Propagation velocity measurement: autocorrelation technique applied to the electromyogram

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Abstract—*Muscle fibre conduction velocity is an important measurement in electrophysiology, both in the research laboratory and in clinical practice. It is usually measured by placing electrodes spaced at known distances and estimating the transit time of the action potential. The problem, common to all methods, is the estimation of this time delay. Several measurement procedures, in the time and frequency domains, have been proposed. Time-domain strategies usually require two acquisition channels, whereas some frequency-domain methods can be implemented using a single one. The method described operates in the time domain, making use of the autocorrelation function of the difference signal obtained from two needle electrodes and only one acquisition channel. Experimental results were obtained from the electromyogram of two biceps muscles (two adult male subjects, nine records each) under voluntary contraction, yielding an average of 3.58 m s^{-1} (SD = 0.04 m s^{-1}) and 3.37 m s^{-1} (SD = 0.03 m s^{-1}), respectively. Several tests showed that the proposed method works properly with electromyogram records as short as 0.3 s.*

Keywords—*Correlation function, Muscle conduction velocity, Needle electromyography*

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1 Introduction

MEASUREMENT OF electrophysiological conduction velocity is based on the estimation of the time required for the action potential to traverse a known distance. Historically, it was first Herman von Helmholtz (GEDDES and HOFF, 1968), in 1850, and, in about 1928, Erlanger and Gasser (ERLANGER and GASSER, 1937), both Nobel laureates, who accurately and very ingeniously measured conduction delays and thus velocities (in nerve). This was a direct approach, applied many times by different investigators in other tissues (such as, for example, the heart or skeletal muscle). Electromyogram (EMG) analysis, in turn, as a much wider subject, is an important research subject nowadays, as demonstrated by recent studies (HARBA and TENG, 1999; PATTICHIS *et al.*, 1999).

A well-known method to estimate transit time makes use of the cross-correlation function between two signals picked up along the propagation path (ZORN and NAEIJE, 1983). It is simple and works well with short data records, but two acquisition channels are usually needed.

Some frequency-domain methods, on the other hand, allow the measurement of the time delay using a single acquisition channel. These methods usually involve strong computational demands and require large numbers of data (PARKER *et al.*, 1977; VICAR and PARKER, 1988).

We show here that, under certain conditions, the autocorrelation function of a bipolar signal provides the same information as cross-correlation. The proposed method requires only one acquisition channel and preserves the characteristics of time-domain methods, such as low computational complexity and proper operation even with short data records.

2 Proposed method

The proposed method operates on the differential signal obtained between two electrodes placed along the propagation path. This bipolar signal can be described by

$$S(t) = Y(t) - Z(t) \tag{1}$$

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where $Y(t)$ and $Z(t)$ are monopolar signals picked up at each electrode location. Its autocorrelation function $\phi_{SS}(\tau)$ is given by

$$\phi_{SS}(\tau) = E\{S(t)S(t+\tau)\} \tag{2}$$

When eqn 1 is applied, this becomes

$$\phi_{SS}(\tau) = E\{(Y(t) - Z(t))(Y(t+\tau) - Z(t+\tau))\} \tag{3}$$

where E stands for the statistical expected value. This autocorrelation function can be expressed in terms of the statistics of $Y(t)$ and $Z(t)$, that is, as

$$\phi_{SS}(\tau) = \phi_{YY}(\tau) + \phi_{ZZ}(\tau) - \phi_{YZ}(\tau) - \phi_{YZ}(-\tau) \tag{4}$$

where $\phi_{YY}(\tau)$ and $\phi_{ZZ}(\tau)$ are the autocorrelation functions of the monopolar signals, and $\phi_{YZ}(\tau)$ represents their cross-correlation function.

Function $\phi_{YZ}(\tau)$ reaches its maximum when the time shift τ equals the transit time Δ. If this delay is large enough, such that the autocorrelation functions $\phi_{YY}(\tau)$ and $\phi_{ZZ}(\tau)$ almost vanish (Fig. 1), it can be seen that

$$\phi_{SS}(\tau) \cong -\phi_{YZ}(\tau) \quad \text{when } \tau \cong \Delta \tag{5}$$

Under the above conditions, finding the $\phi_{YZ}(\tau)$ maximum (cross-correlation method) is equivalent to finding the $\phi_{SS}(\tau)$ minimum. Thus the minimum of $\phi_{SS}(\tau)$ occurs close to $\tau = \Delta$, which becomes the key property for the proposed method. To find out how large the time delay Δ must be to ensure the condition of eqn 5, a specific signal model is needed. In the following Section, we analyse the case of needle electromyography.

3 Application to muscular action potential propagation delays

An expression for the autocorrelation function $\phi_{SS}(\tau)$ of $S(t)$ for EMG signals was derived by PARKER and SCOTT (1973). This analytical expression, which is simple and shows good agreement with experimental data, is given by

$$\phi_{SS}(\tau) = k_1\phi(\tau) + k_2[\phi(\tau+\Delta) - \phi(\tau-\Delta)] \tag{6}$$

where the parameters k_1 and k_2 depend on the statistics of the myoelectric signal and can be determined from experimental data. The function $\phi(\tau)$ corresponds to the autocorrelation function of an assumed 'average action potential' $p(t)$.

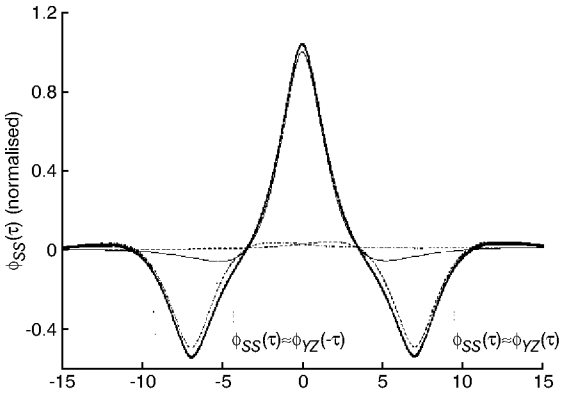

Fig. 1 *Autocorrelation function of bipolar signal $S(t) = Y(r) - Z(t)$ for time delay $\Delta = 7$ ms. Note that, if $\phi_{YY}(\tau)$ and $\phi_{ZZ}(\tau)$ become small enough around $\tau = \Delta$, $\phi_{SS}(\tau)$ is given, approximately, by $-\phi_{YZ}(\tau)$*

In this paper, expr. 7, similar to the expression proposed by PARKER and SCOTT (1973), has been adopted for $p(t)$, where c_0, c_1, and c_2 are constants that must be obtained from experimental data

$$p(t) = \begin{cases} t(c_1 - c_0 t)\exp(-c_2 t) & t \geqslant 0 \\ 0 & t < 0 \end{cases} \tag{7}$$

It was found, from fittings between experimental and theoretical autocorrelation functions $\phi_{SS}(\tau)$, that values of $c_0 = 750\,\text{V s}^{-2}$, $c_1 = 3.5\,\text{V s}^{-1}$ and $c_2 = 750\,\text{s}^{-1}$ lead to good agreement. They correspond to EMG signals detected by needle electrodes (0.3 mm diameter) inserted in the *biceps brachii*.

The average action potential $p(t)$ is a deterministic signal, and thus its autocorrelation function $\phi(\tau)$ is given by

$$\phi(\tau) = \int_{-\infty}^{\infty} p(t)p(t+\tau)dt \tag{8}$$

If we replace eqn 7 in eqn 8 and solve the integral, an analytical expression of $\phi(\tau)$ can be obtained, i.e.

$$\phi(\tau) = e^{-c_0|\tau|}\frac{1}{4}\left[\frac{1}{c_0^3}(3 - 3c_1 + c_1^2) + \frac{|\tau|}{c_0^2}(3 - 3c_1 + c_1^2) - \frac{\tau^2}{c_0}(c_1 - 1)\right] \tag{9}$$

Fig. 2 shows the agreement of two autocorrelation functions experimentally obtained in our laboratory from a *biceps brachii* EMG using a 3 s record and that predicted by eqn 6. One record was obtained at light contraction ($c_0 = 750\,\text{V s}^{-2}$,

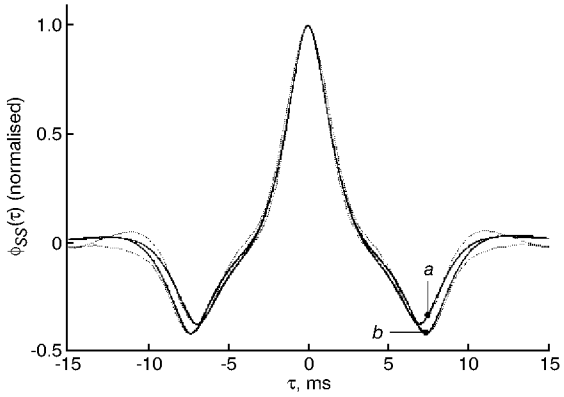

Fig. 2 *Comparison between autocorrelation functions (——) calculated by eqn 6 and (····) from experimental data. (a) Subject 1; low contraction level; $k_1 = 1$; $k_2 = 0.35$; $\Delta = 7$ ms. (b) Subject 2; moderate contraction level; $k_1 = 1$; $k_2 = 0.40$; $\Delta = 7.4$ ms*

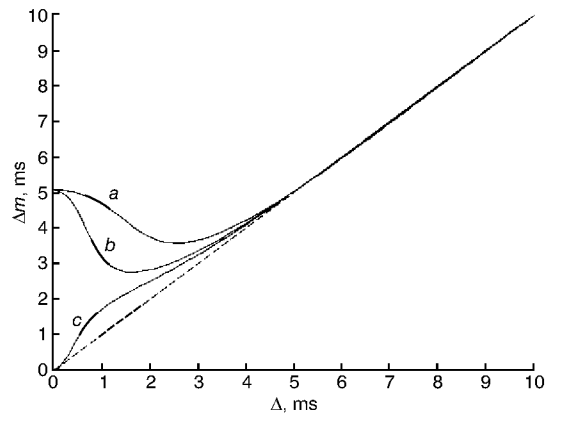

Fig. 3 *Relationship between time delay Δm estimated from minimum of $\phi_{SS}(\tau)$ and true delay time Δ at three different k_2/k_1 values. (a) $k_2/k_1 = 0.2$; (b) $k_2/k_1 = 0.4$; (c) $k_2/k_1 = 0.5$*

Table 1 Time delay and propagation velocity measurements obtained with three methods from EMG records of 1 s duration (see text for details)

	Subject 1		Subject 2	
Method	delay ± SD, ms	velocity ± SD, m s^{-1}	delay ± SD, ms	velocity ± SD, m s^{-1}
Cross-correlation	7.46 ± 0.16	3.39 ± 0.08	7.49 ± 0.12	3.34 ± 0.06
Spectrum dip	7.05 ± 0.32	3.57 ± 0.16	7.20 ± 0.20	3.47 ± 0.10
Autocorrelation	6.98 ± 0.08	3.58 ± 0.04	7.38 ± 0.06	3.37 ± 0.03

$c_1 = 3.5\,\mathrm{V\,s^{-1}}$, $c_2 = 750\,\mathrm{s^{-1}}$, $k_1 = 1$, $k_2 = 0.35$, $\Delta = 7$ ms) from one subject, and the other was obtained at moderate contraction and from another subject ($c_0 = 750\,\mathrm{V\,s^{-2}}$, $c_1 = 3.5\,\mathrm{V\,s^{-1}}$, $c_2 = 750\,\mathrm{s^{-1}}$, $k_1 = 1$, $k_2 = 0.4$, $\Delta = 7.4$ ms). More examples of this kind of agreement can be found in PARKER *et al.* (1977).

From eqn 6, using the expression of $\phi(\tau)$ given by eqn 9, the relationship between the τ value for which $\phi_{SS}(\tau)$ reaches its minimum (noted as Δm) and the true time delay Δ was found. The results, numerically obtained, are shown in Fig. 3. For time delays Δ longer than 4.5 ms, deviations from the 1 : 1 straight-line relationship are smaller than 2%.

Using a distance D between electrodes of 25 mm and assuming a maximum expected velocity of 6 m s^{-1}, a minimum delay of 4.2 ms results, and the error is less than 2.5% (a reasonable value considering the usual error in length determinations). This was the electrode separation used for the measurements in this paper.

4 Validation of the method

To validate the method, an experimental set-up was designed for comparison of the proposed method results with those obtained from two other accepted ones: the cross-correlation method (ZORN and NAEIJE, 1983) and the spectrum dip method (VICAR and PARKER, 1988). A needle electrode set (Fig. 4) was prepared to implement simultaneously the three methods. Three signals were acquired: $X_1(t)$, $X_2(t)$, transversal to the propagation path, for the cross-correlation method according to ZORN and NAEIJE (1983), and $S(t)$ along the propagation path, for the spectrum dip and for the proposed method. Signals were picked up using acupuncture needles of 0.3 × 30 mm, and amplification and data acquisition were carried out with a system* that includes a general-purpose differential amplifier†. Sampling was performed at a rate of 5000 samples s^{-1}, taking records of 1 s duration. The amplifier was AC coupled to remove DC components.

Transit time was estimated from $X_1(t)$ and $X_2(t)$ by means of the standard cross-correlation technique (ZORN and NAEIJE, 1983) and also from $S(t)$ using the spectrum dip method. The latter is based on the fact that there are 'nulls' or dips at the frequencies $f_d = k/\Delta$, where k is an integer number. This is because $S(t)$ contains the difference between two signals, one of which is a delayed version of the other (VICAR and PARKER, 1988; LINDSTRÖM and MAGNUSSON, 1977). The spectral density of the experimental data was calculated by the Welch procedure, using segments of 1024 samples (204 ms) and an overlap of 50% (SCHWARTZ and SHAW, 1975).

To compare the measurements from the different methods, 18 EMG intramuscular records of 1 s length were obtained from the biceps of two male adults (nine per subject), using bare acupuncture needles. Subjects were asked to contract the muscles lightly. Table 1 shows the time delay and propagation velocity obtained with the three methods. There is good agreement between them.

Fig. 5 illustrates the cross-correlation function between the transversal signals $X_1(t)$ and $X_2(t)$, noted as $\phi_{X_1X_2}$, and the autocorrelation $\phi_{SS}(\tau)$ of the bipolar signal $S(t)$ obtained with only one pair of electrodes. It is seen how the maximum of $\phi_{X_1X_2}(\tau)$ agrees with the $\phi_{SS}(\tau)$ minimum.

Finally, Figs 6 and 7 show, respectively, the autocorrelation and the spectral density of the differential signal $S(t)$, taking record segments with lengths of 2.0, 1.0, 0.5 and 0.3 s, respectively. Although the spectrum histogram increases its variance for short record lengths, hindering dip estimation, the autocorrelation method still remains readable.

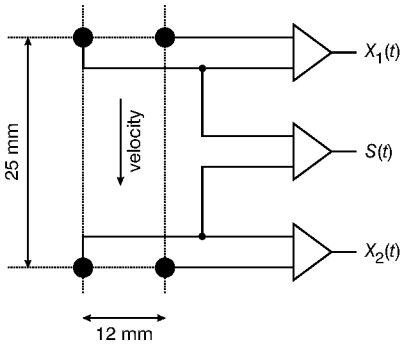

Fig. 4 *Basic experimental layout showing position of two electrode pairs and their connections to amplifiers. Observe that middle one gives off bipolar signal S(t)*

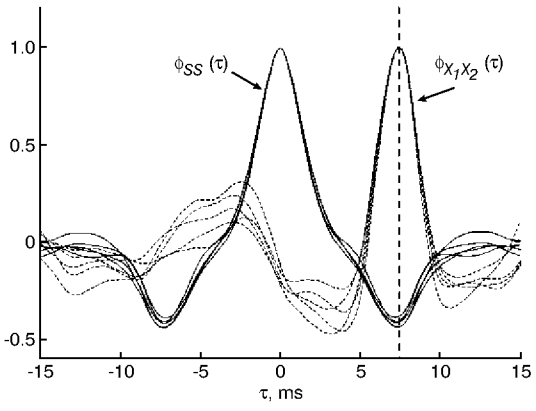

Fig. 5 *Autocorrelation function of bipolar signal S(t) and cross-correlation function between transversal signals $X_1(t)$ and $X_2(t)$. Note that minimum of $\phi_{SS}(\tau)$ is very close to $\phi_{X_1X_2}(\tau)$ maximum. These results correspond to records from subject 2*

* BIOPAC
† Series 100A

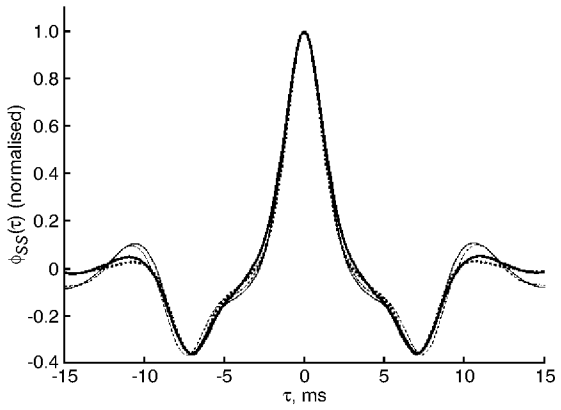

Fig. 6 *Autocorrelation function $\phi_{SS}(\tau)$ for different data record lengths: (——) $L = 2.0\,s$; (——) $L = 1.0\,s$; (–·–·) $L = 0.5\,s$; (– – –) $L = 0.3\,s$*

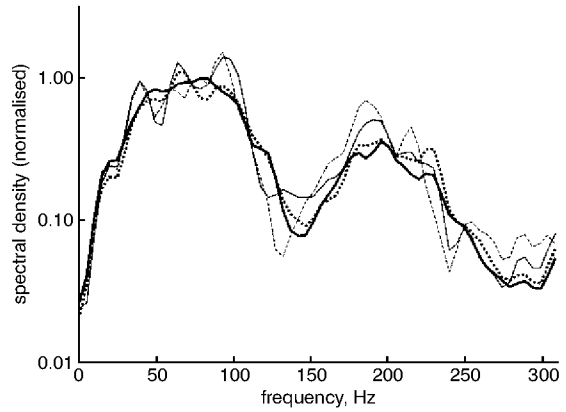

Fig. 7 *Spectrum of EMG bipolar signal S(t) for various record lengths. Interval between dips is related to transit time. Spectrum's variance increases as record length decreases, hindering determination of dips. (——) $L = 2.0\,s$; (——) $L = 1.0\,s$; (–·–·) $L = 0.5\,s$; (– – –) $L = 0.3\,s$*

5 Discussion

The proposed method shares desirable properties with both time- and frequency-domain approaches. As with standard time-domain methods, it is computationally simple and efficient and it does not require long data records. As with frequency-domain strategies, only a pair of electrodes is needed. The method operates using physiological electromyographic activity (voluntary contractions of the subject) and thus it does not call for external stimulation. Avoiding long data records has the additional advantage of simplifying the stationarity requirement, which, in long data records, may not be easy to satisfy. The idea could be applied to other physiological variables where delays play a role.

Fibre-ending effects or other non-travelling components were not considered in this work. It is emphasised that the method supplies a first, easy to obtain, coarse approximation.

In conclusion, a method for the estimation of skeletal muscle electrical activity propagation velocity *in vivo* is described. It works in the time domain, uses a single EMG acquisition channel and requires a reduced number of data for each measurement. It was experimentally tested against a standard spectrum dip estimator and using a cross-correlation technique. The results confirm the feasibility of the proposed approach. It may find a place in clinical electromyography and also in other areas.

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