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ORIGINAL ARTICLE

Dario Farina · Pascal Madeleine
Thomas Graven-Nielsen · Roberto Merletti
Lars Arendt-Nielsen

Standardising surface electromyogram recordings for assessment of activity and fatigue in the human upper trapezius muscle

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Abstract The objectives of this work were to determine optimal surface electromyogram (EMG) electrode locations, and inter-electrode distance (IED), when assessing activity and fatigue in the human upper trapezius muscle. Surface EMG signals were recorded from the upper trapezius muscle of 11 healthy male subjects using a linear array of 16 surface electrodes. Five arm positions were investigated (arms at the side of the body, 45° and 90° flexion, 45° and 90° abduction). Fatiguing (1 kg hand load held for 3 min) and non-fatiguing (no load, 0.5 kg and 1 kg hand load held for 3 s) contractions were made. The variabilities of the average rectified value, root mean square, mean and median power spectral frequency and slope over time of these parameters as functions of electrode location and IED (from 5 mm over a range of 35 mm in steps of 5 mm) were quantitatively evaluated. A criterion for selecting the optimal electrode position was applied. This criterion indicated an optimal location measured from the acromion (38% of the distance from the lateral edge of acromion to the spine of the seventh cervical vertebra) which was statistically the same for all the EMG descriptors, arm positions and IED investigated. Finally, it was found that both EMG variables and indexes of muscle fatigue depended on IED which should thus be properly standardised. On the basis of the sensitivity of the EMG descriptors to electrode location and cross-talk reduction, an IED of 20 mm is suggested when a global analysis of activity in the upper trapezius muscle is made using a single pair of electrodes. This study emphasises that a surface EMG analysis of the upper trapezius muscle, following a proper placement of the electrodes and selection of IED, can give reliable indications of muscle activity and fatigue. Data on the myoelectric manifestations of muscle fatigue of the upper trapezius muscle are provided for the optimal electrode location.

Keywords Surface electromyography · Linear electrode arrays · Innervation zone · Upper trapezius muscle assessment

Introduction

Considerable effort has been devoted in the past to understanding the sensitivity of variables of the surface electromyogram (EMG) to the parameters of the detection system (Hermens et al. 2000). It is well known that features of the surface EMG signal strongly depend on electrode location (Gydikov and Kosarov 1972; Zuniga et al. 1970), inter-electrode distance (IED) and detection spatial filter (Korosec 1999; Merletti and Roy 1996; Merletti et al. 1999b, c; Roy et al. 1986). Predictions from models have been of help in understanding the variations of surface EMG amplitude and spectral content along the muscle fibres. The presence of two waves of excitation that propagate from the end-plates to the tendons implies that not all the locations for the detection of the signal are equivalent (Dimitrov and Dimitrova 1974). Modelling studies indicate that end-of-fibre and end-plate effects determine large biases in the estimation of amplitudes (Dimitrova 1974; Gydikov et al. 1986) and spectral variables (Dimitrov and Dimitrova 1998a, b). The innervation zone (IZ) corresponds to a minimum in amplitude and maximal in mean and median power spectral frequencies (MNF, MDF, respectively) of the surface EMG signals detected in a single differential configuration. Thus, electrode locations in general should be chosen on the basis of information about the position of the IZ. The IZ can be

D. Farina (✉) · R. Merletti
Centro di Bioingegneria, Dept. of Electronics,
Politecnico di Torino, Corso Duca degli Abruzzi 24,
Turin 10129, Italy
E-mail: farina@athena.polito.it
Tel.: +39-011-4330476
Fax: +39-011-4330404

D. Farina · P. Madeleine · T. Graven-Nielsen · L. Arendt-Nielsen
Centre for Sensory-Motor Interaction,
Aalborg University, Aalborg, Denmark

detected by using multi-channel surface EMG systems, such as linear electrode arrays (Masuda et al. 1985; Merletti et al. 1999a). However, in clinical examinations or in long-term measurements in field studies, the use of complex detection systems may not be feasible and a general indication is needed of the regions of the muscle from which reliable assessments of muscle activity using surface electrodes is possible. The methodological aspects of electrode placement are even more important in contractions at different muscle lengths since there will be changes in the muscle-electrode relative position (Farina et al., in press; Rainoldi et al. 2000).

Musculo-skeletal disorders of the neck and shoulders are frequently reported among workers in different occupations. The involvement of a great number of muscles of the neck-shoulder region during static and dynamic tasks highlights the complexity of the shoulder girdle. In occupational studies, the trapezius muscle is usually investigated by analysis of the surface EMG signal (Capodaglio et al. 1996; Chan et al. 2000; Hansson et al. 2000; Jensen et al. 1993b; Madeleine et al. 1999) since this muscle is superficial and its activity is influenced by pain in the neck-shoulder region (Madeleine et al. 1999; Westgaard 1999). Both amplitude and frequency surface EMG analysis (Hagberg and Hagberg 1989; Nieminen and Hameenoja 1995; Madeleine et al. 1999; Oberg et al. 1990) and assessment of muscle fatigue (Hagberg and Kvarnstrom 1984; Hagg 1992; Oberg et al. 1994; Persson et al. 2000) based on single differential detection systems have been often used. Some studies have also addressed the methodological problems of electrode location and geometrical artefacts in the upper trapezius muscle (Jensen et al. 1993a; Jensen and Westgaard 1997; Kleine et al. 2000; Oberg et al. 1992), providing important indications about the potential and limitations of surface EMG techniques in estimating load and fatigue of the shoulder (for a review, see Mathiassen et al. 1995).

Recommendations concerning methodological issues related to the design of detection systems and electrode placement, however, still lack a general consensus. In past studies, only limited quantitative analyses of the variability of the EMG descriptors with electrode location have been provided. Moreover, the suggested electrode locations indicated in the literature have been for specific EMG variables (e.g. amplitude in Jensen et al. 1993a), while it is not known whether each EMG descriptor requires for its optimal estimation a particular electrode placement or if the same location can be used for the assessment of amplitude, frequency content and fatigue. Finally, there is no report in the literature which gives an indication of how IED affects the selection of the optimal electrode location and of the sensitivity of EMG features to muscle-electrode movements. The main purpose of this work was to fill this gap in the methodological aspects of the assessment of the surface EMG of the human upper trapezius muscle. The study also provided indications about activity in the upper trapezius muscle and fatigue in different postures in a group of healthy subjects.

Methods

Subjects

A group of 11 male subjects [mean (SD) age 25.2 (2.7) years, body mass 71.5 (6.2) kg, height 180.4 (7.9) cm, distance from the acromion to C7 21.5(1.0) cm] participated in the experiment after giving informed consent. All the subjects were healthy and had no history of injuries or neck-shoulder pain. The study was conducted in conformity with the Declaration of Helsinki.

Experimental protocol

After placement of the electrodes for signal detection (see below), the subject stood in an erect posture (shoulder girdles abducted) with the two arms in one of the five positions investigated (0° abduction and 0° flexion, i.e. arms at the side of the body, 45° and 90° flexion, 45° and 90° abduction). The elbows were held straight with the hands pronated at 90° from the anatomical position. The five positions were investigated in a random sequence. For each position, three reference contractions, lasting 3 s, were made at no load, and supporting loads of 0.5 kg and 1 kg in both hands (experiment 1). A rest of 2 min was given between each reference contraction. After the reference contractions, the subject was asked to maintain the selected arm position supporting a 1 kg load in each hand for 3 min (fatigue task; experiment 2). After each fatigue task, the subjects rested for 15 min on a chair. The same procedure was repeated once in each experiment session, without removal of the electrodes, for each of the five arm positions.

Signal recording

The EMG signals were detected from the surface of the skin above left upper trapezius muscle using a linear array (Masuda et al. 1985; Merletti et al. 1999a) of 16 silver electrodes (bar 5 mm long, 1 mm diameter, 5 mm IED between centres). The array was placed on the straight line between the spine of the seventh cervical vertebra (C7) and the lateral edge of acromion (Jensen et al. 1993a). The electrode locations over the muscle will be indicated in the following as the distance from acromion, normalized with respect to the acromion-C7 distance (and reported in percentages). The location of each single differential recording system is defined as the mid-point between the two electrodes constituting the system. Signal quality was checked in a few trials before placing the array in order to select the best orientation of the array corresponding to a clear propagation of the motor unit action potentials (MUAP) from the IZ to the tendon region. The array was located so as to cover the main IZ and to follow the propagation of the action potentials from the IZ to the distal tendon region. The array was fixed with adhesive tape and was flexed so as to follow the natural shape of the back. The amount of muscle covered by the surface electrodes was 75 mm (16 electrodes and 5 mm IED). The skin was cleaned and slightly abraded before electrode placement.

The signals were detected in single differential mode to minimise line interference, amplified and filtered (10–500 Hz, 3 dB bandwidth), sampled at 2,048 Hz, converted to a numerical format using a 12 bit A/D converter and stored on a disk (amplifier LISiN-SEMA Electronics, Turin, Italy). The single differential detection was performed between adjacent electrodes resulting in an IED of 5 mm. By summation of consecutive single differential signals detected with 5 mm IED, the single differential signals resulting from IED multiple of 5 mm (i.e. 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm and 40 mm IED) were obtained. Examples of surface EMG signals detected during one experiment session in the five arm positions with 5 mm IED are shown in Fig. 1. The presence of propagating MUAP is evident in the five cases. The IZ can be located by visual inspection of the array signals as the point of inversion of the propagation of the MUAP.

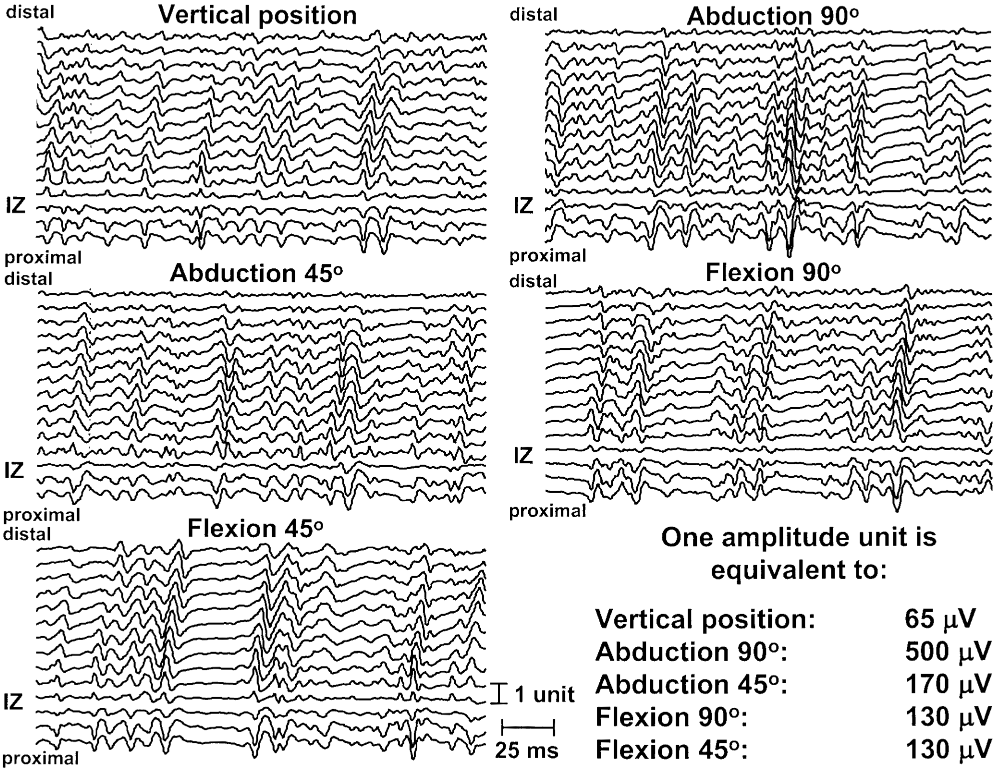

Fig. 1 Surface electromyogram signals detected from one of the subjects in the five arm positions investigated supporting a hand load of 1 kg, using a linear array of 16 electrodes in single differential mode with interelectrode distance of 5 mm (non fatiguing contractions). The concomitant presence of travelling and non-travelling components can be observed. In all the positions the innervation zone (*IZ*) can be clearly detected. For each condition, the signal recorded more distally and that more proximally is indicated

EMG signal analysis

Average rectified values (ARV), root mean square values (RMS), MNF and MDF were calculated from all the signals detected in epochs of 1 s, without overlapping, using algorithms that have been described in many previous publications (for a recent review, see Farina and Merletti 2000). The computations were performed for eight IED (5–40 mm in steps of 5 mm) and for all electrode locations (15 locations for 5 mm IED, 14 locations for 10 mm IED, etc. up to 8 locations for 40 mm IED). The three estimates of each EMG variable obtained from the 3 s signals in experiment 1 were averaged after discarding any epochs showing artefacts. Linear regression analysis over time was applied to the data from experiment 2 (fatiguing contractions) and the slopes of the EMG variables, estimated over the 3 min interval, were used as indexes of fatigue (Merletti et al. 1990; Merletti and LoConte 1995).

The effect of electrode location on EMG variables and indexes of muscle fatigue was assessed by:

1. The difference between the maximal and the minimal values of the estimations along the array (i.e. the maximal percentage variation, Δ_{tot}, expected from different electrode locations)
2. The minimal difference between estimates from adjacent electrode locations (i.e. the minimal percentage variation, Δ_{min}, expected from electrode movements of ±5 mm).

Specifically, the following definitions have been introduced:

$$\Delta_{\mathrm{tot}} = \frac{\max_i \gamma_i - \min_i \gamma_i}{\bar{\gamma}} \times 100$$

$$\Delta_{\mathrm{min}} = \min_i \left\{ \frac{|\gamma_i - \gamma_{i-1}| + |\gamma_i - \gamma_{i+1}|}{2\gamma_i} \right\} \times 100$$

where γ_i represents the value of a generic EMG variable or index of muscle fatigue estimated at location i and $\bar{\gamma}$ is the mean value of the estimates along the array.

The *best* electrode location was defined as that corresponding to Δ_{min}. This criterion for selecting the optimal electrode location resulted in the minimal sensitivity to small differences in electrode location (smaller than ±5 mm). A similar approach, but applied to estimations of mean muscle fibre conduction velocity and MNF, for the objective selection of electrode location has previously been used for the biceps brachii muscle (Merletti et al. 2002) and has provided highly reliable estimations of EMG variables. The location of the IZ and its shift with respect to the recording electrodes has been estimated from the signals in experiment 1 by monitoring the dip in EMG ARV with 5 mm IED (Masuda et al. 1985).

Statistical analysis

Regression lines of ARV, RMS, MNF and MDF as functions of time were computed using the least squares method. The data were analysed using one-, two- or three-way repeated measurements analysis of variance (ANOVA), followed by post-hoc Student-Newman-Keuls (SNK) pair-wise comparisons when required. Statistical significance was set to $P < 0.05$. Data are presented as means and standard errors (SE).

Results

Experiment 1 – non-fatiguing contractions

Location of the IZ and its shift with arm position

A characteristic amplitude pattern along the array, with a plateau region, a dip corresponding to the main IZ of the superficial motor units (MU) and a decrease approaching the distal tendon region, was observed in all cases. The dip in EMG amplitude corresponded to a peak in frequency variables and the decrease of amplitude at the tendon was associated with an increase of the characteristic frequencies (Fig. 2). The dip in amplitude

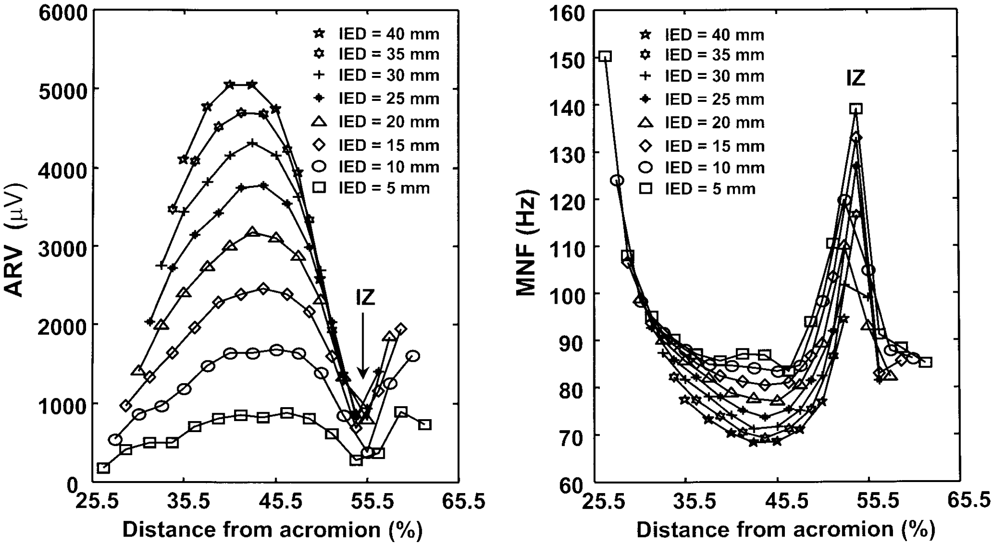

Fig. 2 Example of variability of average rectified value (*ARV*) and mean power frequency (*MNF*) as a function of electrode location and interelectrode distance (*IED*) in one subject. The arms are 90° abducted and supporting a 1 kg hand load (non-fatiguing contractions). The distance from the acromion is given as a percentage of the acromion-C7 distance

and the peak in frequency variables always corresponded to the point of inversion of MUAP propagation (see also Fig. 1). The RMS and MDF showed patterns along the array similar to those of ARV and MNF, respectively. By visual inspection of the raw data, or by the analysis of the patterns of amplitude and frequency variables, a single main IZ was identified in all cases.

The location of IZ, as a percentage of the distance between the acromion and C7 (measured from the acromion) was significantly different among the five arm positions (one-way ANOVA, $F=6.06$, $P<0.001$) and was on average 53.21 (0.94)%, 52.50 (1.03)%, 54.11 (1.13)%, 51.84 (1.35)%, 52.07 (1.28)% in the five arm positions (0° abduction and 0° flexion, 45° and 90° flexion, 45° and 90° abduction). The post-hoc SNK test disclosed pair-wise differences between the location of IZ at 45° abduction and at all the other arm positions except for 0° abduction and 0° flexion.

Variability of amplitude and spectral features

The Δ_{tot} (Eq. 1) for the four EMG variables computed from the reference contractions for different IED are shown in Fig. 3. The Δ_{tot} decreased for increasing IED from about 60% to about 40% in case of frequency variables and from about 115% to about 75% in case of amplitude variables. A three-way (IED, EMG variable and arm position) ANOVA of Δ_{tot} revealed a statistically significant dependence of Δ_{tot} on IED ($F=30.59$, $P\ll0.001$) and EMG variable ($F=76.19$, $P\ll0.001$) but not on arm position. The post-hoc SNK test disclosed pair-wise differences between 5 mm and 10 mm IED and all the other IED, between 15 mm IED and all the others except 20 mm and 25 mm, and between the pairs 20–40 mm, 25–40 mm, and 30–40 mm. In addition, the post-hoc SNK tests disclosed no statistically significant difference between ARV Δ_{tot} (mean 86.43%) and RMS Δ_{tot} (mean 85.33%) and between MNF Δ_{tot} (mean 45.81%) and MDF Δ_{tot} (mean 48.20%). The ARV and RMS Δ_{tot} were significantly higher than MNF and MDF Δ_{tot} ($P<0.001$).

The $\Delta_{\min}$ (Eq. 1) for the four EMG variables as a function of IED for the reference contractions is shown in Fig. 4. A three-way (IED, EMG variable, arm position) ANOVA of $\Delta_{\min}$ revealed a statistically significant dependence of $\Delta_{\min}$ on IED ($F=4.76$, $P<0.001$) and EMG variable ($F=31.66$, $P\ll0.001$) but not on arm position. The post-hoc SNK test disclosed pair-wise differences between 5 mm IED and all the other IED. The post-hoc SNK test disclosed no statistically significant difference between ARV (mean 4.41%) and RMS (mean 4.09%) $\Delta_{\min}$ and between MNF $\Delta_{\min}$ (mean 2.07%) and MDF $\Delta_{\min}$ (mean 2.62%). The ARV and RMS $\Delta_{\min}$ were significantly higher than MNF and MDF $\Delta_{\min}$ ($P<0.001$). A rather wide range of minima of $\Delta_{\min}$ is observed in the IED range 15–25 mm.

Dependence of EMG variables on IED

The dependence of the EMG variables on IED in the five arm positions in the case of the optimal ($\Delta_{\min}$) location (for all IED the optimal location identified for IED = 5 mm has been used) is shown in Fig. 5. The amplitude monotonically increases and the characteristic frequencies decrease along the IED range investigated. The relative increase of the amplitude with IED is much higher than the relative decrease of the characteristic frequencies. A three-way ANOVA of ARV (arm position, IED and load in the reference contraction) was significant ($F=24.84$, $P\ll0.001$; $F=42.61$, $P\ll0.001$; $F=8.47$, $P<0.01$, respectively). The post-hoc SNK test disclosed pair-wise differences between the arm position 0° abduction and 0° flexion and the position with arms abducted at 90° and abducted at 45° ($P<0.01$) and between arms at 90° and 45° abduction. Moreover, there was a statistically significant difference of ARV

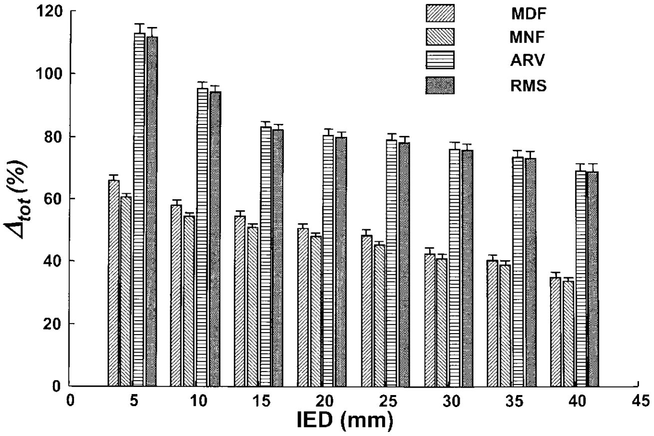

Fig. 3 Mean (SE, $n = 165$) of the maximal variation (Δ_{tot}, expressed as percentages) for the four electromyogram variables as a function of interelectrode distance (*IED*) for all the reference (non-fatiguing) contractions recorded (11 subjects, 3 reference contractions, 5 arm positions, for a total of 165 contractions). *MDF*, *MNF* Mean and median power frequency, respectively, *ARV* average rectified value, *RMS* root mean square

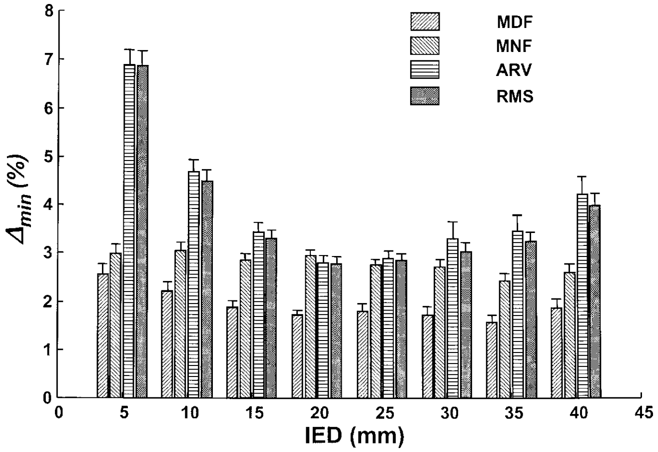

Fig. 4 Mean (SE, $n = 165$) of minimal variation (Δ_{min}, expressed as percentages) for the four electromyogram variables as a function of *IED* for all the reference (non-fatiguing) contractions recorded (11 subjects, 3 reference contractions, 5 arm positions, for a total of 165 contractions). Definitions as for Fig. 3

computed from the different IED except for 15 mm and 20 mm, 25 mm and 30 mm, and 35 mm and 40 mm. Statistically significant differences in ARV were found between the 1 kg hand load [634.8 (41.7) µV] and the other loads ($P < 0.01$) but not between no load and the 0.5 kg hand load [441.9 (38.5) µV for no load and 475.1 (28.9) µV for 0.5 kg]. The same results were obtained from RMS analysis.

A three-way ANOVA of MNF (arm position, IED and load in the reference contraction) indicated a significant dependence on IED ($F = 24.82$, $P \ll 0.001$) but not on arm position or load. Pair-wise differences were found between MNF computed with 5 mm, 10 mm and 15 mm IED and all the other IED except between 10 mm and 15 mm. Similar results were obtained for MDF.

Experiment 2 – fatiguing contractions

Variability of fatigue indexes as a function of electrode location

The Δ_{min} of slope for the four EMG variables for different IED are shown in Fig. 6. A three-way ANOVA (IED, EMG variable and arm position) of Δ_{min} slope revealed a statistically significant dependence on IED ($F = 15.03$, $P \ll 0.001$) but not on EMG variable or arm position. The post-hoc SNK test disclosed pair-wise differences for the IED of 5 mm and all the other IED values ($P < 0.001$) and for 10 mm IED and IED equal to, or larger than, 25 mm.

Dependency of fatigue indexes on IED

The slopes of the four variables in the five arm positions as a function of IED for the location corresponding to Δ_{min} (for all IED the optimal location identified for IED = 5 mm has been used) are shown in Fig. 7. A two-way (arm position and IED) ANOVA of ARV slope revealed a statistically significant dependence on arm position ($F = 11.95$, $P \ll 0.001$) and IED ($F = 27.77$, $P \ll 0.001$). The post-hoc SNK tests disclosed pair-wise differences between all the arm positions ($P < 0.01$) except between abduction 45° and flexion 45°. Moreover, the post-hoc SNK tests disclosed pair-wise differences between all pairs of IED which differed by 10 mm or more. The same results were obtained for RMS.

A two-way (arm position and IED) ANOVA of MNF slope revealed a statistically significant dependence on arm position ($F = 4.37$, $P < 0.01$) but not on IED. The post-hoc SNK tests disclosed pair-wise differences between the arm position 45° flexion and all the other arm positions. The same results were obtained for MDF.

Optimal electrode location

The optimal electrode location was defined as that corresponding to Δ_{min} and was expressed as the distance from the acromion as a percentage of the acromion-C7 distance. This criterion led to an electrode location for each condition analysed (arm position, IED, EMG descriptor). The hypothesis that optimal electrode location was not dependent on the different conditions and that a unique location could be used for a large set of experimental conditions was tested. The EMG descriptors included in the statistical analysis were ARV, RMS, MNF and MDF initial values (from experiment 1) and slopes (from experiment 2). A three-way (arm position, IED and EMG descriptor) ANOVA of electrode location was not significant. The average optimal electrode location (average for all the conditions and EMG

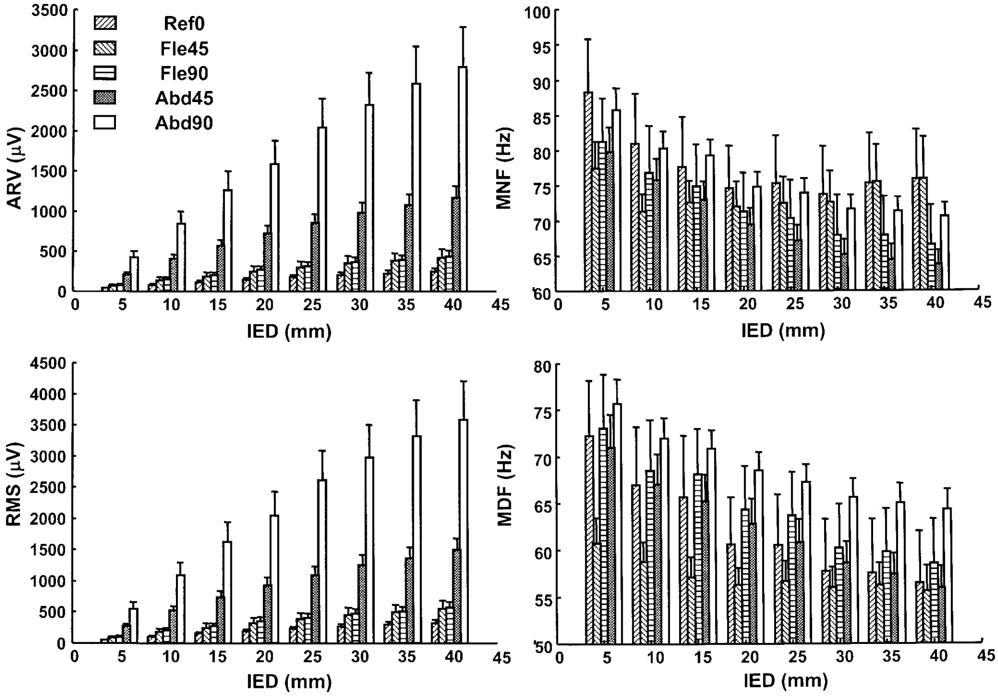

Fig. 5 Mean (SE, $n = 11$) of the four electromygram variables as a function of *IED* for the location corresponding to the minimal variation in case of IED = 5 mm, for all the arm positions and 1 kg hand load (non-fatiguing contractions). Ref0 indicates the position with hands at 0° abduction and 0° flexion, Fle45 at 45° flexion, Fle90 at 90° flexion, Abd45 at 45° abduction, Abd90 at 90° abduction. Definitions as for Fig. 3

descriptors, $n = 3{,}520$, resulting from eight IED, five arm positions, eight EMG descriptors, including the four EMG variable absolute values and slopes, 11 subjects) was 38.33 (0.11)%, corresponding to an average lateral distance of approximately 25 mm from the mid-point between the acromion and C7.

Discussion

Location of the IZ and its shift with changes in arm position

It was found that the upper trapezius muscle presents only one main IZ for the superficial MU in all the subjects investigated and in all arm positions. The location of IZ was on average about 52% of the distance between the acromion and C7, measured from the acromion. The small SE of the location of IZ indicated that the determination of IZ is very reproducible among different subjects. These results are in agreement with those reported by Jensen et al. (1993a) who showed the presence of a dip in the signal amplitude of the surface EMG on average at 52% of the distance from the acromion to C7. Similar indications have previously been provided by Veiersted (1991) who reported a dip in the amplitude of the EMG at 56% of the distance from the acromion to C7. The mid-point between the acromion and C7 has been, in contrast, suggested by Zipp (1982) as a good electrode location. The present study confirmed (Jensen et al. 1993a) that the mid-point between C7 and the acromion is a location to be avoided for electrode placement. We have investigated arm positions in the frontal and sagittal plane and observed a maximal average difference among IZ locations in the five positions of approximately 2% of the distance between the acromion and C7. The shift of the IZ with respect to the recording electrodes in different arm positions was expected, since in the different positions the trapezius muscle fibres have different lengths, and the skin moves over the muscle. The difference in IZ location was, however, small and statistically significant for only one arm position with respect to the others. This is in agreement with the results reported by Jensen et al. (1993a) who observed an approximately constant ratio between EMG amplitude at 0° and 90° arm abduction for almost the entire plateau amplitude region detected in their study.

Electrode placement

The need for standardised electrode locations in the upper trapezius muscle has been underlined in many recent reports (see for example Hermens et al. 2000; Jensen et al. 1993a). The results of this study on the maximal difference between amplitude and spectral variable estimates observed in the investigated electrode locations (Fig. 3) substantiate the importance of standardisation of electrode placement procedures. If placed in different locations in the 75 mm muscle portion investigated, with small IED, amplitude values and frequency variables may show differences of more than 100% and 60%, respectively (Fig. 3). With increasing IED the situation may improve, but the differences in estimation variables obtained in different locations are still unacceptable (Fig. 3). For proper comparisons between experimental sessions, standardisation is thus extremely important.

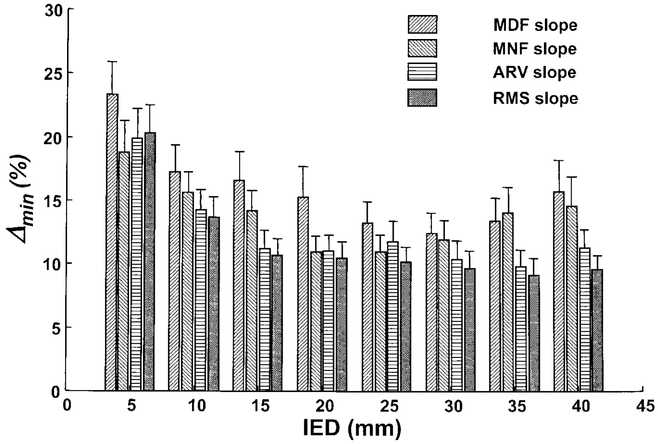

Fig. 6 Mean (SE, $n = 55$) of the minimal variation of the slope ($\Delta_{\min}$, expessed as percentages) for the four electromyogram variables as a function of *IED* for all the fatiguing contractions recorded (11 subjects and 5 arm positions, for a total of 55 contractions). Definitions as for Fig. 3

The main elements of novelty of this study with respect to previous work on electrode placement on the upper trapezius muscle were that a quantitative criterion was used to select the best position for placing the electrodes and that a large range of experimental conditions was studied. A previous study provided indications limited to EMG amplitude, to a fixed interelectrode distance and did not include fatigue related EMG changes (Jensen et al. 1993a).

The results that the optimal electrode location obtained in the present work was not significantly different for five arm positions, a large IED range and all the EMG descriptors analysed, including both absolute values and slopes of the EMG variables, provided a strong basis for the standardisation of electrode location. It indicated that single channel surface EMG analysis is a reliable tool for assessing activity in the upper trapezius muscle and its fatigue in a variety of experimental conditions. The shift of IZ was in fact rather limited in the range of arm positions investigated and did not affect significantly optimal electrode placement.

The present work also provided numerical indications of the sensitivity of EMG descriptors to small relative movements in electrode-muscle position in the optimal location indicated. This information is of paramount importance in ascertaining if differences between subject groups can be considered physiologically relevant or rather due to recording variability. It was shown, for example, that slopes of the EMG variables are more affected by small differences in electrode location than initial values of the EMG variables (compare results from Figs. 4 and 6). This result should be interpreted also in the light of the sensitivity of the EMG descriptors to other parameters in the EMG system, such as the subcutaneous tissue thickness (Farina and Rainoldi 1999).

IED selection

No studies have reported how IED affects the EMG descriptors and their sensitivity to electrode location in the upper trapezius muscle. In this work we found that IED strongly affects the EMG descriptors and provided the basis for a standard IED. All EMG descriptors were statistically influenced by IED except for the slopes of the frequency variables.

Amplitude and frequency variables have been observed to increase and decrease monotonically with IED, respectively (Fig. 5). From simulation studies a similar behaviour has been observed (Blok and Stegeman 1997). Moreover, the higher dependence of amplitude variables from IED with respect to frequency variables was also predicted from the analysis of simulated signals (Dimitrov and Dimitrova 1977; Lateva et al. 1990). In contrast with the present results, some modelling investigations have shown a plateau of amplitude values for IED larger than 25–30 mm (Blok and Stegeman 1997). However, this behaviour strongly depends on the properties (conductivity and thickness) of the subcutaneous tissue layers (Farina and Rainoldi 1999) and on the source depth (Dimitrov and Dimitrova 1977; Roeleveld et al. 1997). Thus, direct comparison with modelling studies may remain difficult. Moreover, cross-talk from other active muscles influences the estimated EMG amplitude in different ways for different IED, as detection systems with smaller IED are more selective (Merletti and LoConte 1995). The slope of the EMG amplitude also strongly depended on IED (Fig. 7).

Since EMG descriptors significantly change for small IED differences, IED should be properly standardized in comparing results from different studies. The selection of the IED should be based on quantitative criteria which describe how the reliability of the EMG analysis depends on IED. We observed that large IED reduce the dependence of EMG variables with respect to electrode location (see, for example, Figs. 3, 4, 6). Even though this effect was to be expected, it had never been investigated systematically before. Generally, larger IED are to be preferred if the anatomical landmarks of the muscle fibres cannot be assessed by a preliminary multichannel surface EMG investigation. From the present data, it appears that $\Delta_{\min}$ reaches a minimum around 20–25 mm IED (Figs. 4, 6). With respect to the case of 5 mm IED, $\Delta_{\min}$ of amplitude variables decreases on average to less than a half with larger IED (Fig. 4). A similar relative decrease of $\Delta_{\min}$ was observed for the slopes of the EMG variables (Fig. 6). In almost all the cases, for IED larger than 20–25 mm, $\Delta_{\min}$ did not change significantly with respect to its minimal value or slightly increased (see Fig. 4 for amplitude and Fig. 6 for frequency variables).

Cross-talk signals also depend on IED (Winter et al. 1994), with smaller IED resulting in higher selectivity than larger ones. Moreover, cross-talk depends also on electrode location. Recordings from the bulky belly of the upper trapezius muscle have been commonly

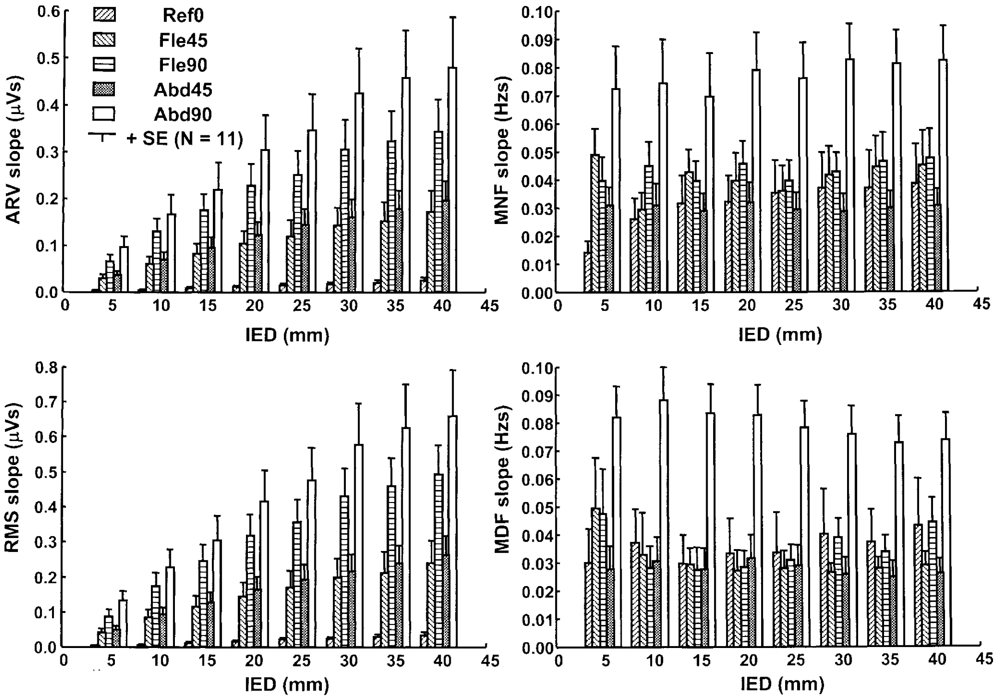

Fig. 7 Mean (SE, $n = 11$) of the slopes (absolute values) of the four electromyogram variables as a function of *IED* for the location corresponding to the minimal variation ($\Delta_{\min}$) in case of IED = 5 mm, for all the arm positions (fatiguing contractions). Ref0 indicates the position with hands at 0° abduction and 0° flexion, Fle45 at 45° flexion, Fle90 at 90° flexion, Abd45 at 45° abduction, Abd90 at 90° abduction. Definitions as for Fig. 3

assumed to be uncontaminated, while cross-talk is a recognised problem when detecting at locations where the upper trapezius is thin and covers other muscles, such as close to the vertebral column or close to the acromio-clavicular joint (Mathiassen and Winkel 1990). For this reason, very large IED should be avoided since they lead to low spatial selectivity and to a larger detection volume. Although the quantitative significance of cross-talk at different electrode locations above the upper trapezius muscle remains to be investigated, from our data on the variability of EMG features with electrode location we suggest an IED of 20 mm (also in line with previous recommendations by Hermens et al. 2000), which leads to a minimum of $\Delta_{\min}$ for almost all the EMG descriptors investigated. Larger IED lead to non significant decreases of $\Delta_{\min}$ for the most variables and probably determine higher cross-talk signals (Winter et al. 1994).

Amplitude and frequency variable selection

The ARV and RMS showed no statistically significant different $\Delta_{\min}$ either related to the absolute variable or to the slopes of the variable. The small difference in $\Delta_{\min}$ between the two variables was probably due to the variance of the two estimators which is known to be very similar (Farina and Merletti 2000). For frequency variables, the $\Delta_{\min}$ of the initial values and the slopes of MDF were not statistically different from the corresponding $\Delta_{\min}$ values for MNF. These results imply that the choice of the EMG spectral and amplitude descriptors is not relevant for getting reliable results, compared to the selection of IED and electrode location.

Conclusion

The main findings of this study were:

1. A single main IZ having a reproducible location (52%–54% of the distance between the acromion and C7) among subjects, corresponding to a dip in amplitude and a peak in spectral variables of EMG, was found in the upper trapezius muscle. The IZ shift in the range of arm positions investigated was significant only for one of the positions with a rather limited difference with respect to the others (maximal difference of 2.27% of the acromion-C7 distance, i.e. on average 4.8 mm).
2. The criterion applied for the selection of the best electrode placement indicated a lateral distance of approximately 25 mm from the mid-point between the acromion and C7. The criterion led to an optimal location for all EMG descriptors (absolute values and slopes of MDF, MNF, ARV, RMS) which does not depend on IED (in the range 5–40 mm) or arm position. Thus it can be used for a large set of experimental conditions.
3. The values of the EMG variables and slopes of the amplitude variables during fatigue significantly depend on IED. The IED should thus be standardised in order to compare muscle activity and fatigue in different studies.
4. Increasing IED from 5 mm to around 20 mm led to a marked decrease of the EMG descriptor $\Delta_{\min}$, while, for IED larger than 20 mm, $\Delta_{\min}$ did not further significantly decrease; it even slightly increased. A value of approximately 20 mm IED is suggested for a global muscle analysis.

5. The EMG descriptors computed from the optimal electrode locations defined allowed the statistical differentiation between activity and fatigue manifestations in the upper trapezius muscle in the different conditions investigated.

The contribution of this work was to provide indications about IED selection and electrode location for the assessment of the upper trapezius muscle in a large range of experimental conditions. The finding that the quantitative criterion used to select electrode locations led to non-statistically different optimal locations in all the conditions examined (different arm positions, IED and EMG descriptors) provided a strong basis for the standardisation of electrode placement and IED that has been recommended in previous studies. Reference data of myoelectric activity and manifestations of muscle fatigue in the experimental conditions investigated and with the optimal electrode location found have also been provided.

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References

Blok JH, Stegeman DF (1997) Simulated bipolar sEMG characteristics. In: Hermens HJ, Freriks B (eds) The state of the art on sensors and sensor placement procedures for surface electromyography: a proposal for sensor placement procedures. Roessingh Research and Development, Enschede, pp 60–70

Capodaglio P, Jensen C, Christensen H (1996) Quantification of muscular activity in the shoulder region during monotonous repetitive work. Med Lav 87:305–313

Chan RF, Chow C, Lee GP, To L, Tsang XY, Yeung SS, Yeung EW (2000) Self-perceived exertion level and objective evaluation of neuromuscular fatigue in a training session of orchestral violin players. Appl Ergon 31:335–341

Dimitrov GV, Dimitrova NA (1974) Extracellular potential field of a single striated muscle fibre immersed in anisotropic volume conductor. Electromyogr Clin Neurophysiol 14:423–436

Dimitrov GV, Dimitrova NA (1977) Bipolar recording of potentials generated by excitable fibres in a volume conductor. Agressologie 18:235–252

Dimitrov GV, Dimitrova NA (1998a) Fundamentals of power spectra of extracellular potentials produced by a skeletal muscle fibre of finite length. I. Effect of fibre anatomy. Med Eng Phys 20:580–587

Dimitrov GV, Dimitrova NA (1998b) Fundamentals of power spectra of extracellular potentials produced by a skeletal muscle fibre of finite length. II. Effect of parameters altering with functional state. Med Eng Phys 20:702–707

Dimitrova NA (1974) Model of the extracellular potential field of a single striated muscle fiber. Electromyogr Clin Neurophysiol 14:53–66

Farina D, Merletti R (2000) Comparison of algorithms for estimation of EMG variables during voluntary isometric contractions. J Electromyogr Kinesiol 10:337–350

Farina D, Rainoldi A (1999) Compensation of the effect of subcutaneous tissue layers on surface EMG: a simulation study. Med Eng Phys 21:487–496

Farina D, Merletti R, Nazzaro M, Caruso I (in press) Effect of joint angle on EMG variables in muscles of the leg and thigh. IEEE Eng Med Biol Mag

Gydikov A, Kosarov D (1972) Volume conduction of the potentials from separate motor units in human muscle. Electromyogr Clin Neurophysiol 12:127–147

Gydikov A, Gerilovski L, Radicheva N, Troyanova N (1986) Influence of the muscle fiber end geometry on the extracellular potentials. Biol Cybern 54:1–8

Hagberg C, Hagberg M (1989) Surface EMG amplitude and frequency dependence on exerted force for the upper trapezius muscle: a comparison between right and left sides. Eur J Appl Physiol 58:641–645

Hagberg M, Kvarnstrom S (1984) Muscular endurance and electromyographic fatigue in myofascial shoulder pain. Arch Phys Med Rehabil 65:522–525

Hagg GM (1992) Interpretation of EMG spectral alterations indexes at sustained contractions. J Appl Physiol 73:1211–1217

Hansson GA, Nordander C, Asterland P, Ohlsson K, Strömberg U, Skerfving S, Rempel D (2000) Sensitivity of trapezius electromyography to differences between work tasks – influence of gap definition and normalisation methods. J Electromyogr Kinesiol 10:103–115

Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G (2000) Development of recommendations for SEMG sensors and sensor placement procedure. J Electromyogr Kinesiol 10:361–374

Jensen C, Westgaard RH (1997) Functional subdivision of the upper trapezius muscle during low-level activation. Eur J Appl Physiol 76:335–339

Jensen C, Vasseljen O, Westgaard RH (1993a) The influence of electrode position on bipolar surface electromyogram recordings of the upper trapezius muscle. Eur J Appl Physiol 67:266–273

Jensen C, Nilsen K, Hansen K, Westgaard RH (1993b) Trapezius muscle load as a risk indicator for occupational shoulder-neck complaints. Int Arch Occup Environ Health 64:415–423

Kleine BU, Schumann DF, Stegeman DF, Scholle HC (2000) Surface EMG mapping of the human trapezius muscle: the topography of monopolar and bipolar surface EMG amplitude and spectrum parameters at varied forces and in fatigue. Clin Neurophysiol 111:686–693

Korosec D (1999) Analysis of one-dimensional signals by processing of their time-frequency representations. Thesis, University of Maribor, Maribor

Lateva ZC, Dimitrov GV, Dimitrova NA (1990) Power spectra of single infinite fibre extracellular potentials recorded by a bipolar electrode. Med Biol Eng Comput 28:537–543

Madeleine P, Lundager B, Voigt M, Arendt-Nielsen L (1999) Shoulder muscle coordination under chronic and experimental neck-shoulder pain. An occupational pain study. Eur J Appl Physiol 79:127–140

Masuda T, Miyano H, Sadoyama T (1985) The position of innervation zones in the biceps brachii investigated by surface electromyography. IEEE Trans Biomed Eng 32:36–42

Mathiassen SE, Winkel J (1990) Electromyographic activity in the shoulder-neck region according to arm position and glenohumeral torque. Eur J Appl Physiol 61:370–379

Mathiassen SE, Winkel J, Hägg GM (1995) Normalisation of surface EMG from the upper trapezius muscle in ergonomic studies – a review. J Electromyogr Kinesiol 4:197–226

Merletti R, Lo Conte LR (1995) Advances in processing of surface myoelectric signals. I. Med Biol Eng Comput 33:362–372

Merletti R, Roy S (1996) Myoelectric and mechanical manifestations of muscle fatigue in voluntary contractions. J Orthop Sports Phys Ther 24:342–353

Merletti R, Knaflitz M, De Luca CJ (1990) Myoelectric manifestations of muscle fatigue during voluntary and electrically elicited contractions. J Appl Physiol 68:1657–1667

Merletti R, Farina D, Granata A (1999a) Non-invasive assessment of motor unit properties with linear electrode arrays. Electroencephalogr Clin Neurophysiol [Suppl] 50:293–300

Merletti R, Lo Conte L, Avignone E, Guglielminotti P (1999b) Modelling of surface EMG signals. I. Model and implementation. IEEE Trans Biomed Eng 46:810–820

Merletti R, Roy S, Kupa E, Roatta S, Granata A (1999c) Modelling of surface EMG signals. II. Model based interpretation of surface EMG signals. IEEE Trans Biomed Eng 46:821–829

Merletti R, Farina D, Gazzoni M, Schieroni MP (2002) Effect of age on muscle functions investigated with surface electromyography. Muscle Nerve 25:65–76

Nieminen H, Hameenoja S (1995) Quantification of the static load component in muscle work using nonlinear filtering of surface EMG. Ergonomics 38:1172–1183

Oberg T, Sandsjo L, Kadefors R (1990) Electromyogram mean power frequency in non-fatigued trapezius muscle. Eur J Appl Physiol 61:362–369

Oberg T, Sandsjo L, Kadefors R (1992) Arm movement and EMG mean power frequency in the trapezius muscle: a comparison between surface and intramuscular recording techniques. Electromyogr Clin Neurophysiol 32:87–96

Oberg T, Sandsjo L, Kadefors R (1994) Subjective and objective evaluation of shoulder muscle fatigue. Ergonomics 37:1323–1333

Persson AL, Hansson GA, Kalliomaki A, Moritz U, Sjolund BH (2000) Pressure pain thresholds and electromyographically defined muscular fatigue induced by a muscular endurance test in normal women. Clin J Pain 16:155–163

Rainoldi A, Nazzaro M, Merletti R, Farina D, Caruso I, Gaudenti S (2000) Geometrical factors in surface EMG of the vastus medialis and lateralis. J Electromyogr Kinesiol 10:327–336

Roeleveld K, Stegeman DF, Vingerhoets HM, Zwarts MJ (1997) How inter-electrode distance and motor unit depth influence surface potentials. In: Hermens HJ, Freriks B (eds) The state of the art on sensors and sensor placement procedures for surface electromyography: a proposal for sensor placement procedures. Roessingh Research and Development, Enschede, pp 55–59

Roy SH, De Luca CJ, Schneider J (1986) Effects of electrode location on myoelectric conduction velocity and median frequency estimates. J Appl Physiol 61:1510–1517

Veiersted KB (1991) The reproducibility of test contractions for calibration of electromyographic measurements. Eur J Appl Physiol 62:91–98

Westgaard RH (1999) Muscle activity as a releasing factor for pain in the shoulder and neck. Cephalalgia 25:1–8

Winter DA, Fuglevand AJ, Archer SE (1994) Crosstalk in surface electromyography: theoretical and practical estimates. J Electromyogr Kinesiol 4:15–26

Zipp P (1982) Recommendations for the standardization of lead positions in surface electromyography. Eur J Appl Physiol 50:41–54

Zuniga N, Truong XT, Simons DG (1970) Effects of skin electrode position on average electromyographic potentials. Arch Phys Med Rehabil 51:264–272