Reproducibility of MUAP properties in array surface EMG recordings of the upper trapezius and sternocleidomastoid muscle

Laura A.C. Kallenberg[1], Stephen Preece[2], Chris Nester[2] and Hermie J Hermens[1, 3]

[1] Roessingh Research and Development, Enschede, the Netherlands

[2] Centre for rehabilitation and human performance, University of Salford, Manchester, UK

[3] Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, Enschede, the Netherlands

Corresponding author:

L.A.C. Kallenberg

Roessingh Research & Development

P.O. Box 310

7500 AH Enschede

The Netherlands

Tel.+31 (0)53 4875767

Fax +31 (0)53 4340849

E-mail: l.kallenberg@rrd.nl

Keywords

Array surface EMG, multi-channel surface EMG, motor unit action potentials, reproducibility, neck-shoulder muscles, agreement, reliability

Abstract

The use of array surface EMG recordings for detailed assessment of motor control and muscle properties is increasing. Motor unit action potentials (MUAPs) and their properties can be extracted from these recordings. The objective of this study was to determine the reproducibility of variables obtained from array surface EMG recordings of the shoulder and neck muscles during different functional tasks.

Eight-channel linear arrays were placed on the upper trapezius (UT) and sternocleidomastoid (SCM) muscles of 12 healthy subjects. Subjects performed 3 tasks: shoulder abduction (90 degrees), ironing (repetitively touching two ends of a horizontal bar in front of the subject), and 90 degrees head turning. The protocol was performed twice while electrodes remained on and repeated a third time a week later.

Three global and six MUAP-related variables were calculated. Intra-class correlation coefficients (ICC) were calculated to assess reliability and smallest detectable changes (SDC) were calculated to assess agreement.

In general, the EMG variables showed high levels of reliability which suggests they may be effective for differentiating between subjects. SDC was found to be considerably lower for the frequency-related (5-23%) than for the amplitude-related variables (15-78%), indicating that the frequency-related variables may be more suitable for investigating interventions which aim to modify motor control. There was no difference in reproducibility between global and MUAP-related variables, which justifies their complementary use.

1 Introduction

Array surface electromyography (sEMG) is a promising tool for noninvasive muscle characterization. Array sEMG is recorded by placing a 1-or 2D electrode array with closely spaced electrodes (<10 mm inter-electrode distance) on the skin overlying a muscle. With this technique, information about motor unit (MU) anatomy (e.g. location of the innervation zone), MU size and physiology (e.g. muscle fiber conduction velocity, recruitment strategy) can be obtained noninvasively [e.g. Merletti *et al.* 2003; Drost *et al.* 2006; De Luca *et al.* 2006; Kallenberg and Hermens 2006b]. Over recent years it has been used in a number of important applications. For example, array EMG techniques have been used to demonstrate differences in motor control between sufferers of neck pain and healthy control subjects [Falla *et al.* 2004]. A recent study showed that array sEMG variables were able to discriminate chronic neck pain patients from healthy controls, while conventional sEMG variables did not show differences [Kallenberg *et al.* 2006].

Assessment of reproducibility has been identified as a key factor which allows for standardization of EMG methodology and comparison between different operators [Merletti *et al.* 2001;Hermens *et al.* 2000]. Although the reproducibility of sEMG variables derived from bipolar sEMG signals has been widely studied, there have only been a small number of studies investigating the reproducibility of variables derived from array sEMG signals [Falla *et al.* 2002b; Farina *et al.* 2004; Rainoldi *et al.* 2001; Rainoldi *et al.* 1999]. The results of these studies suggest that array sEMG techniques can be used to obtain reproducible variables for muscle characterization. However, previous work has been carried out using tasks in which subjects maintained a resisted isometric voluntary contraction at a predetermined force threshold, often 50% of the maximal voluntary contraction. It is therefore unclear whether array sEMG variables obtained during common functional tasks are reproducible.

EMG studies of the upper trapezius and sternocleidomastoid (SCM) muscles have demonstrated differences in motor control and peripheral muscle properties between sufferers of neck pain and healthy control subjects [Kallenberg *et al.* 2006; Veiersted *et al.* 1993; Falla *et al.* 2004]. Given the potential link between chronic neck pain and muscle dysfunction, it is important to be able to characterize neck and shoulder muscles, such as the trapezius and SCM during low-load function tasks in a reproducible way. In addition, interventions which aim to modify muscle activation patterns, such as myofeedback training, have been shown to reduce the symptoms associated with neck pain [Hermens and Hutten 2002; Vollenbroek-Hutten *et al.* 2006]. Good reproducibility of the EMG variables is essential to enable quantification of the changes in motor control and muscle properties associated with such interventions. Therefore, two neck-shoulder muscles were selected for the present study. Although the reproducibility of sEMG variables obtained from conventional recordings has been studied previously for the trapezius muscle [Aaras *et al.* 1996; Veiersted 1996; Nordander *et al.* 2004], there has been no study of the reproducibility of variables derived using array sEMG techniques. For the SCM, variables derived from array sEMG signals have been shown to be reproducible during submaximal isometric fatiguing contractions [Falla *et al.* 2002b]. However, there has been no study of the reproducibility of sEMG variables from the SCM during functional tasks.

The aim of this study was to assess the within-day and between-days reproducibility of variables obtained from linear array sEMG signals during a number of functional tasks. Two aspects of reproducibility can be discerned [de Vet *et al.* 2006]: agreement and reliability. Agreement quantifies the similarity between repeated measurements (within-subjects) and reflects the measurement error. Reliability is the ability of a single variable to distinguish between subjects despite the measurement error; thereby relating the measurement error to the variability between subjects. It is calculated by dividing the inter-subject variance component by the total variance.

Reliability is clinically relevant for the diagnostic value of a variable, while agreement is relevant for assessing changes within a subject over time [de Vet *et al.* 2006]. Both aspects were investigated for a number of variables obtained from array sEMG recordings.

2 Methods

2.1 Subjects

Twelve volunteers (10 male and 2 female) aged between 21 and 45 years (mean (SD) 32 (8) years, height 175 (6) cm, weight 70.2 (10.8) kg, distance of seventh cervical vertebra to acromion 25.4 (2.2) cm) participated in the study. Ten of the twelve subjects were right-handed. Subjects were included in the study if they had no past history of neck, back or shoulder pain or any neurological disorders. Each subject gave informed consent to be included in the study and ethical approval was granted by the local ethics committee.

2.2 SEMG recordings and experimental procedure

Adhesive linear electrode arrays (SPES Medica, Milan, Italy) consisting of a flex print with 8 Ag/AgCl bar-shaped electrodes (width 1 mm, length 3 mm) with an inter-electrode distance of 5 mm were used. One was placed on the upper trapezius muscle (UT) and one was placed on the sternocleidomastoid muscle (SCM) of the dominant side. See Figure 1 for a picture of the experimental setup, and Figure 2 for a schematic representation of the electrode array and the recorded signals. In between the flex print and the skin an adhesive foam with cavities (6 x 2 x 2 mm) was placed. Conductive gel (20 µl for each electrode of the array) was used to assure proper skin-electrode contact and was inserted with a gel dispenser (model Eppendorf AG-Multipette plus, Hamburg, Germany) through small holes in the flex print into the cavities of the foam. A ground electrode was placed on the palmar side of the dominant wrist.

Insert Figure 1 and 2 about here

Before electrode placement, the skin was cleaned using abrasive paste. For the upper trapezius, the electrode array was placed on the line from the spinous process of the seventh cervical vertebra (C7) to the acromion with the centre of the array 2 cm lateral from the midpoint, in accordance with the SENIAM recommendations for surface EMG recordings [Hermens *et al.* 2000]. Myoelectric signals were collected from the sternal head of the SCM. For this muscle, placement was done according to the recommendations by Falla et al. [Falla *et al.* 2002a]. The array was placed on the line from the sternal notch to the inferior point of the mastoid process, with the center of the array approximately at one third from the sternal notch. This was expected to result in placement of the electrode array between the innervation zone and the tendon, such that unidirectionally propagating MUAPs were recorded. The signals were visually inspected online. Propagation of signals and minimal shape differences between subsequent signals were used as criteria for correct placement in between the innervation zone and tendon, and alignment of the electrode array in parallel to the muscle fibers. If these criteria were not fulfilled, the electrode array was removed from the skin, the skin was cleaned to remove the conductive gel, and the array was repositioned.

The monopolar signals were amplified using their average as a reference with a gain of 20, low-pass filtered (anti-aliasing, 553 Hz) and 22-bits AD-converted (resulting in a resolution of 71.5 nV per bit) with a 32-channel surface EMG amplifier (Twente Medical Systems International, Oldenzaal, the Netherlands, sample frequency 2048 Hz, input resistance $>10^{12}$ Ohm, common mode rejection ratio >100 dB, noise <1 μV RMS).

Two tasks were selected for the trapezius and one for the SCM. For each of the three tasks EMG data was collected from the subject’s dominant side. For the first trapezius task, subjects stood facing forwards and abducted their shoulders to 90° with elbows fully extended. They were further instructed to fully relax the wrist and allow the fingers to point vertically downwards. The tester then ensured that the top of the wrist was level with the superior aspect of the clavicle.

This position was held for 10 seconds whilst myoelectric signals were collected from the trapezius muscle.

The second trapezius task was designed to simulate the action of ironing. A solid horizontal surface was first positioned at the height of the subject’s anterior superior iliac spine (ASIS). Two dots were then marked on the surface. The first was positioned 20 cm anterior and 30 cm lateral to the ASIS at the dominant side and the second 20 cm anterior and 50 cm medial to the dominant ASIS. The subject was then instructed to move their hand between the two dots in such a way that the middle finger alternately touched each dot on each count of a metronome set to 70 bpm. For this task myoelectric signals were collected from the trapezius muscle over a 1 minute period.

Head turning was selected as the SCM task because the SCM muscle acts to turn the head obliquely to the contralateral side. For this task subjects stood facing forwards and rotated their head to the non-dominant side whilst maintaining constant neck flexion/extension. Subjects were instructed to look at a target object which was positioned on a wall at head height directly to the side of the subject. This position was held for 10 seconds whilst myoelectric signals were collected from the SCM muscle.

2.3 Data analysis

All data was offline band-pass filtered with a second order zero phase shift Butterworth filter (10-400 Hz). From array sEMG electrode recordings motor unit action potentials (MUAPs) can be distinguished and their propagation along the muscle fibers can be tracked [Gazzoni *et al.* 2004; Schulte *et al.* 2003]. At least four out of the seven bipolar channels (with an IED of 5 mm) showing unidirectional propagating signals were selected manually for calculation of MUAP shape properties. MUAPs were detected from these selected channels with a method developed by Gazzoni et al. (2004) that uses the Continuous Wavelet Transform to identify shapes that were similar to a mother wavelet (i.e. the first order Hermite-Rodriguez function). The CWT uses two parameters, being a time shift (related to the location in time where a similar shape occurred) and a scale factor that is related to the amplitude and width of the wavelet. The CWT of each channel is calculated for a range of different values for both parameters. The squared output of the CWT (ranging from 0 to 1) is a measure for the similarity between the mother wavelet and the signal at a certain time instant. This output can be plotted in a three-dimensional graph against the time instant and the scale factor, resulting in a so-called scalogram.

The algorithm started with calculating the CWT for the first channel. When the scalogram reached a maximum that was higher than a user-defined threshold (set to 0.1 in this study), a candidate MUAP was found at the time instant and scale factor corresponding to the maximum. The algorithm then searched for candidate MUAPs that were located in the surrounding channels within a time delay corresponding to a conduction velocity between 2 and 10 m/s. When the candidate was present in a minimal number of adjacent channels (set to 3 in this study), the candidate was considered a MUAP. Then, the CWT was calculated for the next channel. The algorithm cycled through the channels in this way. Outputs of the algorithm were the firing times and the corresponding MUAP shapes on each channel. The length of the MUAP was defined by the scale factor corresponding to the maximum of the scalogram. Next, a Hanning window with a length equal to the length of the MUAP was applied to suppress the edge effects due to truncation of the MUAP. For more details, see [Gazzoni *et al.* 2004; Farina *et al.* 2000; Kallenberg and Hermens 2006a, Kallenberg and Hermens 2006b].

Once each MUAP had been identified, six variables (MUAP Rate, RMS_{MUAP}, VPP_{MUAP}, $FMEAN_{MUAP}$, $FMED_{MUAP}$, and $Duration_{MUAP}$) were derived which describe a range of muscle characteristics.

Firstly, MUAP Rate (MR) was calculated counting the number of automatically detected MUAPs per second. This variable reflects the input of the central nervous system to the muscle. Next the variables RMS (RMS_{MUAP}) and peak-to-peak value (VPP_{MUAP}) were derived. RMS_{MUAP} was calculated by taking the square root of the sum of all squared data samples of the MUAP, divided by the number of samples and VPP_{MUAP} was calculated as the difference between the maximal and the minimal value of the MUAP. These two variables reflect the size of the MUAP which is related to the size of the motor unit (determined by its number of fibers and their diameter), and to its distance from the detection point.

Mean ($FMEAN_{MUAP}$) and median ($FMED_{MUAP}$) frequency of the power spectrum of each MUAP were obtained using the fast Fourier-transform (with a Hanning window with a length equal to the length of the MUAP). The MUAP shapes were zero-padded to obtain a frequency resolution of 1 Hz. $FMEAN_{MUAP}$ and $FMED_{MUAP}$ reflect the frequency content of the MUAP, which is related to the MUAP duration [Hermens *et al.* 1992] and muscle fiber conduction velocity [Lindstrom and Magnusson 1977; Dumitru *et al.* 1999; Arendt-Nielsen and Mills 1985].

MUAP duration ($Duration_{MUAP}$), was calculated as the time interval centered around the middle of the MUAP that contained 90% of the total energy of the MUAP.

The six variables describing the detected MUAPs were calculated separately from each of the manually selected bipolar channels and averaged to give the final values used in the statistical analysis.

In addition to characterizing individual MUAP properties, three global surface EMG variables were derived from bipolar EMG signals. In accordance with the SENIAM guidelines for conventional sEMG [Hermens *et al.* 2000] bipolar signals with an IED of 2 cm were constructed from the same set of monopolar signals that were used in MUAP detection, resulting in a maximum of 4 bipolar signals. The signals were inspected visually for the presence of artefacts and noise. Epochs containing artefacts were removed and channels with noise were discarded. Global RMS (RMS_G), mean power frequency ($FMEAN_G$) and median power frequency ($FMED_G$) were calculated from adjacent, non-overlapping signal epochs of one second for each of the bipolar signals. $FMEAN_G$ and $FMED_G$ were calculated using the Fast Fourier Transform with a rectangular window with a length of one second. Each variable was then averaged over all epochs (ten for the shoulder abduction and head turn task, and 60 for the ironing task) and across the different bipolar signals and the mean value was used for the statistical analysis.

Indexes of reproducibility were calculated for the six MUAP-related variables (MR, RMS_{MUAP}, VPP_{MUAP}, $FMEAN_{MUAP}$, $FMED_{MUAP}$, $Duration_{MUAP}$,) and for the three global surface EMG variables (RMS_G, $FMEAN_G$ and $FMED_G$). Within-day (trial 1 compared to trial 2) and between-days reproducibility (trial 1 compared to trial 3) were analyzed separately. The total variance consisted of a between-subject, within-subject, and residual component. The within-subject component was either caused by to trial-to-trial (within-day) or day-to-day variance (between-days).

Two aspects of reproducibility can be discerned: reliability and agreement [de Vet *et al*. 2006]. Reliability is commonly assessed with the Intraclass Correlation Coefficient (ICC). ICC quantifies the proportion of the variance which can be attributed to the individual subjects as a ratio of the total variance due to all possible sources of variability, such as trials, days, subjects, and conditions. It is common practice to take values of ICC>0.6 to indicate good reliability and ICC>0.8 to indicate excellent reliability (Bartko 1966). Although ICCs are widely used to quantify reliability, implicit in the calculation is the assumption that the between-subject variability is greater than the within-subject variability. If this condition is not satisfied then the ICC becomes invalid. In order to justify this assumption the F statistic which indicates the ratio of the between-subject variance and all other sources of variance (i.e. within-subject variance and residuals) was calculated.

Agreement is commonly assessed with standard error of the measurement (SEM) and the smallest detectable change (SDC). The SEM is calculated from the square root of the sum of the within-subject variance and the residual variance. The SDC is then given as $1.96*\sqrt{2}*SEM$. These two statistical measures are expressed in the units of the variable being measured and give a direct indication of measurement noise. However, we were interested in differences in reproducibility across the nine EMG variables. Therefore, the relative SDC which is obtained by dividing the SDC by the mean across all subjects was also calculated. This measure indicates the smallest percentage of change that can be reliably detected for a given variable and therefore allows for comparison across the different variables.

Because the majority of the variables were not normally distributed, the Wilcoxon signed rank test was used to assess differences between the first trials of the three tasks.

3 Results

In three subjects, the trapezius muscle was not active during the ironing task. Additionally, the SCM data was of insufficient quality (e.g. power line interference, low signal to noise ratio) for the head turn task from three subjects and the trapezius data was of insufficient quality for one subject in the ironing task. Data from these muscles was therefore excluded from the analysis. For 63% (head turn) to 88% (ironing) of the trials, six or seven (out of seven) bipolar channels were selected for further processing. For the shoulder abduction task, in 8% of all trials five channels were selected, and in 22% four channels were selected. For the ironing task, these figures were 0 and 12% and for the head turn task, these figures were 11 and 26%.

In Table 1, the mean and standard deviation of the EMG variables across all subjects are reported for the first trial of each task. Both the amplitude- and frequency-related variables show higher values for the shoulder abduction task than for the ironing task ($p<0.05$ for all variables except RMS_{MUAP}), indicating that more MUs are recruited and/or their average firing rate is higher during the shoulder abduction task.

Tables 1 and 2a-c about here

Tables 2a-c report ICC, F statistic, SEM and relative SDC for the three different tasks. In general, the within-day reliability is excellent with the majority of the ICC values being above 0.9. The between-days reliability is generally lower than the within-day reliability. However, the majority of the ICC values are higher than 0.7, indicating a good reliability. The reliability of MR is lower than that of the other variables. In agreement, the F statistic is low (< 5) for these variables. For the shoulder abduction task no ICC could be calculated for MR. This is the result of comparable variability between and within subjects (which is also shown in the F statistic that is close to 1). In this scenario the ICC becomes meaningless. For the other variables, the between-subject variability was between 5 and 132 times higher than the within-subject variability.

The SDC shows large variability across the different EMG variables and tasks. In general the between-days SDC was larger than the within-day SDC, as would be expected. The SDC was found to be considerably lower for the frequency-related (5-23%) than for the amplitude-related variables (15-78%). On average the shoulder abduction task showed the lowest SDCs and the ironing task the highest. Overall, there were no clear differences in the agreement variable SDC or the reliability variable ICC between the global variables and the MUAP-related variables.

4 Discussion

The aim of this study was to assess the within-day and between-days reproducibility of variables obtained from linear array sEMG signals. Data was collected from the upper trapezius and SCM muscles during three functional tasks: a shoulder abduction, ironing and head turn task. Reliability, indicating the ability to distinguish between subjects, was quantified using ICC. In order to establish which variables show a high repeated measures precision, agreement was quantified using relative SDC and SEM.

4.1 Reliability of EMG variables

ICC values > 0.6 are commonly accepted as good reliability (Bartko, 1966). In general, the ICC values of the investigated EMG variables were higher than 0.7 during all three tasks. indicating a good reliability. Earlier studies assessing reliability of array sEMG variables also reported good reliability for isometric contractions of upper leg muscles [Rainoldi *et al.* 2001]. For SCM, Falla *et al*. reported good reliability for amplitude variables [Falla *et al.* 2002b]. The present results show that array sEMG variables obtained from SCM and trapezius during functional tasks could be used to distinguish between subjects. Overall, there were no differences in reliability between the global and the MUAP-related variables. In comparison with the global variables, the MUAP-related variables provide more detailed information about MU properties. Due to the short duration of MUAPs, their properties are more difficult to estimate. However, the fact that their reliability is comparable to that of the global variables indicates that MUAP-related variables can be used complementary to the global variables.

For the trapezius, both frequency and amplitude-related variables demonstrated good levels of reliability, with the exception of MR. This finding is in agreement with Veiersted [Veiersted 1996] who reported high reliability coefficients for global EMG variables obtained from low-load repetitive tasks. The good levels of reliability found in this study suggest that the array

EMG variables may be used to distinguish between subjects. Indeed this technique was used to distinguish between subjects with chronic neck pain and controls during low-load computer tasks [Kallenberg *et al.* 2006]. MUAP-related variables were shown to be more discriminative than global EMG variables. In the present study, MUAP-related variables showed ICCs that were comparable to that of global variables, which justifies the use of MUAP-related properties to investigate muscle activity and motor control on a detailed level.

Both the frequency and amplitude-related variables derived from the SCM showed good to excellent levels of reliability, the only exception being MR. Two recent studies also investigated the reliability of EMG variables obtained from the SCM [Falla *et al.* 2002b; Strimpakos *et al.* 2005]. Both these studies used submaximal isometric contractions to induce fatigue and derived frequency- and amplitude-related EMG variables at the start of the contraction and at subsequent time points. Whereas Falla *et al.* [2002b] demonstrated good reliability for the amplitude-related variables but poor reliability for the frequency-related variables, Strimpakos *et al.* [2005] found good reliability for initial median frequency but poor reliability for the RMS slope. In the present study, all EMG variables except MR showed good reliability. In contrast to the mentioned studies, in this study functional tasks were used, during which subjects had probably more freedom in the way they performed the task. This might contribute to a better distinction between subjects. The distinction might further improve from using a combination of variables instead of a single variable. However, the finding of a high ICC in a homogeneous group does not imply that a variable will be able to distinguish between subjects from heterogeneous groups, such as healthy and pathologic. Thus, further work is required to investigate sensitivity and specificity of the EMG variables, found to be reliable in this study.

The only EMG variable showing low levels of reliability was the MR. The MR showed poor reliability in the head turn task and very poor reliability in the shoulder abduction task. For this task an ICC could not be calculated, due to the within-subject variance being higher than the between-subject variance. In both these tasks there is a much higher contraction level than in the ironing task (Table 1). This induces a frequent occurrence of superimpositions that are not recognized by the MUAP detection algorithm, as was confirmed by visual inspection. Even though MR showed a lower reliability, the MUAP properties could reliably be estimated. This might indicate that the sample of detected MUAPs is large enough to make a good estimation of the average MUAP properties even when the total number of detected MUAPs varies across trials.

4.2 Agreement of EMG variables

This study found considerably better agreement of the frequency- than the amplitude-related EMG variables. This is similar to the data reported by Strimpakos et al. [2005]. In their study of different isometric contractions of the SCM, they found the best agreement for initial median frequency but low levels of agreement for RMS slope. Therefore it would appear that frequency-related variables could be more suitable for assessing changes in muscle properties which may result from a clinical intervention, such as myofeedback training.

The between-days SDC values for the head turn task are generally lower than for the other two tasks. This may reflect variability across testing sessions due to electrode position (see section 4.3). In general the within-day agreement is better than the between-days agreement.

The SDC values of the ironing task were higher than those of the shoulder abduction task. This is most likely related to the task itself, since also the within-day SDCs were higher. The ironing task requires a low contraction level, which results in a lower signal to noise ratio of the EMG signals. Furthermore, the task is dynamic, meaning that the muscle length might change during the contraction or the skin may move with respect to the muscle. However, visual inspection of each subject during data collection showed that there was little movement of the shoulder girdle during this task. Therefore, it is not clear whether the poorer levels of agreement for this task can be attributed to tissue movement. An inherent variability in motor control between repetitions of the task may also contribute to the observed variability.

4.3 Other methodological issues

The poorer agreement for the head turn task than for the shoulder abduction task may be related to variability in the location of the array with respect to the muscle. Although anatomical landmarks were used for placement, the exact location of the array is dependent on the precise position of the head (in terms of rotation and neck flexion). In comparison to the trapezius muscle, the skin overlying the SCM can move to a large extent, which may change of the position of the array relative to the muscle. Furthermore, the line from the sternal notch to the inferior point of the mastoid process follows a curved path across the contour of the neck, which complicates placement. However, although the SDC values for amplitude-related variables for the head turn task were relatively high, those for frequency-related variables were between 9-23%, indicating acceptable measurement precision.

MR was higher in the SCM muscle than in the trapezius muscle, while its RMS_G value was lower than that of trapezius during the shoulder abduction task. RMS_G is determined by both the number of MUAPs and their size. The lower RMS_{MUAP} values in the SCM muscle in comparison to the trapezius during the shoulder abduction task most likely explain the relatively low RMS_G value in the SCM. The lower RMS_{MUAP} values could either be explained by a larger distance between electrode and the muscle, or the MUs in the SCM might be smaller than in the trapezius.

Conclusion and clinical implications

This study investigated reproducibility of array sEMG variables measured from the upper trapezius and SCM muscles during three functional tasks. The high reliability levels of the EMG variables imply that they could be used to distinguish between subjects, which may prove to be important for clinical practice. Agreement was shown to be considerably better for the frequency- than for the amplitude-related variables, suggesting their use in studies investigating interventions which aim to modify muscle properties or motor control. There was no difference in reproducibility between global and MUAP-related variables, which justifies their complementary use.

Reference List

Aaras A, Veierod MB, Larsen S, Ortengren R, Ro O. Reproducibility and stability of normalized EMG measurements on musculus trapezius. Ergonomics 1996; 39(2): 171-85.

Arendt-Nielsen L, Mills KR. The relationship between mean power frequency of the EMG spectrum and muscle fibre conduction velocity. Electroencephalogr Clin Neurophysiol 1985; 60(2): 130-4.

Bartko JJ. The intraclass correlation coefficient as a measure of reliability. Psychol Rep 1966; 19: 3-11.

De Luca CJ, Adam A, Wotiz R, Gilmore LD, Nawab SH. Decomposition of surface EMG signals. J Neurophysiol 2006; 96(3): 1646-57.

de Vet HC, Terwee CB, Knol DL, Bouter LM. When to use agreement versus reliability measures. J Clin Epidemiol 2006; 59(10): 1033-9.

Drost G, Stegeman DF, van Engelen BG, Zwarts MJ. Clinical applications of high-density surface EMG: a systematic review. J Electromyogr Kinesiol 2006; 16(6): 586-602.

Dumitru D, King JC, Zwarts MJ. Determinants of motor unit action potential duration. Clin Neurophysiol 1999; 110(11): 1876-82.

Falla D, Dall'Alba P, Rainoldi A, Merletti R, Jull G. Location of innervation zones of sternocleidomastoid and scalene muscles--a basis for clinical and research electromyography applications. Clin Neurophysiol 2002a; 113(1): 57-63.

Falla D, Dall'Alba P, Rainoldi A, Merletti R, Jull G. Repeatability of surface EMG variables in the sternocleidomastoid and anterior scalene muscles. Eur J Appl Physiol 2002b; 87(6): 542-9.

Falla D, Jull G, Rainoldi A, Merletti R. Neck flexor muscle fatigue is side specific in patients with unilateral neck pain. Eur J Pain 2004; 8(1): 71-7.

Farina D, Fortunato E, Merletti R. Noninvasive estimation of motor unit conduction velocity distribution using linear electrode arrays. IEEE Trans Biomed Eng 2000; 47(3): 380-8.

Farina D, Zagari D, Gazzoni M, Merletti R. Reproducibility of muscle-fiber conduction velocity estimates using multichannel surface EMG techniques. Muscle Nerve 2004; 29(2): 282-91.

Gazzoni M, Farina D, Merletti R. A new method for the extraction and classification of single motor unit action potentials from surface EMG signals. J Neurosci Methods 2004; 136(2): 165-77.

Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol 2000; 10(5): 361-74.

Hermens HJ, Hutten MMR. Muscle activation in chronic pain: its treatment using a new approach of myofeedback. Int J Ind Ergon 2002; 30: 325-336.

Hermens HJ, van Bruggen TAM, Baten CTM, Rutten WLC, Boom HBK. The median frequency of the surface EMG power spectrum in relation to motor unit firing and action potential properties. J Electromyogr Kinesiol 1992; 2: 15-25.

Kallenberg LA, Hermens HJ. Motor unit action potential rate and motor unit action potential shape properties in subjects with work-related chronic pain. Eur J Appl Physiol 2006a; 96(2): 203-8.

Kallenberg LA, Hermens HJ. Behaviour of motor unit action potential rate, estimated from surface EMG, as a measure of muscle activation level. J Neuroengineering Rehabil 2006b; 3(1): 15.

Kallenberg LA, Hermens HJ, Vollenbroek-Hutten M.M. Distinction between computer workers with and without work-related neck-shoulder complaints based on multiple surface EMG parameters. Int J Industr Ergon 2006; 36: 921-929.

Lindstrom LH, Magnusson RI. Interpretation of myoelectric power spectra: a model and its applications. IEEE Trans Biomed Eng 1977; 65(5): 653-662.

Merletti R, Farina D, Gazzoni M. The linear electrode array: a useful tool with many applications. J Electromyogr Kinesiol 2003; 13(1): 37-47.

Merletti R, Rainoldi A, Farina D. Surface electromyography for noninvasive characterization of muscle. Exerc Sport Sci Rev 2001; 29(1): 20-5.

Nordander C, Balogh I, Mathiassen SE *et al*. Precision of measurements of physical workload during standardised manual handling. Part I: surface electromyography of m. trapezius, m. infraspinatus and the forearm extensors. J Electromyogr Kinesiol 2004; 14(4): 443-54.

Rainoldi A, Bullock-Saxton JE, Cavarretta F, Hogan N. Repeatability of maximal voluntary force and of surface EMG variables during voluntary isometric contraction of quadriceps muscles in healthy subjects. J Electromyogr Kinesiol 2001; 11(6): 425-38.

Rainoldi A, Galardi G, Maderna L, Comi G, Lo Conte L, Merletti R. Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle. J Electromyogr Kinesiol 1999; 9 (2): 105-19.

Schulte E, Farina D, Rau G, Merletti R, Disselhorst-Klug C. Single motor unit analysis from spatially filtered surface electromyogram signals. Part 2: conduction velocity estimation. Med Biol Eng Comput 2003; 41(3): 338-45.

Strimpakos N, Georgios G, Eleni K, Vasilios K, Jacqueline O. Issues in relation to the repeatability of and correlation between EMG and Borg scale assessments of neck muscle fatigue. J Electromyogr Kinesiol 2005; 15(5): 452-65.

Veiersted KB. Reliability of myoelectric trapezius muscle activity in repetitive light work. Ergonomics 1996; 39(5): 797-807.

Veiersted KB, Westgaard RH, Andersen P. Electromyographic evaluation of muscular work pattern as a predictor of trapezius myalgia. Scand J Work Environ Health 1993; 19(4): 284-90.

Vollenbroek-Hutten M, Hermens H, Voerman G, Sandsjo L, Kadefors R. Are changes in pain induced by myofeedback training related to changes in muscle activation patterns in patients with work-related myalgia? Eur J Appl Physiol 2006; 96(2): 209-15.

Table 1 Group means and standard deviations for the EMG parameters during the different tasks, first trial. Shoulder abduction task (duration ten seconds) and ironing task (duration one minute): data from the trapezius muscle, head turn task (duration ten seconds): data from the sternocleidomastoid muscle. * indicates significant difference ($p<0.05$) between ironing and head turn task, † indicates significant difference between head turn and shoulder abduction, $^{\#}$ indicates significant difference between shoulder abduction and ironing.

	Shoulder abduction (n=12)		**Ironing (n=8)**		**Head turn (n=9)**	
Parameter	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
RMS$_G$ (uV)	$152^{\#}$	52.2	77.3	30.0	90.3	61.9
FMEAN$_G$ (Hz)	$98.0^{\#}$	17.5	67.6	10.5	85.3	10.4
FMED$_G$ (Hz)	$83.1^{\#}$	11.0	57.6	13.3	78.2	10.1
MR (pps)	$72.5^{\#}$	13.3	27.3^{*}	11.1	88.7	27.3
RMS$_{MUAP}$ (uV)	$46.2^{\#}$	15.7	35.1	11.0	37.2	22.5
VPP$_{MUAP}$ (uV)	$130^{\#}$	47.1	94.7	32.0	108	67.2
FMEAN$_{MUAP}$ (Hz)	$131^{\#}$	13.3	114^{*}	9.19	145	17.1
FMED$_{MUAP}$ (Hz)	$123^{\#}$	12.7	107^{*}	9.36	138	17.3
DURATION$_{MUAP}$ (ms)	$6.95^{\#}$	0.43	7.43^{*}	0.28	$6.32^{\dagger}$	0.50

Table 2a Intra-class correlation coefficients (ICC), F statistics (F), standard error of the measurement (SEM) and relative smallest detectable change (SDC) for the trapezius during the shoulder abduction task (n=12)

	Trial 1 x 2				**Trial 1 x 3**			
	ICC	**F**	**SEM**	**Relative SDC**	**ICC**	**F**	**SEM**	**Relative SDC**
RMS_G (uV)	0.967	54.5	9.27	16.91	0.850	12.6	22.9	41.8
$FMEAN_G$ (Hz)	0.986	132.4	2.06	5.82	0.965	59.3	3.19	9.04
$FMED_G$ (Hz)	0.978	92.9	1.61	5.38	0.915	21.1	2.94	9.81
MR (pps)	0.923	24.2	4.17	16.0		0.811	13.2	50.5
RMS_{MUAP} (uV)	0.949	38.2	3.31	19.8	0.776	7.78	8.07	48.4
VPP_{MUAP} (uV)	0.953	40.1	9.55	20.3	0.793	8.32	23.3	49.5
$FMEAN_{MUAP}$ (Hz)	0.971	103	2.18	4.61	0.874	15.3	4.55	9.62
$FMED_{MUAP}$ (Hz)	0.969	105	2.14	4.81	0.870	15.0	4.46	10.0
$DURATION_{MUAP}$ (ms)	0.968	57.3	0.07	2.98	0.876	16.1	0.14	5.61

*MR: reliabilty between trial 1 and 3 is poor. Estimation of the ICC was not valid, statistical model resulted in negative estimated variances.

Table 2b Intra-class correlation coefficients (ICC), F statistics (F), standard error of the measurement (SEM) and relative smallest detectable change (SDC) for the trapezius during the ironing task (n=8)

	Trial 1 x 2				**Trial 1 x 3**			
	ICC	**F**	**SEM**	**Relative SDC**	**ICC**	**F**	**SEM**	**Relative SDC**
RMS_G (uV)	0.908	49.2	8.52	30.5	0.785	8.15	13.8	49.4
$FMEAN_G$ (Hz)	0.958	42.7	2.08	8.53	0.927	22.8	3.22	13.2
$FMED_G$ (Hz)	0.951	35.3	2.76	13.3	0.912	20.4	4.02	19.3
MR (pps)	0.643	4.30	6.20	63.0	0.682	5.27	7.64	77.6
RMS_{MUAP} (uV)	0.783	11.7	5.05	39.9	0.649	5.44	6.79	53.7
VPP_{MUAP} (uV)	0.823	16.6	13.3	38.9	0.709	6.66	18.2	53.2
$FMEAN_{MUAP}$ (Hz)	0.912	20.9	2.61	6.37	0.850	11.5	3.98	9.71
$FMED_{MUAP}$ (Hz)	0.931	28.9	2.37	6.11	0.870	13.4	3.68	9.49
$DURATION_{MUAP}$ (ms)	0.615	3.81	0.17	6.18	0.732	6.10	0.14	5.12

Table 2c Intra-class correlation coefficients (ICC), F statistics (F), standard error of the measurement (SEM) and relative smallest detectable change (SDC) for the sternocleidomastoid during the head turn task (n=9)

	Trial 1 x 2				**Trial 1 x 3**			
	ICC	**F**	**SEM**	**Relative SDC**	**ICC**	**F**	**SEM**	**Relative SDC**
RMS$_{G}$ (uV)	0.959	41.3	9.86	38.8	0.836	12.8	17.3	66.5
FMEAN$_{G}$ (Hz)	0.938	30.2	12.6	8.17	0.911	18.7	21.6	9.28
FMED$_{G}$ (Hz)	0.914	21.5	2.51	9.59	0.760	6.65	2.85	15.8
MR (pps)	0.928	24.1	2.71	22.6	0.602	3.88	4.45	60.4
RMS$_{MUAP}$ (uV)	0.952	36.8	7.22	36.1	0.827	9.87	19.3	58.8
VPP$_{MUAP}$ (uV)	0.949	36.3	4.85	38.0	0.776	7.35	7.90	67.3
FMEAN$_{MUAP}$ (Hz)	0.952	72.1	14.8	7.15	0.774	7.80	26.3	20.6
FMED$_{MUAP}$ (Hz)	0.946	65.9	3.74	7.95	0.761	7.42	10.8	22.6
DURATION$_{MUAP}$ (ms)	0.950	34.9	0.19	4.78	0.818	10.2	0.63	13.3

Figure 1: Measurement setup during the ironing task. Subjects had to alternately touch two dots on a solid horizontal in front of them. Two linear arrays of eight electrodes were placed on the sternocleidomastoid muscle and the trapezius muscle of the dominant side.

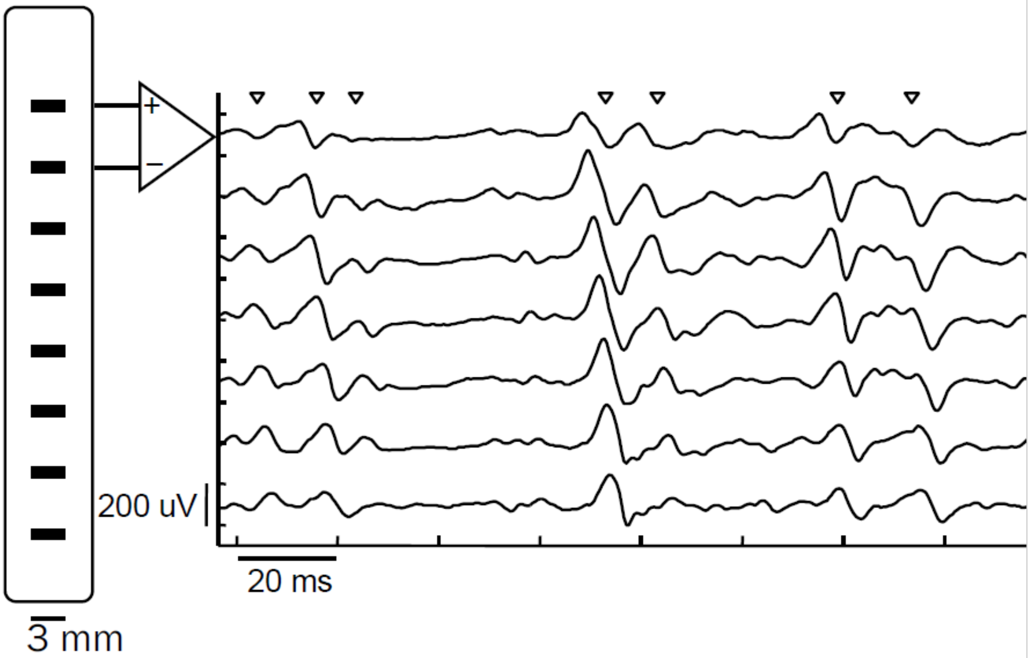

Figure 2: Example of bipolar signals obtained during the ironing task. The electrode array is schematically drawn at the left side. The triangles above the signals indicate locations of the detected motor unit action potentials.