Facultad de Ciencias Económicas y Empresariales

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Application of a Novel Automatic Duration Method based on the Wavelet Transform on Pathological Motor Unit Action Potentials

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Key words: Motor unit action potential, Duration, Quantitative electromyography, Wavelet transform, Hilbert transform
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1 Introduction

Analysis of the motor unit action potential (MUAP) is an essential aspect of needle EMG studies. The MUAP waveform is quantitatively characterized by several parameters of which duration is indispendable, as the rest of parameters are measured within the MUAP time span defined by its duration (Stalberg et al., 1986). MUAP duration is related to the number of muscle fibers in the motor unit and to the temporal dispersion of the activation times of the fibers and their conduction velocities (Stalberg et al., 1996). The MUAP onset is usually an abrupt takeoff due to the muscle fiber depolarization. However the offset is more difficult to determine as the final phase of the potential returns to the baseline very slowly and asymptotically without a distinct end point (Sonoo and Stalberg, 1993). This final slow afterwave has been related to the shape of the intracellular action potential (Lateva and McGill, 1998).
It has been demonstrated in real electromyographic (EMG) recordings and simulation studies that the extinction of the action potentials continues for over 20 miliseconds (ms) after the main spike of the MUAP (Lateva and McGill, 1998; Dumitru and King, 1999; Dumitru et al., 1999). Real routine EMG signals almost invariably show slow baseline fluctuations and other noise such that it is very difficult to distinguish the full extension of the final portion of the MUAP. Thus, this work is devoted to the "clinical MUAP duration", i.e., that which can be observed in routine neurophysiological practice and which has clinical meaning, different from the "physiologic MUAP duration" (Dumitru and King, 1999; Dumitru et al., 1999).
On the other hand, the duration markers define the boundaries of the MUAP waveform and thereby separate the parts of the recorded signal that will be analyzed from what can be considered as baseline or background activity. Thus, duration is the MUAP parameter that should be determined first. The procedure of measuring MUAP duration presents hard intrinsic difficulties, and therefore manual duration measurement has been previously described as "an arbitrary task" (Sonoo, 2002). However, the manual placement of duration markers does not guarantee an accurate duration measurement and low degrees of reliability of manual duration markers have been reported (Stalberg et al., 1986; Nandedkar et al., 1988; Chu et al., 2003; Takehara et al., 2004b; Rodríguez et al., 2007a).
A number of automatic algorithms have been designed (Stalberg et al., 1986; Nandedkar et al. 1995) to try to overcome the limitations of subjective assessment of the MUAP duration. But, as reported by others (Bischoff et al., 1994; Stalberg et al., 1995; Takehara et al., 2004a), conventional automatic algorithms imply the necessity of continuous visual supervision and frequent

manual readjustments of the duration markers. These methods fail to estimate correctly the duration measurement due to the presence of fluctuations in the baseline and to noise and other potentials. Unfortunately, such baseline irregularities and noise are common in routine EMG signals.
A recently published algorithm was proposed by the authors (Rodríguez et al., 2007b) based on the discrete wavelet transform (DWT), which is a processing technique that simultaneously obtain a time scale representation of the signal. In this transform, high frequency noise and baseline fluctuations can be put aside. This automatic method achieved excellent and accurate results significantly better than other available algorithms. In this paper we test the performance of this novel algorithm over pathological signals, and it is compared to some well-known automatic duration algorithms: Turku method 1, Turku method 2, Uppsala method 2, Aalborg method (Stalberg et al., 1986) and Nandedkar's method (Nandedkar et al., 1995). In the next sections, the electromyography equipment and the characteristics of the EMG signals used in this work are desribed, as well as the automatic duration methods applied and the statistical tools used to extract the results and conclusions.

2 Material

We analyzed 313 recordings containing a 5 seconds long EMG signal during slight contractions: 68 signals from 14 normal deltoid muscles, 35 from muscles with fibrillations, 105 from muscles with myopathies, 27 from chronic neurogenic muscles, and 72 from subacute neurogenic muscles. The pathological signals come from different muscles: tibial anterior, gastrocnemius medialis, abductor digiti minimi, abductor hallucis, first dorsal interosseous, extensor digitorum communis, abductor pollicis brevis, and vastus medialis. These signals were acquired with another electromyograph, a Medelec Synergy Mobile electromyograph of 5 channels (Oxford Instruments Medical, Inc.), using concentric needle electrodes (type DCN37; diameter = 0.46 mm, recording area = 0.07 mm^2; Dantec). The filter setting was 3 Hz to 10 kHz with a sampling rate of 20 kHz and 16-bit analog-to-digital conversion. The digitized signals were stored on the hard disk of a PC computer and further analysis was performed off-line.
The multi-MUAP procedure of an automatic decomposition method was used to extract MUAPs from the continuous EMG signals (Florestal et al., 2006). Epochs of 50 or 100 ms containing discharges of the same MUAP were obtained. Next, the waveforms of the isolated discharges of each MUAP were aligned in the time axis by maximum correlation (Proakis and Manolakis, 1996; Campos et al., 2000) and in the voltage axis by euclidean distance minimization (a selection algorithm orders the discharges in accordance to their euclidean distance to the average of MUAP discharges). Besides, interactive

tools were implemented to visualize the set of the extracted discharges of the same MUAP in raster and superimposed modes in order to discard undesirable MUAPs. The MUAP waveform was finally obtained using a novel method of sample estimation based on an algorithm of sliding windows (referencia congreso castellon). This method optimizes the MUAP waveform extraction procedure and can be applied even in presence of intense superposition of discharges from other motor units.
Well defined waveforms (avoiding superimpositions, gross baseline fluctuations and secondary potentials) of at least 3 up to 10 discharges (mean 9.9 and standard deviation 0.7 discharges per MUAP) were selected for each studied MUAP. All the selected MUAP waveforms were well-defined over baseline activity and had a "rise-time" < 1 ms (most of them less than 500 μs).
A total of 339 MUAPs were accepted for analysis: 68 from normal deltoid muscles, 44 fibrillation potentials, 124 from myopathic muscles, 20 from chronic neurogenic muscles and 83 from subacute neurogenic muscles. Notice that in relation to the number of analyzed signals, the number of extracted MUAPs is reduced. This is as a consequence of the extraction process, in which we looked for MUAPs free of distortions in the analysis window, as baseline fluctuation and secondary potentials.

3 Methods

3.1 Determination of the gold standard of the duration marker positions

The high variability in the manual placement of duration markers generates difficulty to achieve the best manual position among a set of several measurements. Therefore, a method was devised by the authors to find the "most likely" MUAP start and end points. Over the whole set of 348 MUAPs, two senior electromyographists made three independent measurements of the duration. To perform this task they were provided with a software interactive tool (designed in $Matlab^{TM}$ 7) that showed the MUAP waveform and the set of the extracted discharges in raster and superimposed modes. The sensitivity scale was fixed at 100 μV/cm to place the duration markers. From the six manually marked positions for the start or end markers, the "most likely" placement was the mean point of the three closest positions using a probabilistic procedure (Fig. 1). This was considered our gold standard position (GSP). For more detail read Rodríguez et al. (2007a).
Besides, in this work the MUAPs which were selected present a high degree of agreement in the start and end duration markers placed by the senior electromyographists. For the selected MUAPs, the mean and standar deviation obtained from the range of the three closest markers to calculate the GSP were 0.02 and 0.05 ms for the start marker and 0.1 and 0.1 ms for the end

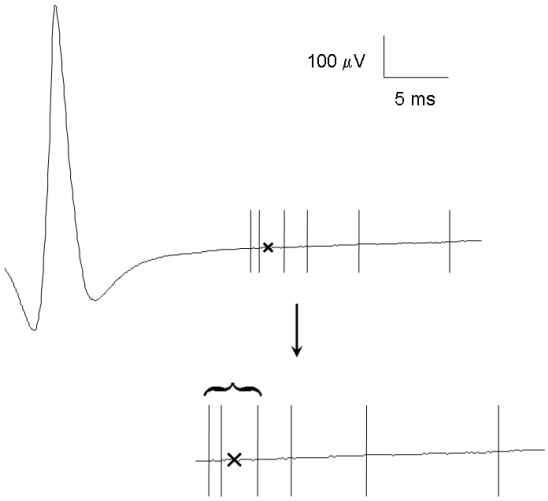

Fig. 1. Example of determination of the gold standard of the duration markers positions (GSP) from six manual marker positions for the end point (continuous vertical lines). The GSP (x) is calculated as the mean position of the three closest manual marker positions.

marker.

3.2 Automatic methods for the measurement of MUAP duration

Six automatic methods for the measurement of MUAP duration were used: five well-known conventional ones (CAMs), and a recent method based on the wavelet transform. We have to stand out that the six methods have been applied to the MUAP representative waveforms extracted using the algorithms described above, i.e., under the same conditions.

3.2.1 Conventional automatic methods

Four CAMs analyzed are sufficiently described in their reported description in Stalberg et al. (1986): the Turku method 1 (T1), the Turku method 2 (T2), the Uppsala method 2 (U2) and the Aalborg method (AM). The fifth CAM method is also detailed in Nandedkar et al. (1995), it is named Nandedkar's method, NAM. The most important differences among these methods can be found in the extraction procedure of the MUAP waveform and in the posterior criteria applied to find the start and end duration markers:

- Extraction procedure of the MUAP waveform. These methods calculate the MUAP duration within a 40, 50 or 100 ms long analysis window.

· In T1 and T2, MUAPs are manually isolated with a trigger level and averaged 100 discharges to reduce the high frequency noise and the presence of other MUAPs in the analysis window.

· In AM, MUAPs are automatically isolated and classified by a template-matching method using the main spike of the potential. From the set of discharges of the same MUAP, the 3 most similar are selected to obtain the averaged waveform.

· In U2, MUAPs are manually isolated and the MUAP waveform is obtained by averaging 20 to 200 discharges.

· In NAM, MUAPs are automatically isolated, identified and classified using multi-MUAP analysis. From 50 to 65 discharges are extracted for each MUAP and the averaged waveform is obtained using median averaging.

- Criteria to find the MUAP start and end markers:

· T1 and T2 estimate the baseline that must be subtracted as the average of samples at both 3 and 4 ms ends of the analysis window and NAM calculates baseline as the average of the first 5 ms. However U2 and AM calculate the baseline as the electrical zero.

· Once the baseline is subtracted, T1 and U2 begin their searches for the MUAP start or end from the start or end of the analysis window, respectively, T2 and AM begin from a triggering point in the rising slope of the main spike, and NAM begins its search from the maximum peak.

· T1, T2, AM and U2 use amplitude or/and slope thresholds to the amplitude/slope values of samples or windows of samples. Otherwise, NAM combines thresholds to the area under the MUAP and thresholds to the amplitude sample values.

In this work, the number of discharges selected per MUAP ranged from 3 to 10 and this fact could make us think that these methods might have not been rendered their best performance in our set of signals. This may be true in some way, but it is not related to the extraction process applied here, as the whole extraction procedure of the MUAP waveform applied here (including multi-MUAP, matching method, manual supervision and advance sliding window method) ensures the selection of undistorted waveforms of the MUAP and also obtains a MUAP waveform free of the presence of secondary MUAPs out of the analyzed one. Probably it can be stated that these automatic methods with their extraction procedures and criteria were optimized to run on a certain equipment, and applying these methods to EMG signals coming from a different equipment with different acquisition features (as the filters

implemented or amplifiers with different signal to noise ratios or other pre-processing techniques) yield worst results in their measurements.

3.2.2 Wavelet based method for measurement of MUAP duration

MUAPs consist of a set of peaks (Fig. 2.a). The recent wavelet transform method (WTM) makes use of the discrete wavelet transform (DWT) with the non orthogonal quadratic spline wavelet (Fig. 2.b) to detect not only the MUAPs but also the start and end points of these peaks. The method selects two intermediate scales (one to find the start and another to find the end marker) that represents the MUAP signal in terms of energy and evades noise and baseline fluctuation. In these scales the peaks related to MUAP peaks are identified (Fig. 2.c) and amplitude and slope thresholds are used to determine MUAP start and end points (Fig. 2.d). For finding MUAP start and end markers, the WBM makes use of 10 parameters including amplitude and slope thresholds. The values of the WTM parameters were already set in a previous work (Rodríguez et al., 2007b), applying a genetic algorithm with 64 MUAPs from tibialis anterior and first dorsal interosseous muscles recorded with a different electromyograph (Counterpoint, Dantec Co., Denmark). The WTM is described in detail in Rodríguez et al. (2007b).

3.3 Accuracy assessment of the automatic measurements

To analyze the accuracy of the 6 automatic methods for MUAP duration measurement, we used the GSP explained previously (Sect. **??**). For the five different MUAP groups (normal, fibrillation, myopathic, chronic neurogenic and subacute neurogenic), we accomplished the following steps:

- Comparison of bias and precision. The differences between the start and end marker positions of each method and the GSP markers were calculated. The results of the methods in each group were compared using a one-factor ANOVA test.

- Calculation of the estimated mean square error values. The mean of the differences between the automatic marker position (considering start and end markers together) and the GSP (i.e., the bias of each method) and the standard deviation (SD) of such differences (the precision) were calculated. We used the estimated mean square error (EMSE) of the differences. The EMSE was calculated as follows:

$$\underset{g}{\mathrm{EMSE}} = \underset{g}{\mathrm{mean}}^2_{d,start} + \underset{g}{\mathrm{var}}_{d,start} + \underset{g}{\mathrm{mean}}^2_{d,end} + \underset{g}{\mathrm{var}}_{d,end} \qquad (1)$$

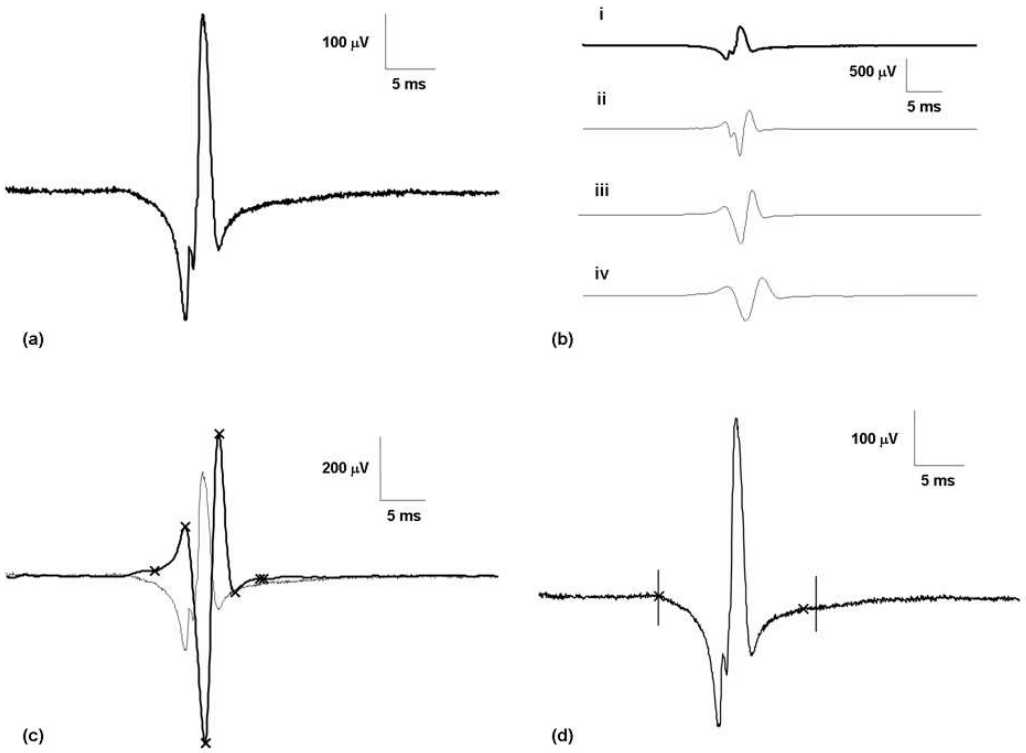

Fig. 2. (a) MUAP in a 50 ms long epoch. (b) The MUAP (i) and the DWT at scales 4 (ii), 5 (iii) and 6 (iv). (c) MUAP time course (dashed black points) and selected wavelet scales for finding start (thick continuous line) and end (thin continuous line) points. Maxima and minima related to the MUAP for 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.

with $\underset{g}{\text{mean}}_{d,start}$ and $\underset{g}{\text{var}}_{d,start}$ being the mean or the variance, respectively, of the differences between the start marker position of the method and the start GSP for each MUAP group; $\underset{g}{\text{mean}}_{d,end}$ and $\underset{g}{\text{var}}_{d,end}$ are equivalent measures for the end marker. Besides we calculated the total EMSE value, $EMSE_T$, for each method:

$$\underset{m}{\text{EMSE}}_T = \frac{\underset{m}{\text{EMSE}}_n \cdot 68 + \underset{m}{\text{EMSE}}_f \cdot 44 + \underset{m}{\text{EMSE}}_{myo} \cdot 124 + \underset{m}{\text{EMSE}}_c \cdot 20 + \underset{m}{\text{EMSE}}_s \cdot 83}{339} \tag{2}$$

where $\underset{m}{\text{EMSE}}_T$ is the total EMSE for each method, and where $\underset{m}{\text{EMSE}}_n$, $\underset{m}{\text{EMSE}}_f$, $\underset{m}{\text{EMSE}}_{myo}$, $\underset{m}{\text{EMSE}}_c$, and $\underset{m}{\text{EMSE}}_s$, is the EMSE value of any method, m, on normal, fibrillations, myopathic, chronic and subacute MUAPs.

- Rate of gross errors. The number of cases in which the absolute difference between the GSP and the automatic marker position was greater than 5 ms was counted for each method. Such cases can be generally considered as

gross errors. The proportions of gross errors corresponding to each method were compared using the Chi-square test.

4 Results

4.1 Comparison of bias and precision

The mean and the SD of the differences (bias and precision, respectively) between the start and end marker positions and GSPs of the six automatic methods are respectively given in Tables 1 and 2. Asterisks are shown to indicate significant differences between a specific method and the WTM.
Table 1 shows the results for the start marker positions. It can be appreciated that the WTM method is the less biased and the most precise method placing the start marker, as it has simultaneously the lowest mean and the lowest SD of differences to the GSP for all the five MUAP groups. Observing the columns, significant differences between T1 and WTM and between AM and WTM can be found in almost all the different MUAP groups. Significant differences are also found between NAM and WTM in normal, myopathic and subacute neurogenic MUAPs. Besides, T2 showed significant difference against WTM in normal MUAPs. U2 did not show significant differences with WTM, but it presents higher SD (lower precision) than WTM.
In Table 2, the results for the end marker positions are shown. Observing the rows in this table, significant differences among all the CAMs and the WTM can be found for normal, myopathic and subacute neurogenic MUAPs. T1 and AM had significant differences with WTM in chronic neurogenic MUAPs and

Table 1
Differences between GSP and the start marker positions assigned by the 6 automatic methods for the different MUAP groups. The mean and SD of such differences (bias and precision, respectively) are given for each method in ms. The asterisk indicates a significant different with that specific method and the WTM. $*$ = $p<0.05$ (one-way ANOVA). Chr. = chronic. Subac. = subacute.

MUAPs/Start	T1	T2	AM	U2	NM	WTM
Normal	0.8/3.0	-0.7/1.6$*$	9.7/7.0$*$	-0.6/2.9	-1.4/1.2$*$	-0.3/1.3
Fibrillations	3.5/6.8$*$	1.2/4.8	3.3/6.8$*$	2.0/6.7	-0.5/1.5	-0.3/0.4
Myopathic	1.4/3.7$*$	-0.9/2.4	2.8/6.0$*$	-1.1/2.7	-1.2/1.0$*$	-0.5/1.1
Chr. Neurogenic	13.4/14.0$*$	1.1/4.8	16.5/12.8$*$	9.3/15.1	1.6/6.7	0.7/2.3
Subac. Neurogenic	2.8/5.2$*$	-0.6/3.2	6.3/8.4$*$	-1.2/2.6	-1.3/1.4$*$	-0.4/1.6

Table 2
Differences between GSP and the end marker positions assigned by the 6 automatic methods for the different MUAP groups. The mean and SD of such differences (bias and precision, respectively) are given for each method in ms. The asterisk indicates a significant different with that specific method and the WTM. $*$ = $p<0.05$ (one-way ANOVA). Chr. = chronic. Subac. = subacute.

MUAPs/End	T1	T2	AM	U2	NM	WTM
Normal	-6.5/8.9$*$	3.6/4.9$*$	-13.6/8.9$*$	4.3/5.2$*$	3.1/3.1$*$	-0.1/3.5
Fibrillations	-2.3/7.9	0.9/4.7	-1.0/4.6	0.6/8.8	2.1/6.4	1.2/2.1
Myopathic	-1.6/6.6$*$	2.9/4.0$*$	2.9/7.1$*$	4.9/ 2.8$*$	4.4/2.9$*$	0.6/2.6
Chr. Neurogenic	-15.1/15.2$*$	7.3/5.9	-15.1/14.3$*$	-5.2/15.2	6.5/10.6	1.4/7.6
Subac. Neurogenic	-5.4/9.0$*$	3.3/5.7$*$	-8.7/11.0$*$	5.9/3.7$*$	4.3/4.2$*$	0.8/4.0

no significant differences were found for the fibrillation MUAPs. Also in this table the WTM presents the best results in terms of bias and precision.
Analyzing the behaviour of the automatic methods when measuring different pathological MUAPs from both tables, it can be observed that in order of goodness of measurements, normal and fibrillation MUAPs are the first two groups, then myopathic and subacute neurogenic and finally, chronic neurogenic MUAPs. Notice that in this last group the precision of all the methods decreases. This is as a consequence of the peculiar characteristics of the analyzed signals, they are the longest MUAPs and present also a great poliphasia. Besides, it can be seen that end marker placements present higher mean and SD in absolute value than the start markers, which indicates that it is more difficult for the automatic methods to place the MUAP end than the start marker.

Table 3
EMSE values of the 6 automatic methods for normal, fibrillation, myopathic, chronic and subacute neurogenic MUAPs.

MUAPs	T1	T2	AM	U2	NM	WTM
Normal	131.1	40.0	407.3	54.3	22.6	14.0
Fibrillations	126.2	47.4	79.3	126.7	47.9	6.1
Myopathic	61.8	31.0	102.7	40.3	30.2	8.6
Chronic Neurogenic	834.6	48.7	868.6	572.6	202.0	12.9
Subacute Neurogenic	145.0	54.0	307.0	56.7	39.8	19.4

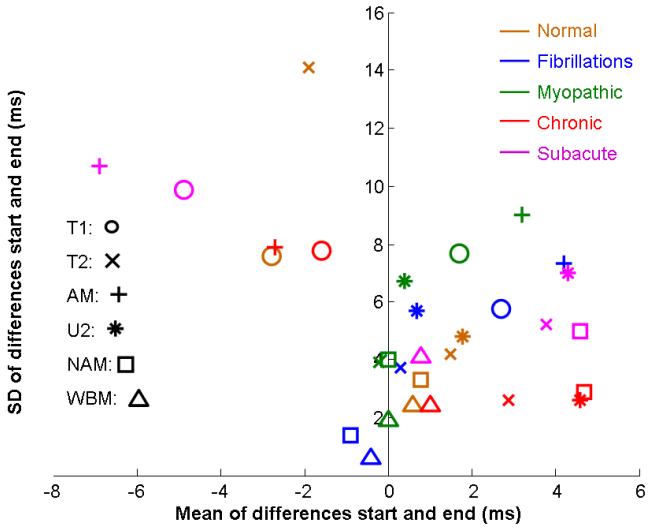

Fig. 3. Bias and precision of the differences between the GSP and the duration marker positions of the automatic methods (considering start and end markers) for normal, fibrillation, myopathic, chronic and subacute neurogenic MUAPs.

4.2 Calculation of the EMSE values

Table 3 shows the EMSE values of all the methods for the five different MUAP groups. For a specific group of MUAPs, if we represent for each automatic method the mean of the differences to the GSP (considering both start and end markers) against the SD of such differences, the EMSE turns out to be the module of the vector, i.e, the distance to the origin of coordinates. 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. Figure 3 shows the representation of the EMSE values of the six methods for the different MUAP groups. As it can be appreciated, the WTM presents the lowest EMSE in all the cases, i.e., the WTM was less unbiased and more precise than the conventional methods. Table 4 shows the total weighted EMSE values for the six automatic methods. Under this criterion, the WTM is the best compared to the CAMs.

Table 4
Total EMSE values of the 6 automatic methods.

	T1	T2	AM	U2	NM	WTM
$EMSE_T$	150.0	41.6	256.0	89.7	43.4	12.2

Table 5
Rate of automatic start marker placements with differences to the GSP greater than 5 ms for the methods and different MUAP groups. The asterisk indicates a significant different with that specific method and the WTM. $*$ = p<0.01 (Chi-square test).

MUAPs/Start Marker	T1	T2	AM	U2	NM	WTM
Normal	5.9	2.9	70.6∗	4.4	0.0	2.9
Fibrillations	20.5∗	13.6∗	20.5∗	13.6∗	2.4	0.0
Myopathic	7.3∗	5.6∗	21.8∗	6.5∗	1.6	0.8
Chronic Neurogenic	51.7 ∗	17.2	58.6∗	24.1	6.9	10.3
Subacute Neurogenic	18.1∗	10.8	37.3∗	6.0	3.6	3.6

4.3 Rate of gross errors

The rate of gross errors for start and end markers of the 6 automatic methods for the five different MUAP groups are shown in tables 5 and 6, respectively. For the start marker, the WTM presents the lowest rate of gross errors for fibrillation and myopathic MUAPs, while NAM presents the lowest rates for normal and chronic neurogenic MUAPs. Besides, significant differences were found between WTM and T1, T2, AM and U2, in fibrillation and myopathic MUAPs. On the other hand, the WTM presents the lowest rates of gross errors for the end marker in all the cases. Significant differences were found between WTM and almost/all the CAMs in normal, myopathic and subacute neurogenic MUAPs.

Table 6
Rate of automatic end marker placements with differences to the GSP greater than 5 ms for the methods and different MUAP groups. The asterisk indicates a significant different with that specific method and the WTM. $*$ = p<0.01 (Chi-square test).

MUAPs/End Marker	T1	T2	AM	U2	NM	WTM
Normal	36.8∗	54.4∗	70.6∗	54.4∗	29.4∗	11.8
Fibrillations	18.2	9.1	9.1	25.0	25.0	9.1
Myopathic	14.5∗	29.0∗	17.7	46.8∗	39.5∗	9.7
Chronic Neurogenic	55.2∗	34.5	58.6∗	51.7∗	37.9	27.6
Subacute Neurogenic	39.8∗	37.3∗	43.4∗	57.8∗	42.2∗	9.6

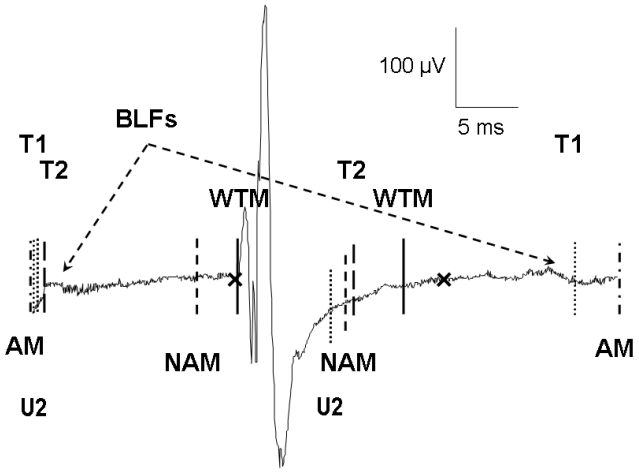

Fig. 4. Errors in positioning start and end markers in the CAMs due to the presence of BLFs at both ends of the analysis window. T1, circle-pointed line; T2, long-dashed line; U2, square-pointed line; AM, dashed-pointed line; NAM, short-dashed line; WTM, continuous line.

4.4 Visual assesment

T1 do not perform correctly since it is a sample-oriented method, it looks for start and end MUAP points that accomplish certain amplitude and slope values. Besides, it begins the search of MUAP start or end points from both ends of the analysis window, and this is not a good choice unless the MUAP waveform is very clean at both ends and does not present baseline fluctuations (BLFs) or irregularities. T2 achieves better results as it is a window-oriented method and begins the search from the triggering point, it looks for start and end points after testing windows of samples meeting some slope and amplitude criteria. AM is also a window-oriented method and begin the search of start or end points from the triggering point, but it does not behave correctly with these kind of signals as its amplitude criteria is small and Synergy signals are more noisy than signals coming from another electromyograph ((Rodríguez et al., 2007b). U2 is a method that begins the searches of start and end points from both ends of the analysis window, that is the main reason for its lower performance. NAM is a more advance method in design, as it also applies measures of area instead of amplitude or slope thresholds as the rest of the CAMs. The main problem of all these CAMs is that they first measure baseline as the electrical zero or as the mean value of some windows of certain length, what in both cases yield constant baseline values, and do not take into account possible BLFz along the analysis window. This is shown in figure 4, as a consequence of BLFs at both ends of the analysis window, the CAMs fail when placing start and/or end markers.

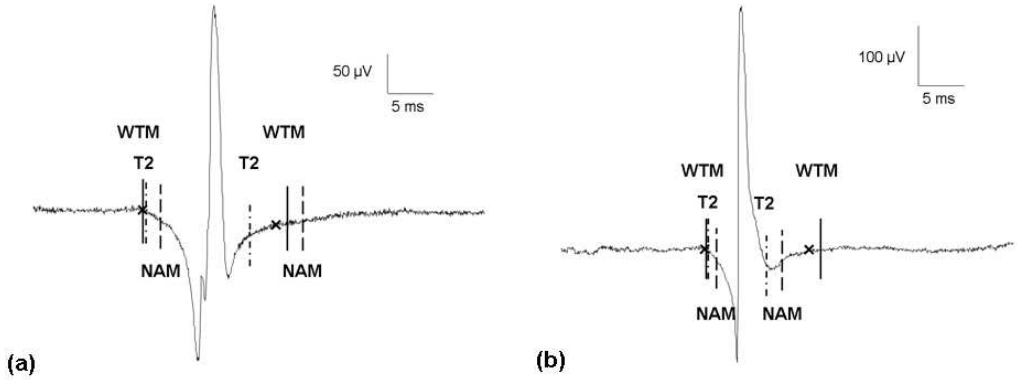

Fig. 5. Examples of duration measurements of T2, NAM, and WTM on normal MUAPs, (a) and (b). GSP are in crosses.

From the numerical results previously shown, we can conclude that the best two CAMs are the T2 and NAM. NAM is a very consistent method when placing the start marker for almost all the different MUAP groups. Otherwise NAM finds more difficult to place end markers, as it shows a higher bias and a greater SD in this case for all kind of MUAPs. T2 presents not so good results, but in terms of EMSE values is comparable to NAM as it presents lower SD in the chronic neurogenic MUAPs. If NAM achieved better results in chronic

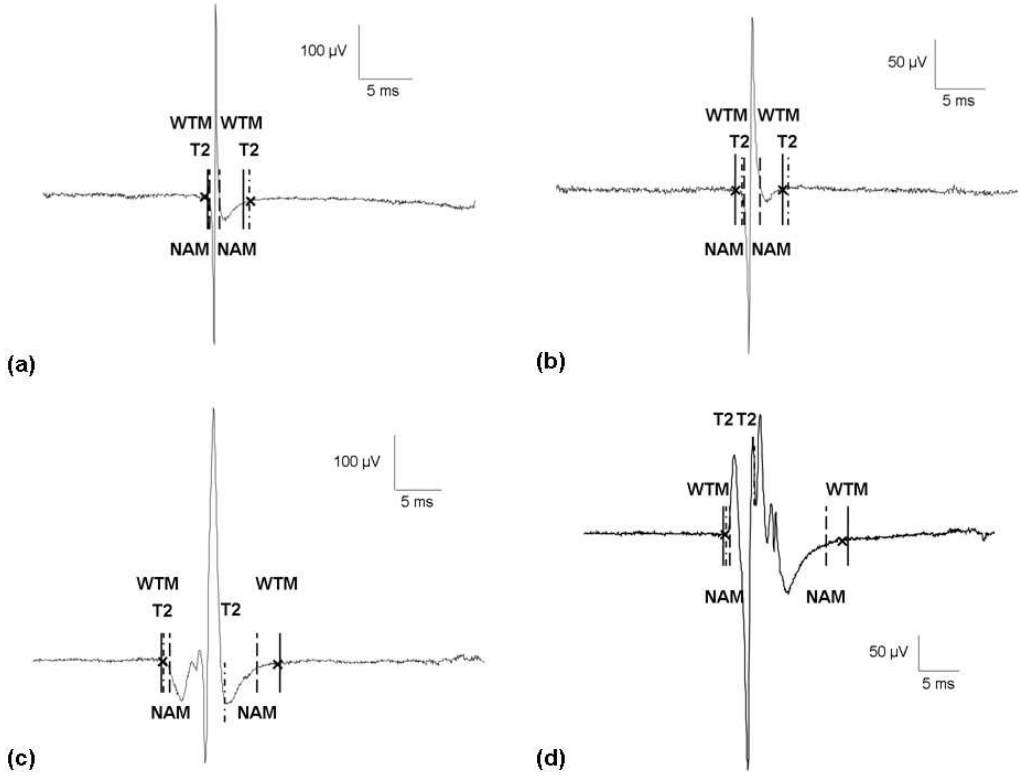

Fig. 6. Examples of duration measurements of T2, NAM, and WTM on fibrillations (a), (b), and myopathic MUAPs, (c) and (d). GSP are in crosses.

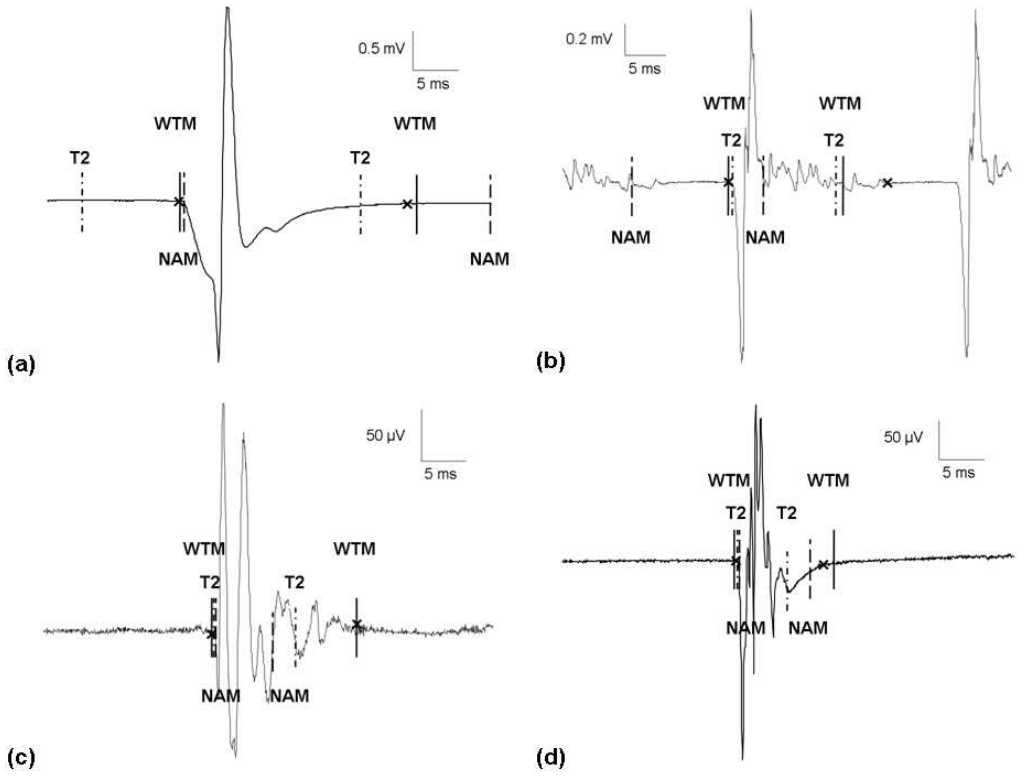

Fig. 7. Examples of duration measurements of T2, NAM, and WTM on chronic (a), (b), and subacute neurogenic MUAPs, (c) and (d). GSP are in crosses.

neurogenic MUAPs, it would have overcome T2.
Some examples of three selected methods (T2, NAM and WTM) over normal and the different pathological MUAP groups are shown in figures 5, 6 and 7. Normal MUAPs can have small (Fig. 5.a) or medium amplitude (Fig. 5.b). T2 and NAM place correctly the start markers near the GSP, while do not perform so well when placing end markers. In both cases WTM shows excellent results. Fibrillation MUAPs are thin and sharp. One fibrillation with low amplitude (Fig. 6.a) an another one with medium amplitude (Fig. 6.b are shown. The three methods perform correctly. Polyphasic and polyphasic serrated myopathic MUAPs are also shown (Figs. 6.c and 6.d). In these cases, T2 fail in positioning the end marker. Chronic potentials can have great amplitude (Fig. 7.a) and also large duration 7.b). Besides they may be polyphasic too (Fig. 7.b). Finally, subacute neurogenic MUAPs can have multiple turns (Fig. 7.c) and be polyphasic too (Fig. 7.d). In all these cases the WTM achieves the best results. Although the WTM performs very well, it has some errors. The WTM fails in positioning the start or end marker when a long tail is present in the MUAP. This low-sloped tail does not reflect any maximum-minimum pair in the DWT (Fig. 8.a), and it cannot be detected. If the wavelet had higher degree of vanishing moments, it should model better the smooth parts of the signal. Besides, it fails when peaks with low relative amplitude are present in the MUAP waveform (Fig. 8.b), as they are below the amplitude thresholds

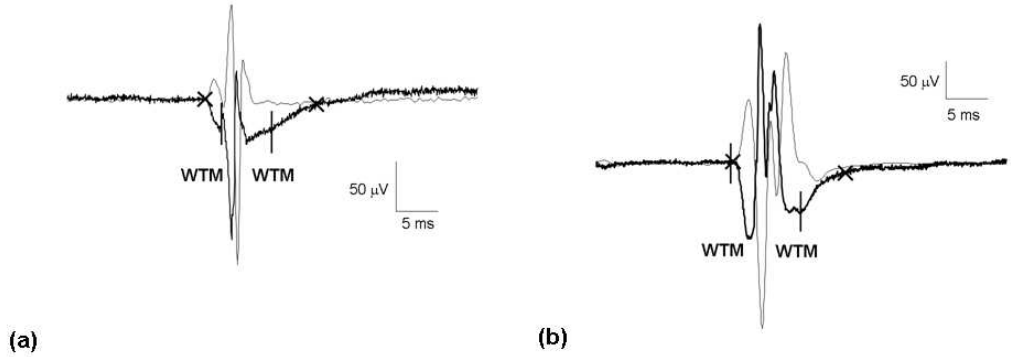

Fig. 8. Errors in WTM when a long tail is present in the MUAP (a), and low amplitud peaks (b).

and then is not counted as belonging to the MUAP.

5 Discussion

Measurement of MUAP duration is still an actual parameter that must be measured in quantitative electromyography. In this paper we have followed a complex processing to obtain clean representative MUAP waveforms with a high agreement in marker placements from neurophysiologists from normal and pathological conditions. All the automatic duration algorithms presented but NAM have been applied to these signals without any previous preprocessing or adjustment as they come from a comercial electromyograph different from the one for which they were desingned. Under these favourable conditions, the novel automatic method for measuring duration based on the wavelet transform provides more accurate duration marker placements and fewer gross aberrant errors for all normal and pathological MUAPs.
The CAMs have been proved to work correctly under normal and fibrillation MUAPs, but with serious problems in myopathic, chronic and subacute neurogeniec MUAPs. The basis of these problems are related to several items. First of all, CAMs assume the baseline to be a constant value and this can result in misplacement of markers (Rodrguez et al, 2006), when baseline is really a low frequency fluctuation. If baseline distortions or fluctuations are present in the MUAP waveform, these constant baseline estimates will make the MUAP start and end search fail, yielding wrong marker placements. Perhaps a good estimation of the baseline course could make CAMs to improve their performance. Secondly, we have assesed that some of these algorithms do not show a good performance when they are applied to signals coming from a different electromyograph. With respect to this, we show that the novel WTM is able to deal with MUAPs coming from different electromyographs, showing its robustness. This fact indicates the superior methodology of the WTM,

which applies the wavelet transform before measuring duration, putting aside noise and low frequency. Besides, a great number of gross errors have been reported by CAMs in this paper, errors that in real clinical practice mean markers readjustment, therefore increasing patient discomfort by increasing the exploration time.

In spite of the WTM robustness, it does present certain limitations. It fails to position the start marker correctly when a MUAP waveform has consecutive turns with a low amplitude variation. Also, the WTM sometimes fails when positioning the end marker of MUAPs with long, low-sloped tails. In spite of some errors in positioning the end point, it is clear that they are not fully dependent on the algorithm execution, because there are difficulties in the definition of clinical MUAP duration (Dumitru and King, 1999; Dumitru et al., 1999) and inherent limitations and randomness in its manual measurement (Sonoo, 2002) which are in some way represented in the automatic method. Nevertheless, further refinement of the method is necessary to obtain the best adaptation to the particular characteristics of the EMG signals and to the intrinsic difficulties of the MUAP duration measurement.

The WTM has good performance to be tested by practical application in a clinical setting. This algorithm could reduce the requirement for manual intervention, therefore facilitating the electromyographist's work. This algorithm works with excellent results with an actual electromyograph as Synergy, which uses multi-MUAP systems. Patient discomfort could be also reduced by reducing the exploration time.

References

Bischoff C, Stalberg E, Falck B, Eeg-Olofsson KE. Reference values of motor unit action potentials obtained with multi-MUAP analysis. Muscle Nerve 1994;17:842-851.

Carlson AB. Communication systems. An introduction to signals and noise in electrical communication. Singapore: McGraw-Hill, 1986.

Chu J, Takehara I, Li TC, Schwartz I. Skill and selection bias has least influence on motor unit action potential firing rate/frequency. Electromyogr Clin Neurophysiol 2003;43:387-392.

Campos C, Malanda A, Gila L, Segura V, Lasanta MI, Artieda J. Quantification of jiggle in real electromyographic signals. Muscle Nerve 2000;23:1022-1034.

Dumitru D, King JC. Motor unit action potential duration and muscle lenght. Muscle Nerve 1999;22:1188-1195.

Dumitru D, King JC, Zwarts MJ. Determinants of motor unit action potential duration. Clin Neurophysiol 1999;110:1876-1882.

OPTIMIZACIN DE LA EXTRACCIN DE LA FORMA DE ONDA DEL POTENCIAL DE UNIDAD MOTORA Gila-Useros L a, Malanda-Trigueros A

b, Navallas-Irujo J b, Rodrguez-Carreo I b, Rodrguez-Falces J b, Garca de Gurtubay-Glligo I aRev Neurol 2008; 47: 438.

Lateva ZC, McGill KC. The physiological origin of the slow afterwave in muscle action potentials. Electroenceph Clin Neurophysiol 1998,109:462-469.

Mallat S, Zhong S. Characterization of signals from multiscale edges. IEEE Trans Pattern Anal Machine Intell 1992;14:710-732.

Mallat S. Wavelet transform maxima and multiscale edges. In: Ruskai MB, editor. Wavelet and their applications. Boston: Jones and Barltett, 1992.

Nandedkar S, Barkhaus P, Sanders D, Stalberg E. Analysis of the amplitude and area of the concentric needle EMG motor unit action potentials. Electroencephalogr Clin Neurophysiol 1988;69:561-567.

Nandedkar S, Barkhaus P, Charles A. Multi motor unit action potential analysis (MMA). Muscle Nerve 1995;18:1155-1166.

Proakis JG, Manolakis DG. Digital signal processing: principles, algorithms and applications. London: Prentice Hall, 1996.

Rodríguez I, Malanda A, Gila L, Navallas J, Rodríguez J. Filter design for cancellation of baseline-fluctuation in needle EMG recordings. Comput Methods Programs Biomed 2006;81:79-93.

Rodríguez I, Gila L, Malanda A, Gurtubay I, Mallor F, Gómez S, Navallas J, Rodríguez J. Motor unit action potential duration, I: variability of manual and automatic measurements. J Clin Neurophysiol 2007a;24:52-58.

Rodríguez I, Gila L, Malanda A, Gurtubay I, Mallor F, Gómez S, Navallas J, Rodríguez J. Motor unit action potential duration, II: a new automatic measurement method based on the wavelet transform. J Clin Neurophysiol 2007b;24:59-69.

Stalberg E, Andreassen S, Falck B, Lang H, Rosenfalck A, Trojaborg W. Quantitative analysis of individual motor unit potentials - a proposition for estandardized terminology and criteria for measurement. J Clin Neurophysiol, 1986;3:313-348.

Stalberg E, Falck B, Sonoo M, Astrom M. Multi-MUP EMG analysis-a two year experience with a quantitative method in daily routine. Electroencephalogr Clin Neurophysiol 1995;97:145-154.

Stalberg E, Nandedkar S, Sanders DB, Falck B. Quantitative motor unit potential analysis. J Clin Neurophysiol, 1996;13:401-422.

Stewart C, Nandedkar S, Massey J, Gilchrist J, Barkhaus P, Sanders D. Evaluation of an automatic method of measuring features of motor unit action potcntials. Muscle Nerve, 1989;12:141-148.

Sonoo M, Stalberg E. The ability of MUP parameters to discriminate between normal and neurogenic MUPs in concentric EMG: analysis of the MUP "thickness" and the proposal of "size index". Electroencephalogr Clin Neurophysiol 1993;89:291-303.

Sonoo M. New attempts to quantify concentric needle electromyography. Muscle Nerve 2002;Suppl 11:S98-S102.

Takehara I, Chu J, Li TC, Schwartz I. Reliability of quantitative motor unit action potential parameters. Muscle Nerve 2004a;30:111-113.

Takehara I, Chu J, Schwartz I, Aye HH. Motor unit action potencial (MUAP) parameters affected by editing duration cursors. Electromyogr Clin Neurophysiol 2004b;44:265-269.

Zalewska E, Hausmanowa-Petrusewicz I. Effectiveness of motor unit potentials classification using various parameters and indexes. Clin Neurophysiol 2000;111:1380-1387.