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Novel Cross Correlation Technique Allows Crosstalk Resistant Reflex Detection from Surface EMG

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Abstract— **Existing methods for withdrawal reflex detection from surface electromyography (sEMG) do not consider the potential presence of electrical crosstalk, which in practical applications may entail reduced detection accuracy. This study estimated muscle fiber conduction velocities (CV) for the tibialis anterior (TA) and soleus (SOL) muscles of both genuine reflexes and identified crosstalk, measured during antagonistic reflex responses. These estimations were used to develop and assess a novel method for reflex detection resistant to crosstalk. Cross correlations of two single differential (SD) sEMG signals recorded along the muscle fibers were performed and two features were extracted from the resulting correlograms (average CV and maximal cross correlation). Reflex detection based on evaluation of the extracted features was compared to a conventional reflex detection method (thresholding of interval peak z-scores), applied on both SD and double differential (DD) sEMG. Intramuscular electromyography (iEMG) was used as validation for reflex detection. Apparent CV due to electrical crosstalk alone were more than one order of magnitude higher than CV estimated for genuine reflexes. Conventional reflex detection showed excellent sensitivity but poor specificity (0.19-0.76) due to the presence of crosstalk. In contrast, cross correlation analysis allowed reflex detection with significantly improved specificity (0.91-0.97). The developed methodology may be readily implemented for more reliable reflex detection.**

I. INTRODUCTION

The nociceptive withdrawal reflex is considered a reliable and objective tool in pain assessment [1]. It is a polysynaptic spinal reflex involving complex muscle synergies. However, most methodologies for assessment of human withdrawal reflexes in the study of pain mechanisms consider only one muscle using standard surface electromyography (sEMG), ignoring the possible interference of electrical crosstalk from adjacent muscles.

Crosstalk caused by signal propagation through the volume conductor is one of the main issues of sEMG and several methods have been proposed to reduce these misleading signal components [2, 3]. It is mainly due to signals generated by the extinction of the intracellular action potential at the fiber endings and may very well, despite the low-pass filtering effect of the tissues, contain high frequency components, rendering high-pass filtering an ineffective method for crosstalk reduction [4, 5]. Moreover, signals detected close to and far from the same active muscle may be poorly correlated. Thus, methods for estimation of crosstalk based on the cross correlation between signals remote from the active muscle and signals detected over the active muscle are not useful [2]. The amount of crosstalk depends on the detection system used; however the use of spatial filtering should be applied with care due the dominance of non-propagating signal components in crosstalk [2, 3]. Unlike crosstalk, the main components of signals generated by superficial motor units with long muscle fibers are propagating waves [2].

This study investigated whether estimations of muscle fiber conduction velocity (CV) reflect the propagating and non-propagating nature of genuine reflexes and crosstalk respectively. A simple estimation of CV was performed based on conveniently recorded standard sEMG whereas an elaborate technique involving multi-channel array sEMG were used for validation. The obtained CV data were utilized to develop a novel methodology for robust reflex detection which was evaluated using intramuscular electromyography (iEMG) for validation of genuine reflex activity.

II. MATERIALS AND METHODS

A. *Materials*

Fifteen male volunteers (mean age 24.4 years, range 19-28 years) participated in the study. Written informed consent was obtained from all subjects prior to participation and the Declaration of Helsinki was respected. The study was approved by the local ethical committee.

B. *Electrical stimulation*

Two surface stimulation electrodes (20 x 15 mm, type 700, Ambu, Denmark) were mounted on the sole of the foot to elicit reflexes in the tibialis anterior (TA) muscle and the soleus (SOL) muscle respectively, as seen in fig. 1. One large common anode (100 x 140 mm, Pals, Axelgaard, USA) was placed on the dorsum of the foot. Each stimulus consisted of a constant current pulse train of five individual 1

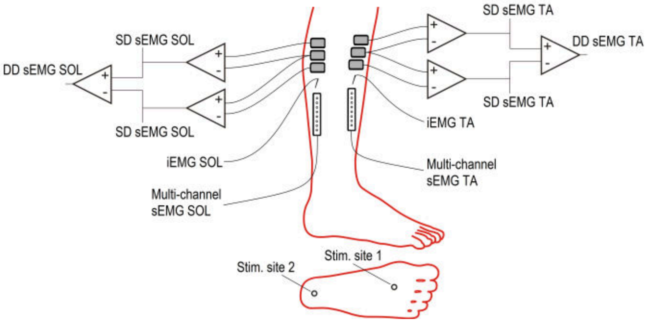

Fig. 1: Experimental setup. Various types of EMG were measured from TA and SOL during reflexes elicited by electrical stimulation of two sites under the sole of the foot.

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ms pulses delivered at 200 Hz by a computer controlled electrical stimulator (Noxitest IES 230, Aalborg, Denmark). The stimulation intensity was set as 1.2-1.5 times the initial reflex threshold for each electrode. The two stimulation sites were stimulated in a random sequence with an interstimulus interval between 10 and 15 s until ten unambiguous reflexes had been recorded from both TA and SOL (see identification criteria below). If a reflex were not elicited by three consecutive stimulations of one site, the reflex threshold for that stimulation site was re-evaluated.

C. *EMG recordings*

Activity in the ipsilateral TA and SOL was measured using single-channel and multi-channel sEMG and also iEMG, see fig. 1 for complete setup.

1) Single-channel sEMG

Three standard surface electrodes (type 720, Ambu, Denmark) were placed in parallel along the main fiber orientation of each of the two muscles with an interelectrode distance (IED) of 2 cm. A common reference electrode (Pals, Axelgaard, USA) was placed on the ipsilateral knee. The tri-polar electrode configuration fed three separate amplifiers for simultaneous recording of two single-differential (SD) and one double differential (DD) sEMG signal from each of the two muscles, see fig. 1. The signals were amplified, filtered (5-500 Hz), sampled (2 kHz) and stored (1 s window including 200 ms pre-stimulation).

2) Multi-channel sEMG

Multi-channel sEMG signals were detected with two linear adhesive arrays (type ELSCH008, Spes Medica, Italy) each consisting of eight electrodes with 5 mm IED in bipolar configuration. The adhesive arrays were placed along the main orientation of the muscles just proximal to the distal tendon. The signals were amplified (EMG-USB2, OT Bioelettronica, Torino, Italy), filtered (10–500 Hz) and sampled at 10 kHz.

3) iEMG

iEMG signals were recorded using custom-made wire electrodes with 5 mm un-insulated tips in bipolar configuration. The signals were amplified (EMGUSB2, OT Bioelettronica, Torino, Italy), filtered (10–500 Hz) and sampled at 10 kHz.

D. *Experimental procedure*

Thick epidermal layers on the sole of the foot were ground off using a callus remover. The subject was sitting relaxed on a chair with the hip, knee and ankle flexed 90 degrees. The subject was thoroughly familiarized with electrical stimulation before the reflex threshold for each of the two stimulation sites was identified as the lowest intensity eliciting at least two reflexes in three consecutive stimulations of each site.

E. *Data analysis*

1) Identification of genuine reflexes

During data acquisition, the recorded signals were visually examined for online identification of reflexes using a set of fixed criteria: A reflex was identified if at least one sizable difference peak occurred in the reflex window, relative to baseline, but not if activity in the reflex window mimicked baseline [6, 9]. The reflex window was defined as the 80-150 ms post-stimulus window. Additional criteria were enforced post acquisition to ensure a homogenous dataset, consisting of sweeps containing a genuine reflex in only one of the two antagonistic muscles for data analysis: *Inclusion*: Reflex identified in all sEMG recordings and a simultaneous reflecting burst of iEMG activity recorded from the same muscle (any concurrent sEMG activity measured over the antagonistic muscle was considered crosstalk.) *Exclusion: (1)* EMG activity in a 200 ms pre-stimulus window. *(2)* sEMG activity not synchronized with iEMG recordings from one of the two muscles. *(3)* iEMG activity in both muscles inside the reflex window. One subject with less than five identified genuine reflexes in each of the two muscles was excluded from the data analysis.

2) Estimation of muscle fiber conduction velocity

Muscle fiber CV was estimated from all multi-channel sEMG recordings with a signal-to-noise ratio (SNR) larger than 7 dB using a maximum likelihood estimator, previously described in [7]. The estimations were based on three to seven channels determined by visual inspection of the signals to avoid disruptive effects of innervation zones. Additionally, a simpler estimation of the muscle fiber CV was performed based on the sEMG signals recorded with tri-polar configurations of standard single-channel sEMG electrodes. The SD signals recorded with single-channel electrodes from all retained sweeps were interpolated to 10 kHz using an antialiasing low-pass finite impulse response filter implemented in Matlab (MathWorks, USA). For each muscle the cross correlation between the proximal and distal SD sEMG signals were calculated and the conduction time (CT) between the two electrode pairs was estimated as the temporal displacement of the peak in the cross correlogram. Average CV was calculated as the IED divided by the estimated CT. Accurate estimation of average CV requires undistorted travel of the signals along the muscle fibers. While this is not always the case in practice due to the finite length of fibers, violations are particularly prone to occur for signal components with long wavelengths relative to the actual length of the muscle fibers [8]. Hence, prior to estimation of CV (and additional feature extraction), the SD sEMG recorded using single-channel electrodes over TA and SOL were high-pass filtered with cut-off frequencies of 80 Hz and 100 Hz respectively.

3) Conventional reflex detection

The SD and DD sEMG signals recorded with standard single-channel electrodes were rectified and their interval peak z-score [6] was calculated as

$$z = (A_{\max} - \mu_{\text{baseline}}) / \sigma_{\text{baseline}}. \qquad (1)$$

$A_{\max}$ is the maximal amplitude measured inside the reflex window whereas μ_{baseline} and σ_{baseline} denotes the mean and standard deviation respectively of a 70 ms pre-stimulus baseline interval. The literature suggests that signals with an interval peak z-score larger than 12 are regarded as a reflex [9].

4) *Cross correlation based reflex detection*

This novel method for reflex detection involved analysis of cross correlations between the two SD sEMG signals recorded over each muscle and evaluation of features extracted from the resulting correlograms. The cross correlations were normalized by the product of the norm of each of the two SD sEMG signals.

A reflex was detected if (1) the CV estimated from the relevant cross correlation was below a fixed threshold specific for each muscle or if (2) the maximal value of the normalized cross correlation was lower than another fixed muscle specific threshold. The thresholds for CV and maximal correlation were identified by simultaneous optimization of both sensitivity (the ability to detect genuine reflexes) and specificity (the ability to not detect crosstalk as genuine reflexes) based on pooled data from all sweeps – i.e. maximization of the intersection of the sensitivity and specificity planes, see fig. 2. If either of the two SD signals had an interval peak z-score below 12, no CV was estimated and the presence of a genuine reflex was rejected. Finally, a reflex was excluded if the corresponding DD signal had an interval peak z-score smaller than 12.

5) *Comparison of methods for reflex detection*

The presented novel cross correlation analysis (XCORR) was compared to conventional reflex detection by evaluation of sensitivity and specificity calculated for each subject individually and for pooled data from all sweeps.

6) *Statistics*

Mann-Whitney U test was used for comparison of CV whereas Friedman test was used for paired comparison of both sensitivity and specificity of methods for reflex detection. Student Newman Keuls test was used for post hoc analysis. $P<0.05$ was considered statistical significant. Results are presented as mean ± standard error of the mean when the underlying data were normal distributed or alternatively as median (lower quartile, upper quartile).

III. RESULTS

The mean number of genuine reflexes identified in each subject in TA and SOL was 22.0 (range 5-36) and 12.9 (range 5-23), respectively.

A. *Muscle fiber conduction velocity*

Due to high selectivity of the multi-channel array electrodes, only 7 and 36 cases of crosstalk (in 308 and 181 recorded reflexes) with a SNR larger than 7 dB were measured over TA and SOL, respectively. However, CV estimated from both multi-channel sEMG and sEMG recorded using tri-polar configurations of single-channel electrodes clearly demonstrated that crosstalk was associated with significant higher estimations of muscle fiber CV than genuine reflexes for both muscles, see table I and II.

B. *Reflex detection*

The thresholds for CV and maximal cross correlation for each muscle are displayed in table III and marked on plots of sensitivity and specificity in fig. 2. Despite the visual complexity, the plots may be consulted for guidance to determine thresholds for future applications where sensitivity and specificity are not equally weighted. The plots of sensitivity and specificity furthermore illustrate how muscle fiber CV has a remarkable discriminative power. Evaluation of CV alone (intersection with the CV-axis in fig. 2) allows a joint value of sensitivity and probability of 0.90 for both TA and SOL. However, especially for TA the introduction of an additional feature (maximal cross correlation) entails a

TABLE I. CV ESTIMATED FROM MULTI-CHANNEL SEMG USING A MAXIMUM LIKELIHOOD ESTIMATOR.

CV [m/s]	**Reflex:**	**Crosstalk:**
TA:	6.0 (5.0,7.1)	168.7 (93.0,198.3)
SOL:	7.8 (6.8,9.9)	90.1 (53.6,146.5)

TABLE II. CV ESTIMATED FROM TWO SD SEMG RECORDINGS USING A CROSS CORRELATION TECHNIQUE.

CV [m/s]	**Reflex:**	**Crosstalk:**
TA:	5.3 (2.8,14.3)	66.7 (50.0,100.0)
SOL:	8.7 (4.2,40.0)	200.0 (100.0,200.0)

TABLE III. IDENTIFIED THRESHOLDS FOR CV AND MAXIMAL CROSS CORRELATION.

Threshold	**CV:**	**Max correlation:**
TA:	34 [m/s]	0.80
SOL:	68 [m/s]	0.82

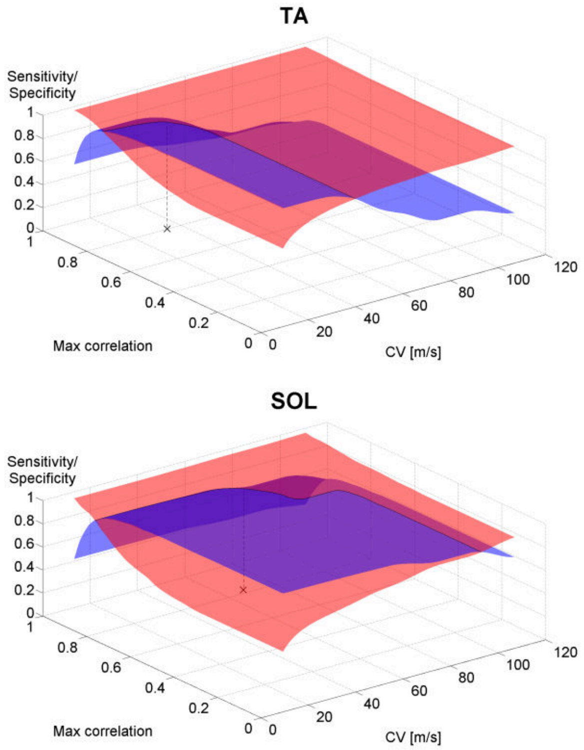

Fig. 2: Plot of sensitivity (red/light) and specificity (blue/dark) for reflex detection based on evaluation of muscle fiber CV and maximal cross correlation estimated from sEMG recorded over TA (top) and SOL (bottom) respectively. The black cross indicates the identified thresholds (see table III for numerical values) entailing a joint value for sensitivity and specificity of 0.96 and 0.91 for TA and SOL respectively.

considerable increase in joint sensitivity and probability to 0.96 and 0.91 for TA and SOL respectively.

Conventional reflex detection resulted in a significantly higher specificity when performed on DD sEMG compared to SD sEMG. However, reflex detection based on evaluation of cross correlations caused a significant increase in specificity compared to conventional reflex detection performed on both SD and DD sEMG signals, see fig. 3 and table IV. No statistical differences could be found regarding the sensitivity of the three detection methods.

IV. DISCUSSION

A novel methodology for accurate and reliable reflex detection resistant to electrical crosstalk has been developed. It may be viewed as binary digital filtering following conventional reflex detection, in order to assess whether a detected reflex indeed is a genuine reflex or merely the result of crosstalk. The basis of evaluation is the composition of propagating and non-propagating signal components which is linked to the estimation of muscle fiber CV.

This study has clearly demonstrated that significantly different CV may be estimated during genuine reflexes and crosstalk, respectively. The apparent CV estimated for crosstalk are unreasonable high from a physiological perspective, reflecting that the main components of the signals are not propagating at all but are observed roughly simultaneously at the two adjacent recording sites. These results confirm the findings of [5] that sEMG signals recorded directly over a single activated muscle have a composition of propagating and non-propagating signal components characteristically different from crosstalk. A property of great applicability, considering the straightforward assessment methodology described in this paper using standard sEMG equipment.

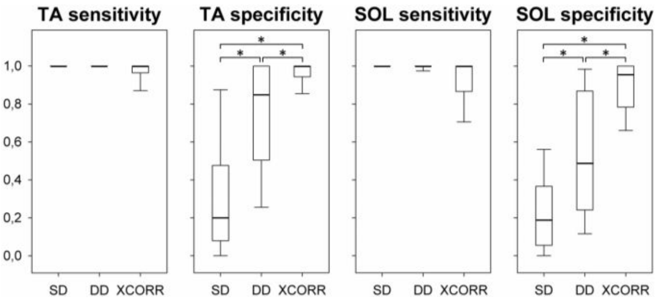

Fig. 3: Box-plot of sensitivity and specificity of reflex detection applying the various methods calculated for each individual subject for both TA and SOL. Asterisks indicate significant post hoc pairwise comparisons.

TABLE IV. SENSITIVITY AND SPECIFICITY CALCULATED FOR POOLED DATA (NO DISTINCTION BETWEEN INDIVIDUAL SUBJECTS).

	SD:	**DD:**	**XCORR:**
TA sensitivity:	1.00	1.00	0.97
TA specificity:	0.31	0.76	0.97
SOL sensitivity:	1.00	0.99	0.92
SOL specificity:	0.19	0.54	0.91

The discrepancy in accuracy of reflex detection for TA and SOL does illustrate a muscle dependency of the presented methodology. Accurate and reliable estimation of CV allows evaluation of whether a signal is dominated by propagating or non-propagating signals components. For that reason, the methodology is best suited for long superficial muscles with parallel fibers, like TA, but even evaluation of a bi-pennate muscle with short non-parallel fibers like SOL allowed reflex detection with excellent accuracy. These results provide a proof of concept. However, since the algorithm relies primarily on the temporal displacement of the maximum cross correlation, further investigation is needed to evaluate the performance of the algorithm when applied on mixed signals (containing both crosstalk and genuine reflex activity).

The interval peak z-score has been demonstrated to enable highly accurate and reliable reflex detection [6, 9]. However, these assessments have been performed with no consideration of crosstalk. This study demonstrates that conventional reflex detection that considers all EMG activity inside the reflex interval to represent genuine reflexes may suffer a critically low specificity, especially when performed on SD sEMG (which is the common practice). The developed methodology hence constitutes an applicable tool for reflex detection with improved accuracy, which may possibly also be utilized for voluntary contractions to ensure a more reliable detection of genuine muscle activation e.g. during gait analysis, biofeedback therapy or prosthetic control.

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