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Influence of Baseline Fluctuation Cancellation on Automatic Measurement of Motor Unit Action Potential Duration

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A significant difference between accuracy pre- and post-BLF removal was found in two CAMs; markers were closer to the GSP after BLF removal. For all MUAPs, the differences between WTM markers and the GSP were the smallest, and significant differences were not found for the WTM before and after BLF cancellation. The management of BLF is an important issue in EMG signal processing and BLF removal must be considered in extraction and analyse of MUAP waveforms. The BLF removal method improved the performance of two CAMs for MUAP duration measurement. The WTM was the most accurate and was not affected by BLF.

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Influence of Baseline Fluctuation Cancellation on Automatic Measurement of the Motor Unit Action Potential Duration

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Abstract

The aim of this work is to analyze the influence of a method for baseline fluctuation (BLF) cancellation for electromyographic (EMG) signals on automatic methods for measurement of the motor unit action potential (MUAP) duration. These methods include four conventional automatic methods (CAMs) and a recently published wavelet transform method (WTM). A set of 182 MUAPs from 170 EMG recordings were studied. The CAMs and the WTM were applied to the MUAPs before and after applying BLF cancellation to the recordings. A gold standard of duration marker positions (GSP) ws manually established. The accuracy of each algorithm was estimated as the dfference between its positions and the GSP. Accuracies were compared for the 5 methods and for each method before and after BLF cancellation. A significant difference between accuracy pre- and post-BLF removal was found in two CAMs; markers were closer to the GSP after BLF removal. For all MUAPs, the differences between WTM markers and the GSP were the smallest, and significant differences were not found for the WTM before and after BLF cancellation. The management of BLF is an important issue in EMG signal processing and BLF removal must be considered in extraction and analyse of MUAP waveforms. The BLF removal method improved the performance of two CAMs for MUAP duration measurement. The WTM was the most accurate and was not affected by BLF.

Key words: Motor unit action potential, Duration, Quantitative electromyography, Baseline cancellation, Wavelet transform

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1 Introduction

To delimit the motor unit action potential (MUAP) and thereby calculate the MUAP duration properly, it is necessary firstly to extract accurately the MUAP waveform and secondly to use specific criteria to place the start and end duration markers. The MUAP duration is thus obtained and several parameters measured within this duration can then be used to characterize the MUAP waveform and to differentiate between normal and pathological MUAPs (Stalberg et al., 1986; Zalewska and Hausmanowa-Petrusewicz, 2000). Manual placement of duration markers is subjective and usually shows low reliability (Stalberg et al., 1986; Nandedkar et al., 1988; Chu et al., 1993; Takehara et al., 2004a; Rodríguez et al., 2007a) and so automatic methods have been designed. After extracting the MUAP waveform and prior to measurement of the MUAP duration, the first step in conventional automatic methods (CAMs), is to estimate the baseline. Some CAMs consider the baseline as the electrical zero of the equipment or as the mean value of the samples within the first and last segments of the MUAP analysis window (Stalberg et al., 1986). In all these methods, the estimated baseline is a constant value. Relative to this baseline level, CAMs use amplitude and slope criteria to determine the position of duration markers (Stalberg et al., 1986). In ideal conditions the baseline would indeed be the electrical zero of the equipment. In a real recording environment, however, a low frequency baseline fluctuation (BLF) and discharges from other nearby motor units (i.e. secondary MUAPs) can be present in the electromyographic (EMG) signal. Such disturbances can disrupt the performance of a CAM and make manual correction necessary in many cases (Takehara et al., 2004b; Stalberg et al. 1995; Bischoff et al., 1994). In this study we use a recently published method designed for the optimum cancellation of BLF in EMG recordings (Rodríguez et al., 2006) and analyze its influence on the behavior of four well-known CAMs and a recent automatic duration methodology based on the discrete wavelet transform (Rodríguez et al., 2007b). To this aim, the CAMs and the wavelet transform based method are applied on MUAPs before and after BLF cancellation. To assess the accuracy of the five different duration estimation methods, a gold standard of duration marker positions (GSP) was obtained by a probabilistic method applied to the manual marker placements of two expert electromyographists (Rodríguez et al., 2007a).

2 Methods

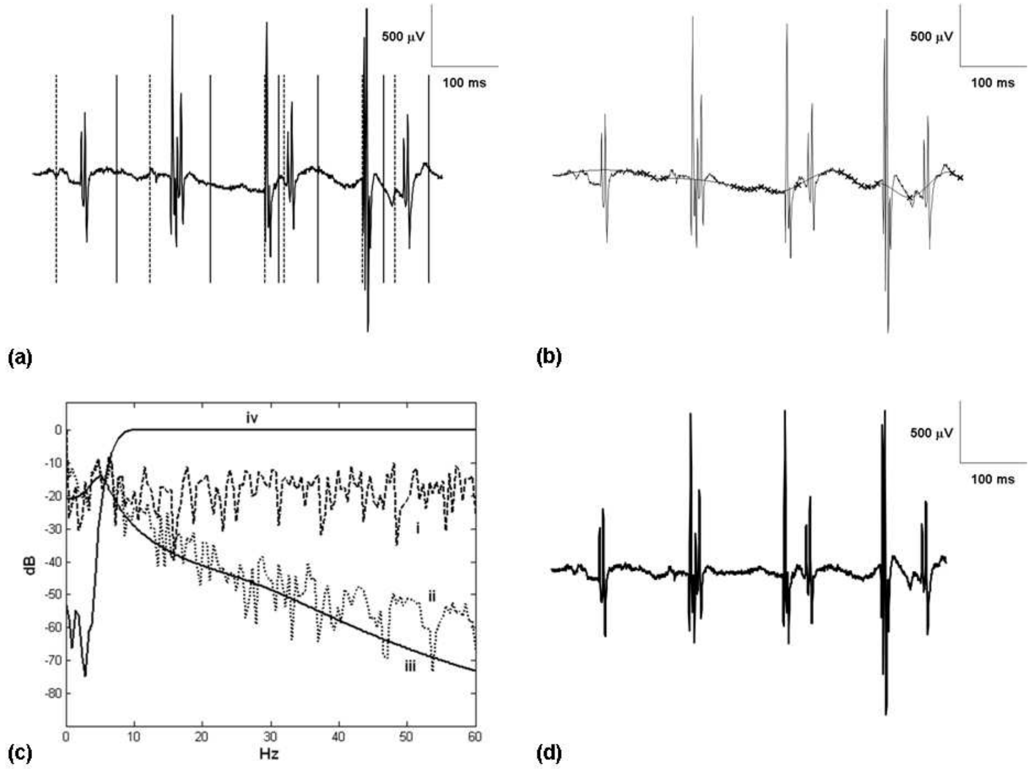
2.1 Subjects and MUAPs

We analyzed 170 continuous EMG signals of two seconds duration, recorded from two different muscles in ten healthy subjects: 60 signals from the first dorsal interosseous (FDI) of three subjects and 110 signals from the tibialis anterior (TA) of seven subjects. The raw EMG signals were recorded at low degrees of voluntary contraction, such us it is performed in currently clinical practice. Most of the recordings shows discharges from 2 or 3 active motor units, and therefore, from 1 to 3 MUAPs were manually extracted from each continuous signal. Recording equipment comprised an electromyograph (Counterpoint, Dantec Co., Denmark) and disposable concentric needle electrodes (type DCN37; diameter = 0.46 mm, recording area = 0.07 mm^2; Dantec). The acquisition bandpass filter had a bandwith from 2 Hz to 10 kHz, and the input signal was sampled at 25.6 kHz and quantized using 12 bits. Data were stored on a PC computer for off-line analysis using a software tool, developed in our laboratory, within the MatlabTM 7 environment (The Mathworks, Natick, MA, USA). We looked through each continuous EMG recording for epochs containing non-distorted discharges in the main spike of the MUAPs. These were manually selected and matched to their respective MUAPs using a home-made software tool to visualize the set of the extracted discharges of the same MUAP in raster and superimposed modes. For each MUAP, selected epochs were firstly aligned with respect to the maximal negative peak of the discharge, which we positioned 15 ms after the start of the 50 ms analysis window. Then, a correlation maximization algorithm for matching the MUAP discharges (Proakis and Manolakis, 1996; Campos et al., 2000) was applied with visual supervision of the waveform alignment. The MUAP waveform was finally obtained as the average of the samples of the aligned discharges. The number of discharges to find the average MUAP waveform ranged from 3 to 29 with mean of 5.0 and standard deviation of 3.4 discharges per MUAP. All of the MUAP waveforms accepted for subsequent studies were well-defined over baseline activity and had a rise-time ¡ 1 ms (in most cases ¡ 500 μs). On completion of this process, we had a total of 182 MUAPs, 115 from the TA and 67 from the FDI. These were the MUAPs analyzed in the rest of this study.

2.2 Baseline fluctuation (BLF) cancellation method

The BLF cancellation method used in this work makes use of several processing techniques applied sequentially. The approach is to estimate the spectral

Fig. 1. (a) EMG signal with detected MUAPs and segmentation. The start points of MUAP segments are marked with dashed vertical lines, and the end points are marked with continuous vertical lines. (b) EMG signal with MUAP-free segments averaged in 10 ms intervals (x) and BLF curve interpolated by cubic splines (continuous black line). (c) EMG signal spectrum (i), reconstructed baseline (cubic splines interpolation) spectrum (ii), AR model spectrum of the reconstructed baseline (iii), and frequency response of the high-pass filter used (iv). (d) Final BLF-removed signal.



content of the BLF, and then use this estimate to design a high-pass FIR filter to remove the BLF present in the signal, i.e. the residual BLF over the cut-off of the high-pass filter of signal acquisition (2 Hz for our recordings). The method is described in detail in Rodríguez et al. (2006). It comprises several phases, that are briefly described next and graphically represented in Fig. 1:

- MUAP detection and segmentation. In the continuous EMG signal, the segments containing MUAP discharges (MUAP segments) and MUAP-free segments are firstly detected and isolated. Segments with potentials (single or superimposed discharges) are detected using the DWT by regarding maxima and minima related to MUAP peaks in the EMG signal (Fig. 1.a).

- MUAP-free segments extraction. The MUAP-free segments are extracted and averaged in intervals of 10 ms to reduce the influence of high frequency noise and other possible artifacts (Fig. 1.b).

- - BLF estimation. A smooth estimation of the BLF is obtained by interpolating the resulting samples with cubic splines (Fig. 1.b).

- Spectral characterization. AR modeling is then applied to the interpolated curve to achieve a spectral characterization of the BLF (Fig. 1.c).

- FIR design. Finally, a high pass FIR filter with the 3-dB cut-off frequency from the AR model is designed (Fig. 1.c).

An EMG signal after applying the BLF removal method is shown in Fig. 1.d. The cut-off frequency obtained for the EMG signal in the figure was 6.5 Hz.

2.3 Determination of the gold standard of the duration marker positions (GSP)

Due to the variability in the manual placement of duration markers and the impossibility of determining which of the manual positions is the best, we designed a method to determine the “most likely” start and end points in a probabilistic manner. For the set of 182 MUAPs from the original recordings, two electromyographists (LG and one other) each made three independent measurements of the duration. To this end the electromyographists were provided with the averaged MUAP and the set of the extracted discharges in raster and superimposed modes. The duration markers were placed using a sensitivity of 100 μV/cm. From the six manually marked positions, the “most likely” position, our GSP, was obtained as the mean point of the three which were closest together (Fig. 2). This process is described in more detail in Rodríguez et al. (2007a).

2.4 Automatic methods for the measurement of MUAP duration

Five automatic methods for the measurement of MUAP duration were used: four well-known conventional ones (CAMs) and the new wavelet transform method (WTM).

2.4.1 Conventional automatic methods

The four CAMs assessed are described in Stalberg et al. (1986) and named the Turku method 1 (T1), the Turku method 2 (T2), the Uppsala method 2 (U2) and the Aalborg method (AM). We analyze these methods because they can be reproducible in accordance with the reported description. The algorithms for duration measurement implemented in the commercial equipments or those

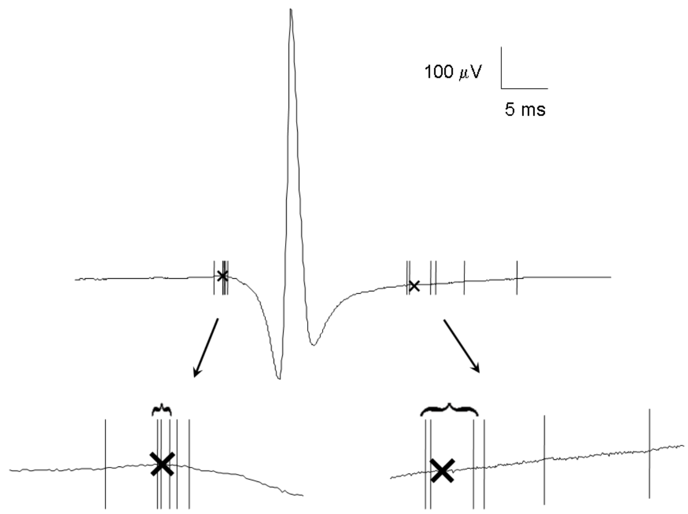


Fig. 2. Example of determination of the gold standard of duration marker positions from six manual marker positions of both start and end point (continuous vertical lines). The procedure sets the GSP (marked with a cross) as the mean position of the three manual marker positions which are closest together.

used in most of the published works are insufficiently described, as it also occurs with algorithms for automatic measurement of other MUAP parameters (Bromberg et al. 1999). The most recent reported algorithm by Nandedkar et al. (1995), which ultimately applies criteria of absolute values of amplitude for searching the start and end points, has not been analysed as the method used to estimate the baseline is not described. The most important differences among the assessed methods are:

- Related to the extraction process of the MUAP waveform. All of these methods measure the MUAP duration over a 40, 50 or 100 ms long analysis window. The main difference is how the MUAP waveform is extracted:

  · In T1 and T2, MUAPs are manually isolated with a trigger level and averaged 100 discharges to reduce the background noise.

  · In AM, MUAPs are automatically isolated with a software trigger level and classified by a template-matching method using the main spike of the potential. From each set of MUAPs, 3 most similar are selected to form the averaged waveform.

  · In U2, MUAPs are manually isolated using a trigger level and a delay line, and the MUAP waveform is obtained by averaging 20 to 200 discharges.

- Related to the criteria to find the MUAP start and end markers:

· T1 and T2 estimate the baseline as the average of samples at both 3 and 4 ms ends of the analysis window, while U2 and AM consider the baseline as the electrical zero.

· T1 and U2 begin their searches for the MUAP onset and offset from the start and from the end of the analysis window, respectively, while T2 and AM begin from a triggering point in the rising slope of the main spike.

As previously commented, the number of discharges manually selected per MUAP was from 3 to 29. Then the extraction process for all the methods could not be completely reproduced from our set of signals to average in some of them more than 100 MUAP discharges. Hence, the behaviour of these methods in this work might not have rendered the best results they are able to provide averaging a number of discharges.

2.4.2 Wavelet transform method (WTM) for measurement of MUAP duration

This method makes use of the discrete wavelet transform to detect the peaks related to the MUAPs and to detect the start and end points of these peaks. This algorithm uses several parameters whose values were fixed by applying genetic algorithms using 64 MUAPs (different from the accepted ones for analysis) from TA and FDI muscles recorded from the same equipment described in section 2.1. The WTM is described in detail in (Rodríguez et al., 2007b). The method comprises the following stages:

- Discrete wavelet transform. First, we apply the DWT with a quadratic spline wavelet (Mallat and Zhong, 1992) that has suitable properties for the task required and is similar to the MUAP waveform (Fig. 3.a).

- Scale selection. We select the maximum energy scale that represents the MUAP signal but excludes high frequency noise and low frequency interferences such as BLF. Different scales for determining the start and end points of MUAPs are selected in accordance with experimental results (Fig. 3.b).

- Determination of MUAP peaks in the selected DWT scale. We use criteria of threshold and slope and an analysis of the specific properties of the selected wavelet in order to find the maxima and minima related to the MUAP in the time domain(Fig. 3.c).

- Determination of MUAP start and end points. From the DWT peaks found in the previous step, a simple slope-based algorithm is applied to find the

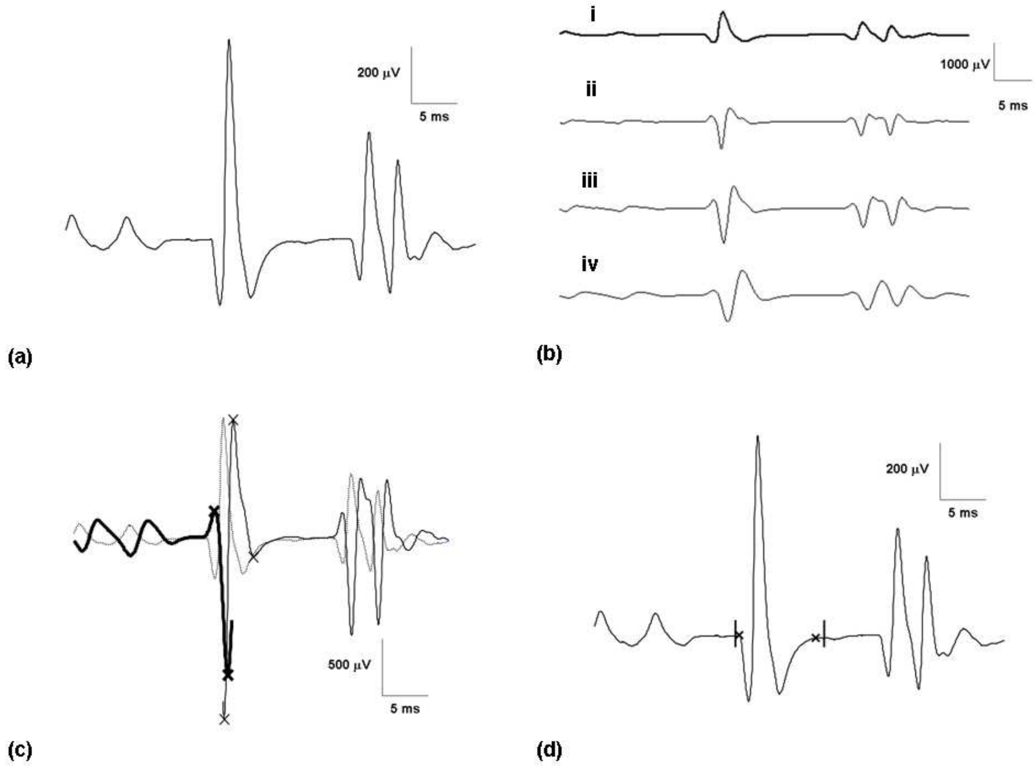


Fig. 3. (a) A 50 ms long epoch of the original EMG signal. (b) The MUAP (i) and the DWT at scales 4 (ii), 5 (iii) and 6 (iv). (c) MUAP time course (dashed black points) and selected wavelet scales for finding start (thick continuous line) and end (thin continuous line) points. Maxima and minima related to the MUAP for the start (thick crosses) and the end (thin crosses). (d) MUAP duration calculated. Onset and offset (vertical lines) are shown and also the GSP markers (crosses) for this MUAP.

MUAP duration (Fig. 3.d).

2.5 Assessment of the accuracy of the automatic measurements

To assess the accuracy of the 5 automatic methods, we calculated, for the start and end markers of our set of 182 MUAPs from both TA and FDI muscles, the mean differences between the automatic marker position and the GSP (i.e. the bias) and the standard deviation (SD) of such differences (i.e. the precision). In order to evaluate whether automatic measurements of MUAP duration depend on the estimate of the baseline, we analyzed the behaviour of the 5 algorithms before and after application of the BLF cancellation method previously presented in section 2.2. Several comparisons of the results of the automatic methods were made:

- Mean differences between the GSP and the start and end markers for each method before and after BLF removal were compared using the paired Student's t test.

- The biases (the mean differences between the start and end markers and the GSP) of the 5 methods were compared using a one-factor analysis of the variance (ANOVA) test.

- From the bias and the precision of each method, the estimated mean square error (EMSE) was calculated and used as the criterion for estimating their respective efficiency. The EMSE was calculated as:

$$\mathrm{EMSE} = \mathrm{mean}^2_{d,start\&end} + \mathrm{var}_{d,start\&end} \tag{1}$$

  with $\mathrm{mean}_{d,start\&end}$ and $\mathrm{var}_{d,start\&end}$ being the mean and the variance of the differences between the start and end marker positions of the method and the start and end marker positions of the GSP.

3 Results

The range of cut-off frequencies estimated for the BLF in the EMG signals after applying the BLF cancellation process were from 0.07 to 15.4 Hz, with mean 5.0 Hz and standard deviation of 3.2 Hz. In spite of using an acquisition high-pass filter of 2 Hz low frequency, its smooth transition band might have passed these BLF frequencies. Figure 4 shows a low activity EMG signal and the MUAP manually extracted before (Fig. 4.a and Fig. 4.c) and after (Fig. 4.b and Fig. 4.d) the BLF cancellation process. The estimated baseline by our method is shown as well and the estimated cut-off frequency of the designed filter was 4.1 Hz.

Table 1 shows, for each of the five methods, the bias and precision with respect to the GSP for the start and the end markers obtained before and after application of the BLF cancellation method.

The highest mean difference and SD values (up to 6.8 and 11.7 ms for start and end markers, respectively) corresponded to T1, while the lowest values were for WTM. In the cases of AM start and end markers and of the U2 start marker, significantly lower values of bias and precision were found after applying the BLF cancellation method. Thus, BLF removal improves the accuracy of these two methods, but not of the T1 and T2 methods. The improvement after optimal BLF removal is probably due to the fact that the in-built baseline estimation of AM and U2 (the baseline is considered the electrical zero) is not sometimes the best election when some parts of the MUAP are higher or lower due to the BLF. The low performance of T1 and T2 methods is due also to their baseline estimation (to average both ends of the analysis window) in which the presence of discharges of secondary MUAPs at both ends of the

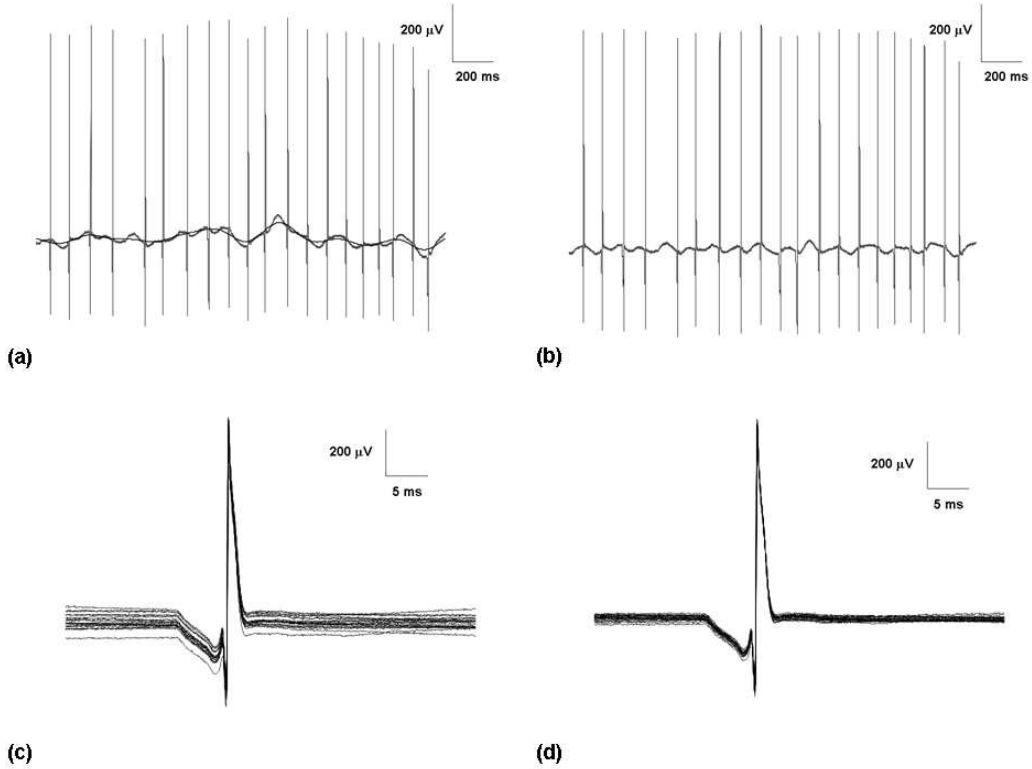


Fig. 4. (a) A 2 seconds long original EMG signal and estimated baseline by our BLF cancellation method. (b) The EMG signal without the estimated baseline. Discharges of the MUAP extracted from the original EMG signal (c) and after BLF removal (d)

analysis window stand out over the baseline, yielding wrong baseline estimates in the epoch averaging process (Rodríguez et al., 2007a).
With regard to start marker positioning, BLF cancellation improved the performance of the U2 such that a significant difference between the T2 and U2 methods was no longer evident, as U2 achieved a similar mean value as T2. As a consequence of this improvement, U2 showed significantly superior performance than T1 after BLF cancellation. With regard to end marker positioning, the BLF cancellation method improved the performance of the AM, which achieved a similar mean value to the WTM and T2 method. Consequently, previously existing differences between AM and WTM and between AM and T2 were no longer statistically significant after BLF cancellation.
The WTM rendered significantly lower mean differences from the GSP than all the other CAMs for the start marker. WTM end marker differences were significantly lower than those of the AM and the T1 method before BLF cancellation and significantly lower than T1 after BLF cancellation. Furthermore, the WTM had the lowest mean and SD of differences from the GSP, indicating that it was the least biased and the most accurate and consistent of the five studied methods. The bias and precision of the WTM were not significantly improved by BLF cancellation, the reason being that the parameters of ampli-

tude and slope used by this method are established for a set of MUAP signals without previous baseline treatment nor other signal processing (Rodríguez et al., 2007b).

In Fig. 5 the mean and the SD of the differences between the automatic positions and the GSP estimates (considering start and end markers conjointly) for

Table 1

Differences between the GSP and the positions assigned by the five automatic methods before and after BLF removal. Horizontal brackets indicate the pairs of methods with a significant difference between their respective mean values. The asterisk and circles without lines indicate the values with significant differences before and after application of the BLF removal method for the same duration measurement method. For differences between the methods ("horizontal comparisons"), the significance level was calculated by a one-factor ANOVA test (using Bonferroni method), and for differences of the same method before and after BLF removal ("vertical comparisons"), by paired t-test. ∘ = p<0.001, + = p<0.01, ∗ = p<0.05

Marker	BLF process	T1	T2	AM	U2	WTM
		mean/SD (bias/precision) ms				
start	before	5.2/7.7	1.8/6.1	2.8/6.2	4.2/7.3	0.0/2.3
				∗	∘	
	after	5.4/7.8	1.9/6.2	2.2/5.7	2.2/6.4	0.0/2.3
end	before	-6.8/11.7	0.4/9.4	-2.0/6.2	-1.5/11.2	0.9/3.0
				∘		
	after	-6.4/11.7	0.3/9.4	-0.8/4.6	-1.3/11.3	0.9/3.0

the five algorithms before and after the BLF cancellation method are graphically represented. The EMSE of each method before and after BLF cancellation is in brackets. In fact, the EMSE value represents the distance to the origin. The lower the mean and the lower the SD, that is the lower EMSE, the more precise the method, with resulting positions more close and centered around the GSP. As can be appreciated from Fig. 5, and in accordance with the results in Table 1, CAMs EMSE values decrease after BLF cancellation. This decrease is more marked in U2 and AM methods. The T1 and T2 methods were not markedly improved by the BLF cancellation, a result which can be explained, as previously commented, by the influence of the presence of secondary potentials on their behaviour. Of the CAMs the AM gave the best results; but, of all the methods, the WTM was the most precise and rendered the marker positions closest to the GSP, with the lowest EMSE both before and after application of the BLF removal method. Some examples of MUAP duration measurement for the AM (the best of the CAMs) and the WTM are shown in Fig. 6.

Note that in some cases the AM overcomes the problem of secondary MUAPs present in the signal (Fig. 6.a). In other cases it does not (Fig. 6.b). The WTM overcame this problem in both the cases shown in Fig. 6.

The AM sometimes loses precision as a consequence of estimating the baseline level to be electrical zero. This error will affect the thresholds, thereby leading to inaccurate start and end MUAP points. This error of the AM, however, can be avoided by applying the BLF cancellation method (Fig. 6.c and d), which renders excellent results since MUAPs are more balanced around zero. On the

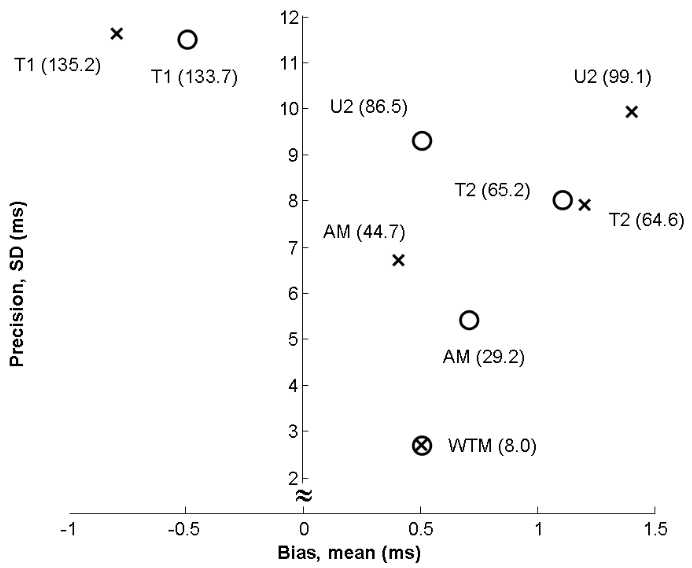


Fig. 5. Bias (mean) and precision (SD) of the automatic methods as indicated by differences between their duration marker positions and the GSP estimates (considering start and end markers conjointly). The estimated mean square error (EMSE) of such differences for each method, before (crosses) and after (circles) the BLF removal process is given in brackets.

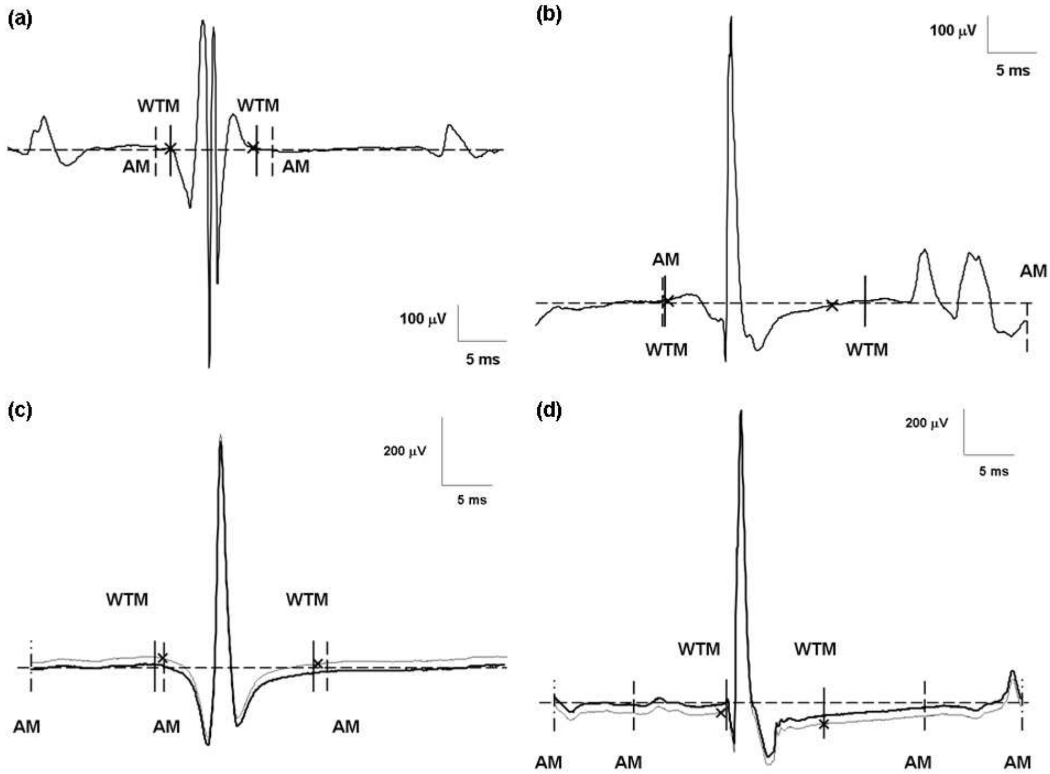


Fig. 6. Examples of GSPs (crosses) and WTM (continuous vertical lines) and AM marker positions. In the first two examples (a) and (b) the average MUAP waveforms did not change after BLF cancellation. The AM positions obtained before BLF removal are represented by dashdot vertical lines and those after BLF removal by dashed vertical lines. In some cases, such as in (a) and (b) and the end marker in (c) the AM positions before and after BLF removal are the same. In (a) both methods overcome the presence of secondary MUAPs at the extremes of the analysis window (before and after the analyzed MUAP). In (b), the end marker obtained by the AM is misplaced due to the presence of secondary potentials at the end of the analysis window. In (c) and (d) averaged MUAPs are shown before (thin black line) and after (thick black line) BLF cancellation method. The AM fails and places the markers at the start and/or end of the analysis window. This is due to shifts of the MUAP down or up with respect to the electrical zero (dashed horizontal lines), which the AM takes as the baseline (dashed vertical lines). The BLF cancellation method resolves this problem with the AM (dotted vertical lines).

other hand, the marker positions of the WTM are closer to the GSP in the raw signal in these examples, and they are not appreciably influenced by the BLF.

4 Discussion

For the automatic measurement of MUAP duration, real EMG signals present several problems such as the presence of secondary MUAPs, high-frequency noise, and BLF. Conventional signal processing methods in quantitative EMG assume the baseline to be constant throughout the EMG signal (Stalberg et al., 1986; Stalberg et al., 1996). But, frequently, the baseline is not stable, and typically shows a slow fluctuation of variable amplitude (Rodríguez et al., 2006).

In these conditions, a poor estimation of the baseline reduces the accuracy of the MUAP duration measurements obtained by the CAMs. If the baseline is taken as the electrical zero without considering possible DC offset in the MUAP, as in the AM and the U2 method, then the application of the amplitude criteria can result in marker misplacement. The CAMs which assume a baseline of electrical zero render better results when a method to cancel out the BLF is applied previously. Other CAMs, such as the T1 and T2 methods, regard the baseline as a straight line at the average of both ends of the MUAP analysis window. The presence of secondary MUAPs in these segments can result in an estimated baseline far from its real course and, consequently, in a misplacement of duration markers. This kind of error cannot be overcome by BLF cancellation, even for the T2 method, where the search of the MUAP onset and offset begins from the trigger point towards the ends of the analysis window. Thus, the accuracy of the T1 and T2 methods does not improve substantially after BLF removal.

The method used here for BLF cancellation is based on a reconstruction of the course of the baseline using the segments of the EMG signal free from MUAP discharges. It was devised to design an optimum filter with a specific cut-off frequency in accordance with the degree of fluctuation in each EMG signal. Therefore, it provides an accurate BLF removal for continuous recordings, precluding any significant distortion of the MUAP waveform, since, as it is known, inappropriate high cut off filter frequency can distort the MUAP waveform, especially in its terminal part (Stalberg et al., 1986; Lang and Vaahtoranta, 1973). The method is previous to the extraction of MUAPs, in contrast to CAMs, where the baseline treatment is performed once the MUAPs have been already extracted, estimating the baseline as a constant value, yielding problems already commented.

The conventional approaches for managing the baseline difficulties are mainly based on averaging a large number of epochs containing the MUAPs discharges, such as in T1 and T2 that use 100 triggered discharges. Besides, there are other procedures for rejecting outlier samples such as median averaging of epochs (Nandedkar et al. 1995; Nandedkar et al. 1989). These processing techniques try to reduce the distortions from secondary MUAPs and the BLF to reach a smooth baseline and therefore to improve the performance of duration methods based on amplitude and slope criteria. In the present work, the

MUAP waveform extraction process has been made manually, that ensures the picking up of undistorted waveforms of the MUAP even with a relative low number of discharges, but it does not overcome the presence of secondary MUAPs out of the analyzed one. The use of shorter recordings is nearer to the desirable conditions on clinical practice, reducing the time of signal acquisition. In respect to these issues, it is clear that identification of discharges, epoch averaging, baseline course estimation and duration marker placement are all interrelated steps in the extraction and delimitation of the MUAP waveform. The present study deals with the influence of the baseline treatment on the duration measurement and it points up the convenience of a specific BLF treatment previous to other processing techniques of the continuous acquired EMG signal, which indeed could improve not only the automatic duration methods, but also the extraction process of the MUAP waveform too.
On the other hand, the WTM for measuring MUAP duration deals with secondary MUAPs, high-frequency noise, and BLF better than the other algorithms we tested, and so provided more accurate duration marker placements. The WTM accommodates these drawbacks as the intermediate scales of the wavelet transform do not include high frequency noise and baseline fluctuation previous to the application of thresholding and slope criteria. Thus, the WTM renders better results than the CAMs, providing duration marker positions closer to the GSPs both before and after BLF cancellation, without effect on the marker positioning.
However, both the BLF cancellation and the WTM method present some limitations, mainly related to the presence of waveforms with low-sloped, long tails, in which determination of end points of MUAPs becomes problematic. In such cases, the DWT applied using the quadratic spline wavelet cannot fully cope with the terminal waveform portions and spectral characterization becomes inaccurate (Rodríguez et al., 2006). These methods have not been assayed with signals from abnormal muscles. In respect to polyphasic MUAPs one would expect a similar performance than in normal ones, since with regard of the spike shape complexity the critical parts of the MUAP duration for duration measurement are the initial and terminal ones and they do not differ significantly between irregular and simple MUAPs. It is probably, however, that the satellites were not properly treated with the duration algorithms in spite of an efficient BLF cancellation. In any case, specific studies with pathological MUAPs are necessary.
Nevertheless, the WTM does still depend on thresholding and slope criteria. As for previously reported automatic methods (Stalberg et al., 1986; Stewart et al., 1989; Stalberg et al., 1996), we established the values of the parameters used in these criteria by finding those values which enabled the algorithm to best reproduce manual duration measurements.
However, duration measurements and the corresponding GSPs vary to some degree from electromyographist to electromyographist, and so, in spite of using a probabilistic approach for determining GSPs among several manual placements, the resulting parameter values are not completely objective. Thus, the

errors in positioning the markers are not fully exclusively dependent on the algorithms execution, since there are difficulties in the exact definition of clinical MUAP duration (Dumitru and King, 1999; Dumitru et al., 1999), as well as inherent limitations and randomness in its manual measurement (Nandedkar et al., 1988; Chu et al., 1993; Soono, 2002; Takehara et al., 2004a; Rodríguez et al., 2007a).
Despite these troublesome issues, the comparative analysis carried out in the present work emphasizes the importance of the baseline treatment to the automatic management of EMG signals: when BLF cancellation was applied there were clear differences in the behavior of the algorithms tested, which in some cases was significantly improved when the BLF cancellation is applied.

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