A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography

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Abstract

Little consensus exists in the literature regarding methods for determination of the onset of electromyographic (EMG) activity. The aim of this study was to compare the relative accuracy of a range of computer-based techniques with respect to EMG onset determined visually by an experienced examiner. Twenty-seven methods were compared which varied in terms of EMG processing (low pass filtering at 10, 50 and 500 Hz), threshold value (1, 2 and 3 SD beyond mean of baseline activity) and the number of samples for which the mean must exceed the defined threshold (20, 50 and 100 ms). Three hundred randomly selected trials of a postural task were evaluated using each technique. The visual determination of EMG onset was found to be highly repeatable between days. Linear regression equations were calculated for the values selected by each computer method which indicated that the onset values selected by the majority of the parameter combinations deviated significantly from the visually derived onset values. Several methods accurately selected the time of onset of EMG activity and are recommended for future use. Copyright © 1996 Elsevier Science Ireland Ltd.

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1. Introduction

The temporal characteristics of electromyographic (EMG) recordings are parameters of neuromuscular function commonly used in the evaluation of posture and movement (e.g. Mann and Hagy, 1980; Cordo and Nashner, 1982; Carey et al., 1983; Lee et al., 1987; Latash et al., 1995). The onset of EMG is one of the most common of these parameters evaluated; however, no standard method of determination of this parameter is used in the literature. In limb movement studies, where the reaction time of the postural muscles may be up to several hundred milliseconds, differences in the time from stimulus to EMG onset with neurological diseases, ageing and postural set may be as low as 20 ms (Traub et al., 1980; Cordo and Nashner, 1982; Woollacott and Manchester, 1993). This indicates that in order to allow comparisons between muscles, experimental conditions and subjects or subject groups, accuracy of onset determination is crucial.

The majority of studies evaluating the temporal parameters of EMG do not report the methods used for the identification of EMG onset (e.g. Belen’kii et al., 1967; Bouisset and Zattara, 1981; Oddsson and Thorstensson, 1987). In studies where the EMG onset determination method is described this is usually performed by visual evaluation of the EMG trace (e.g. Woollacott et al., 1988; Latash et al., 1995), generally without reporting the criteria on which this visually determined decision is made. Several studies report criteria such as the earliest detectable rise in EMG activity above the steady state (e.g. Allum and Pfaltz, 1985; Crenna et al., 1987; Woollacott et al., 1988; Inglis et al., 1994) or the point where the signal first deviates more than 1 or 1.5 SD from the level recorded during the steady state (Nashner et al., 1983; Nashner and Forssberg, 1986) without mention of how this is determined.

Although the nature of visual onset determination is subjective, several authors report the inaccuracy to be as low as ±5–10 ms, without discussion of how this was assessed (Hallett et al., 1975; Horak et al., 1984). This inaccuracy is up to half the experimental difference
reported previously (Traub et al., 1980; Cordo and Nashner, 1982; Woollacott and Manchester, 1993). In several studies, traces were assessed by two examiners and excluded if the identified onsets differed by greater than 5 ms, providing some assurance of reliability (Brown and Frank, 1987; Crenna et al., 1987). Although, intra-tester reliability coefficients of up to 0.78–0.82 have been identified when comparing the visually derived EMG onsets identified by 3 experienced examiners, the percentage of trials in which the same millisecond was chosen as the EMG onset was between 30–36% when comparing examiners and between 47–56% for each examiner between days (DiFabio, 1987). Clearly, much variation in EMG onset determination occurs when this is done visually and is dependent on the experience and skill of the examiner.

In an attempt to increase the objectivity (DiFabio, 1987) of the evaluation of EMG onset and to reduce observer bias (Studenski et al., 1991) an increasing number of studies rely on computer analysis (Table 1). Currently, there is little agreement regarding the most appropriate method. Although each of the computer algorithms use differing criteria to determine the EMG onset, no studies have evaluated the relative accuracy of each or identified if specific trace characteristics require different onset determination methods.

The aim of the current study was to compare a variety of criteria used for the computer determination of EMG onset against the EMG onsets determined visually by an experienced examiner to identify the parameters which provided the most accurate identification of EMG onset. Although it is acknowledged that visual determination of EMG onset is not optimal, it currently provides the only standard against which to compare the computer methods, hence the purpose of the study. Furthermore, the study aimed to identify the appropriate combination of parameters to most accurately determine EMG onset with a variety of trace types. Identification of a computer algorithm that accurately identifies the onset of EMG will provide a method to increase the objectivity of EMG onset determination that is independent of the experience or bias of the examiner.

2. Methods and materials

2.1. Subjects

The study involved a random sample of recordings of EMG activity collected for another study (Hodges and Richardson, in preparation), involving 4 subjects (18–24 years old) of average height (1.59–1.85 m) and weight (55–75 kg). The study was approved by the Medical
The electromyographic activity of a selection of trunk and limb muscles was recorded using a combination of surface and fine-wire electrodes during a series of rapid upper limb movements. Fine wire electrodes were fabricated from Teflon-coated stainless steel wire (75 μm) with 1 mm of wire exposed. The bent tips of the wires were staggered at 1 and 3 mm to help maintain separation between the exposed ends. Electrodes were inserted into transversus abdominis, obliquus abdominis internus, obliquus abdominis externus and posterior gluteus medius. Ag/AgCl surface electrodes were placed in parallel with the muscle fibres with an interelectrode separation of 12 mm over rectus abdominis, the anterior, middle and posterior portions of the deltoid muscle and the lumbar multifidus. Prior to surface electrode attachment the skin was prepared using a standard method to reduce the skin impedance to below 5 kΩ.

In a standing position subjects performed 10 repetitions each of rapid shoulder flexion, abduction and extension in response to a visual stimulus. The movement stimulus was preceded by a visual warning by a random period of between 0.5 and 4 s.

EMG signals were bandpass filtered at 10–1000 Hz (Basmajian and Deluca, 1985; Perry, 1992) and sampled at a rate of 2000 Hz with 12 bit analog to digital conversion using an AMLAB workstation (Associative Measurements, Australia). All data was saved on computer for further analysis.

2.3. Evaluation of movement onset and duration

The duration of the movement of the limb was evaluated to provide a relative indication of the magnitude of the error associated with each computer-based criterion compared to the duration of the movement task. The duration of the movement was measured using a Position Velocity Transducer (UniMeasure, USA) which measures the velocity and distance of distraction of a cable from the apparatus during limb movement. The cable was attached to the wrist at a distance of 0.5 m from the approximate centre of rotation of the shoulder. The data was sampled at 100 Hz and stored on computer for later analysis. For the purpose of the current study the time from the stimulus to the onset of movement and the duration of the movement were evaluated.

2.4. Electromyographic onset determination

Three hundred samples were randomly selected from the available data. Data represented a wide spread of degree of background activity, magnitude of burst and duration of burst and were separated into two categories of 150 traces each on the basis of background activity. All data with background activity greater than 20% of the mean of the rectified burst were categorised into the high background activity group. All traces were evaluated both visually and by a series of computer-based onset determination methods. If no onset could be determined by any particular method it was recorded as a missing value for the statistical analysis. Data in which the EMG onset was obscured by either movement artifact or a heart beat were eliminated so that the ability of the methods to identify true EMG onset could be evaluated. All EMG traces were full wave rectified prior to analysis.

2.4.1. Visual onset determination

An experienced examiner visually determined the onset of EMG activity on the basis of the earliest rise in EMG activity beyond the steady state (Horak and Nashner, 1986; Brown and Frank, 1987). The raw EMG data was not further low pass filtered after the initial 10–1000 Hz band pass filtering which has been recommended previously to facilitate the visual determination (Dick et al., 1986; Latash et al., 1995). This was done to avoid biasing the agreement of the visually determined onsets with computer-based methods using similar data smoothing. All trials were displayed on a computer screen using interactive graphical software enabling the examiner to determine the onset to the nearest millisecond. Each muscle was displayed separately on the screen with no reference to the start of the movement to remove potential bias of the examiner. The examiner calculated the onset times for all traces on 2 separate days, 3 days apart, to evaluate the repeatability of the visual recordings. The mean of the visually determined onset times between days was used for evaluation of the computer-based methods.

2.4.2. Computer-based onset determination

Twenty-seven different combinations of parameters were evaluated in the study. The basic algorithm involved identification of the point where the mean of a specified number of samples exceeded the baseline activity level (averaged for the 50 ms prior to the warning stimulus) by a specified number of standard deviations. The point at which the magnitude of the EMG trace exceeded this preset threshold was determined using a sliding window, the width of which was varied. The time of the initial sample of the window was recorded if the mean of the samples in the window exceeded the threshold. If the mean of the samples in the window did not exceed the criteria the window was advanced one sample at a time until an onset was found. If no onset was found within 2 s (4000 samples) a missing value was recorded for that trace.

The parameters evaluated corresponded to those previously described in the literature (see Table 1). Firstly, the degree of smoothing of the EMG was varied using a sixth order elliptical low pass software filter at each of 3
different values (10, 50, 500 Hz). Although low pass filtering at 10 Hz would remove much of the information of the trace after the initial high pass filtration at this frequency, the principle of filtering at or below the initial high pass filtration has been expounded by several authors (Dick et al., 1986; Steele, 1994) and was included to evaluate the effect of excessive filtering. In contrast, the upper frequency limit of 500 Hz is higher than the majority of the signal detected by surface electrodes, due to low pass filtration by the tissues (Perry, 1992), resulting in minimal further smoothing of the data. This condition was included to evaluate the effect of inadequate filtering. The other parameters evaluated were the number of samples assessed in the sliding window (20, 50, 100 samples or 10, 25, 50 ms) and the magnitude of the deviation from the baseline required to indicate the threshold (1, 2, 3 SD). All 27 possible combinations were evaluated. Processing was done using MATLAB’s signal processing toolkit (The MathWorks, USA).

2.5. Statistical analysis

To evaluate the repeatability of the visually determined onset times between days the coefficient of variation (CV) and root mean square error (RMSE) were calculated. For the comparison of the visual and computer determined onset times the correlation between the two methods was calculated. Pearson’s $r$ determines the closeness of fit of the two variables to a linear relationship, i.e. linear regression line (Weaver, 1983), and is unable to discriminate between relative amplitudes of the two variables. Therefore, linear regression equations were calculated using the mean of the visually determined onset times between days as the independent variable to identify the degree to which the computer-determined values deviated from those determined visually. All analyses were undertaken on the data by group (low and high background activity) and with the data from both groups combined.

3. Results

3.1. Visual determination repeatability

To evaluate the repeatability of the visually determined EMG onset times between days the coefficient of variation (CV) and root mean square error (RMSE) were calculated. For the comparison of the visual and computer determined onset times the correlation between the two methods was calculated. Pearson’s $r$ determines the closeness of fit of the two variables to a linear relationship, i.e. linear regression line (Weaver, 1983), and is unable to discriminate between relative amplitudes of the two variables. Therefore, linear regression equations were calculated using the mean of the visually determined onset times between days as the independent variable to identify the degree to which the computer-determined values deviated from those determined visually. All analyses were undertaken on the data by group (low and high background activity) and with the data from both groups combined.
ing CV of 0.52 and 0.26, respectively, and RMSE of 31.69 and 15.00, respectively.

### 3.2. Visual determination versus computer determination

The correlation between the computer-derived EMG onsets and the visually determined EMG onsets was extremely high for all methods ($r = 0.999, P < 0.0001$). Since the slope of the regression line ($r$) approached 1.0 for all of the methods evaluated, the $y$-intercept value can be considered to accurately depict the degree to which the computer-derived value ($O_c$) varies from the value determined visually ($O_v$), using the equation of the regression line: $O_c = 0.999O_v + y$-intercept.

Therefore, the value of the $y$-intercept indicates the mean value that must be added to the visually determined onset time to approximate the value that would be determined by computer. The $y$-intercepts calculated for all 27 of the evaluated parameter combinations is presented in Table 2.

The $y$-intercept for the majority of methods was significantly different from zero. Three combinations of parameters resulted in regression lines with a $y$-intercept that did not significantly deviate from the visually derived data (50 ms/1 SD/50 Hz, 25 ms/3 SD/50 Hz and 10 ms/1 SD/500 Hz). The $y$-intercept for the rest of the parameter combinations ranged from 20.6 to 153.49 ms (ignoring the sign of the value).

The number of traces in which no onset could be determined by each method was also calculated (Table 2). The number of trials rejected was zero for the majority of trials but was as great as 240 when the criteria were most conservative (50 ms/3 SD/500 Hz).

### 3.3. Background activity level comparison

When the computer and visually derived EMG onsets were compared for the low and high background activity groups separately there was some overlap between the methods with $y$-intercepts not significantly different from zero (Table 2). The 25 ms/3 SD/50 Hz and 50 ms/1 SD/50 Hz parameter combinations satisfied this criteria for both groups. For the low background activity group the 50 ms/2 SD/50 Hz and 10 ms/1 SD/500 Hz parameter combinations also satisfied this criteria as did 25 ms/2 SD/50 Hz for the high background activity group.

The number of trials rejected with no discernible onset was greatest for the high background activity group. This occurred most frequently for the 50 ms/3 SD/500 Hz parameter combination, rejecting 142 of the 150 trials in this group.

### 3.4. Movement reaction time and duration

The mean ± SD of the reaction time (stimulus to movement initiation) for the movement of the limb was 285 ± 33 ms and the mean movement duration (movement initiation to completion) was 194 ± 36 ms. Therefore, the mean duration of the recording from stimulus to the completion of movement was 479 ms. The errors in determination of the EMG onset ranged from 7 to 167% of the reaction time and 4 to 99% of the total movement time.

### 4. Discussion

The results indicate that the EMG onsets determined by the computer using the majority of the parameter combinations assessed vary significantly from the EMG onsets selected by visual determination. Although two parameter combinations accurately approximated the onset times regardless of the level of background, it was more common for the measurement to be less accurate when the background activity was high. Care should be used when selecting the appropriate analysis technique since errors of up to 167% of the reaction time may result from inappropriate methods, which is far in excess of the differences in EMG onset previously reported between postural conditions, age groups and pathologies (Traub et al., 1980; Cordo and Nashner, 1982; Woollacott and Manchester, 1993).

The high correlation between the visually derived values and those identified using each of the computer methods indicates that the associated error is systematic, i.e. all computer-derived EMG onsets using a particular method vary from the visually derived values by the same amount. Accordingly, comparisons between muscles with similar background EMG activity is reasonable with any method since the error is identical. In contrast, when relating the onset of EMG to a time or movement event or when muscles with differing levels of background EMG activity are to be compared the systematic error is critical and the combination of parameters should be considered.

### 4.1. Influence of parameters on onset determination

Low pass filtration is performed to remove the higher frequency components of the signal producing a smoother trace to assist the identification of the EMG onset (Soderberg and Cook, 1984) (Fig. 1). However, excessive smoothing of the data results in a loss of information and inaccurate identification of EMG onset (Halbertsma and DeBoer, 1981; Soderberg and Cook, 1984; Gabel and Brandt, 1994). Correspondingly, the errors associated with low pass filtration at a frequency identical to the lower limit of the initial bandpass filtering (10 Hz) in the current study resulted in errors of 56.44–144.87 ms prior to the visually determined value. Care must be taken when considering the results of studies where excessive smoothing of the data is undertaken (e.g. Dick et al., 1986; Steele, 1994).

In contrast, insufficient data smoothing results in delayed identification of EMG onset due to the high frequency changes in amplitude, resulting in a reduced mean...
were found to be non-significantly different from the parameter combinations involving each threshold level condition relative to the other threshold criteria, individual cate delayed EMG onset determination with the 3 SD condition. Although the results of the current study indicated the EMG onset when it occurs. The frequency of changes in baseline activity, which is rarely silent in pos-

Another method used to reduce the influence of background activity is the subtraction of the mean of the baseline activity level from the trace (Bullock-Saxton, 1994). This method would fail to remove erratic bursts of baseline activity of larger amplitude than the mean. Although several researchers have recommended instructing the subject

4.2. Influence of the signal-to-noise ratio

The benefit of a threshold based on the statistical deviation from the baseline is that it is normalised to the erratic changes in baseline activity, which is rarely silent in post-tural tasks. Consequently, the onset value identified by computer for traces with high background activity was consistently delayed relative to the visually determined value (Fig. 2). Although it was anticipated that different parameter combinations would be ideal for each background activity level group, there was considerable overlap between the most accurate parameter combinations for each group (Table 2).

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Fig. 1. Representative EMG traces from a single trial indicating effect of low pass filtering. (A) Full wave rectified raw EMG; (B) 500 Hz low pass filter; (C) 50 Hz low pass filter; (D) 10 Hz low pass filter. The onset determined using the 25 ms and 1 SD criteria is marked for each filter type as well as the visually determined onset for the full wave rectified raw EMG trace. Note the inaccuracy in onset determination resulting from the different levels of smoothing of the data.
to consciously relax the muscles of interest prior to data collection to limit the influence of this problem (Lee, 1980; Badke and DiFabio, 1985), potential changes in behaviour caused by this intervention need to be considered.

The most accurate comparison between muscles is achieved when the characteristics of the EMG traces are similar. When the trace characteristics vary widely, particularly in terms of the signal-to-noise ratio, then the use of separate onset determination criteria should be considered.

4.3. Other criteria involved in EMG onset determination

Several studies have included further criteria to minimise the chance of type I errors such as dictating that the median value (Lee et al., 1987) or a minimum number of samples within the window are required to exceed the threshold (Studenski et al., 1991; Steele, 1994). The addition of these criteria would assist in the rejection of erratic short duration bursts of background activity. Assignment of the middle sample of the window rather than the initial sample as the onset may reduce the influence of slope of EMG increase.

In contrast to the statistically based threshold criteria, several authors have developed methods based on the time taken to reach a predetermined EMG amplitude (Greenisen et al., 1979; Bullock-Saxton et al., 1993; Bullock-Saxton, 1994). Identification of the EMG onset as the point where the EMG amplitude reaches 5% of the peak value following prior subtraction of the background activity level (Bullock-Saxton et al., 1993; Bullock-Saxton, 1994) is potentially inaccurate due to the sensitivity of this technique to the magnitude of the peak and the rate of increase in amplitude which are likely to vary between muscles. The onset of EMG would be delayed when the EMG trace is of large amplitude and when the rate of increase is gradual. Other methods in which a minimum magnitude criteria is used would also be associated with delayed EMG onset identification (Happee, 1992).

Several authors have suggested techniques to average (Bogey et al., 1992; Gitter, 1994) or summate (Ellaway, 1978) EMG traces to determine a representative timing profile that is less influenced by random variation. The accuracy of these techniques has not been evaluated against visual determination of onset time.

4.4. Considerations for computer determination of EMG onset

Interference of EMG traces by movement artifact or electrocardiograms may obscure the onset of EMG activity (Bruce et al., 1977) (Fig. 3). For this reason, any completely automated method for identification of EMG onset needs to recognise and reject traces in which the EMG onset is confused by this interference. Currently, no method exists with the complex pattern recognition skill required to perform this task. Until this is achieved it is necessary to visually check each trace against the computer-derived value to ensure that the onset is meaningful. In the current study, traces in which the onset was obscured were excluded so that the accuracy of each method could be determined for the evaluation of true EMG onset. Furthermore, visual verification of the trace can ensure that the onset of EMG has not be overlooked if the burst duration is short or of low magnitude (Neafsey et al., 1978; Lee et al., 1987).

Finally, regardless of the criteria used the onset of EMG determined by computer is likely to be influenced by the rate of increase in EMG amplitude (Walter, 1984), such as slow movements, which would result in a delay in onset identification (Horak et al., 1984; DiFabio, 1987). It is recommended that special care be taken with the visual verification of computer-determined onset times with this type of data and lower threshold values may be beneficial. Further evaluation of threshold levels for the determination of onset with this type of data would be beneficial.

4.5. Conclusions and recommendations

In summary, several combinations of parameters have been identified that allow for accurate determination of EMG onset using computer-based algorithmic calculations. The advantage of these methods is an increased objectivity of analysis, reduced time required to perform the analysis and a reduced requirement for experimenter
experience, as the only requirement is to ensure that movement artifact or other interference is not wrongly determined as the EMG onset. It is recommended that the characteristics of the EMG trace should be considered when selecting the appropriate parameter combination for analysis.

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