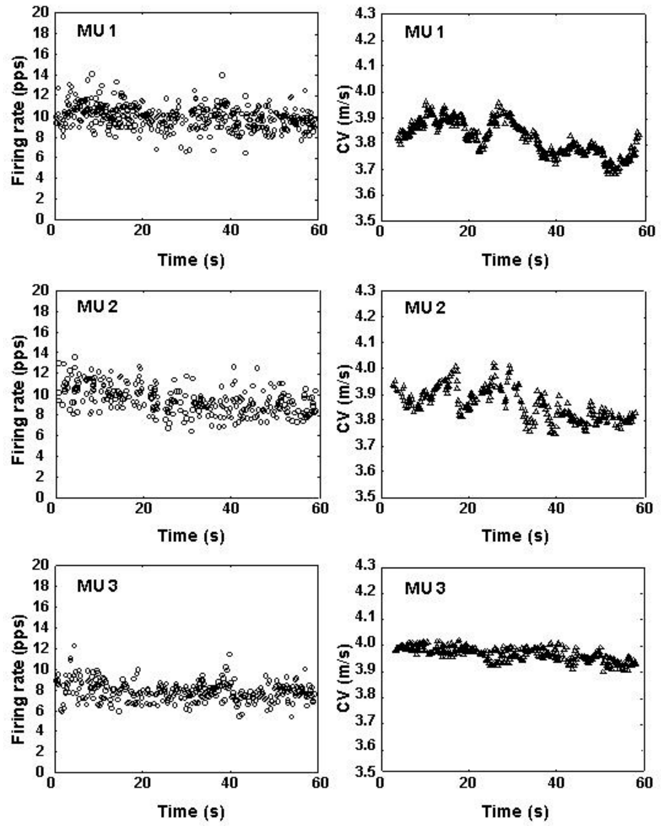

Fig. 3. Examples of instantaneous firing rate estimation and corresponding CV estimation over time for three MUs detected during voluntary activation of the tibialis anterior muscle in isometric conditions for one minute at 25 % MVC. The number of averages is 20 for the three MUs. Decrease of both firing rates (especially for MU 2) and CV is evident.

In this particular example, a variation of CV as small as about 0.1 m/s (decrease of about 2.5 % with respect to initial value) can be detected with the proposed technique.

Fig. 3 shows an example of fatigue analysis of three MUs detected from one of the subjects during the one minute contraction at 25% MVC of the tibialis anterior muscle. The estimated instantaneous firing rate of the MUs is also shown. Firing rates and CV of the single MUs are decreasing with time as a consequence of muscle fatigue.

TABLE I

MEAN AND STANDARD DEVIATION OF SINGLE MU CV INITIAL VALUES, SLOPES, CV STANDARD DEVIATION WITH RESPECT TO THE REGRESSION LINE (46 MUS) AND GLOBAL CV INITIAL VALUES AND SLOPES (11 SUBJECTS) OBTAINED BY TWO AND MULTI-CHANNEL TECHNIQUES FROM 60 AND 30 SECOND LONG CONTRACTIONS.

	60 second long contractions	**30 second long contractions**
Initial CV values (multi-channel), N = 46	4.11 ±0.30 m/s	4.13 ±0.36 m/s
Initial CV values (two channels), N = 46	4.12 ±0.72 m/s	4.13 ±0.75 m/s
CV standard deviation with respect to linear regression (multi-channel), N = 46	0.15 ±0.12 m/s	0.16 ±0.15 m/s
CV standard deviation with respect to linear regression (two channels), N = 46	0.37 ±0.24 m/s	0.38 ±0.30 m/s
Estimated CV slope (multi-channel), N = 46	-0.0032±0.0021 m/s^2	-0.0040±0.0062 m/s^2
Number of MUs for which fatigue is detected (multi-channel), N = 46	35/46	30/46
Number of MUs for which fatigue is detected (two channels), N = 46	33/46	19/46
Initial global CV values (two channels), N = 11	4.32 ±0.98 m/s	4.32 ±1.01 m/s
Estimated global CV slope (two channels), N=11	-0.0026±0.0025 m/s^2	-0.0020±0.0042 m/s^2
Number of subjects for which fatigue is detected by global CV (two channels), N = 11	9/11	5/11

Forty-six MUs have been simultaneously detected by means of intramuscular wires and surface array in 11 subjects. The mean firing rate of the detected MUs during the first 3 s of contraction was 12.7 ±1.7 pps (pps: pulses per second), thus the temporal resolution in CV estimation over time was in average around 1.6 s (corresponding to 20 averages). The number of channels selected by the automatic technique was between 4 and 8 (5.3 ±1.3 channels) depending on muscle fiber length. Mean results obtained from 46 detected MUs analysed over the entire contraction time (60 s) and the first half of the contraction time are shown (Tab. I). Mean CV initial values are not statistically different with two and multi-channel techniques but the standard deviation of initial CV values is less than an half when multi-channel techniques are used with respect to what obtained with two channel methods. The residual standard deviation with respect to the regression line was consistently lower when CV was computed using all suitable channels with respect to the two-channel estimations. In case of 60 second contractions, the number of MUs for which fatigue could be detected (slope of the regression line statistically different from zero and negative) was almost the same for multi-channel and two channel estimation. However, if only the first 30 s of each 60 s contraction were considered, fatigue could still be detected in 30 MUs out of 46 using multi-channel estimation and in only 19 MUs out of 46 using two channel estimation.

IV. Discussion

The method proposed is derived from the combined use of techniques developed previously. The detection of the surface EMG signal with linear electrode arrays has been used for more than 15 years [8] and refined in more recent years [4][6][11]. Spike triggered averaging is a well known method and has been applied for single MU force twitch estimation and surface potential amplitude estimation [13]. The main contribution of the present work is to adapt these techniques for the development of an advanced spike triggered averaging method with important improvements in performance with respect to traditional techniques. The results shown demonstrated that CV changes of single MUs during voluntary contractions can be reliably detected with high temporal resolution. Moreover, no statistical difference between CV estimations performed with multi and two channel based techniques was found, indicating that the bias in CV estimation was not different (end of fiber and IZ effects do not have different effects on multi and two channel techniques) and that only variance decreased. It should be noted that the comparison between the two-channel and the multi-channel based methods has been performed in optimal conditions for the two-channel methods. EMG signals were in fact collected with linear arrays, with the possibility of assessing MU structural properties and of selecting the best alignment of the recording electrodes with the muscle fibers. Thus it is likely that the performance which would be achieved with the use of only two couples of recording electrodes would be worse than that reported here for two-channel methods.

V. Conclusions

A method for the analysis of single MU control and conduction properties has been described in this paper. It represents a consistent improvement with respect to previously applied spike triggered averaging techniques. The elements of novelty with respect to previous studies are: 1) the simultaneous detection of iEMG and sEMG signals from the same MUs in the two directions of propagation after estimating anatomical landmarks of the MUs on the skin with the surface array technique, 2) the estimation of CV of the single MUs by multi-channel methods allowing to consistently decrease the variance of estimation, and 3) the application of the spike-triggered averaging technique of the surface EMG signal to assess muscle fatigue of individual MUs. It has been shown that changes in CV of single MUs as small as 0.1 m/s can be reliably detected by a limited number of averages, thus allowing good temporal resolution (1-2 s).

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