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Sensitivity of trapezius electromyography to differences between work tasks — influence of gap definition and normalisation methods

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Abstract

Surface electromyography (EMG) has been used extensively to estimate muscular load in studies of work related musculoskeletal disorders, especially for the trapezius muscle. The occurrences of periods of EMG silence (gaps), the time below a predetermined threshold level (muscular rest) and various percentiles of the amplitude distribution (APDF) are commonly used summary measures. However, the effects of the criteria used to calculate these measures (e.g., gap duration, threshold level, normalisation method) on the sensitivity of these measures to accurately differentiate work loads is not well known.

Bilateral trapezius EMG was recorded, for a full workday, for 58 subjects following both maximal (MVE) and submaximal (RVE) reference contractions. Gap frequency, muscular rest, and percentiles were derived for eight fundamental work tasks. The calculations were performed using different gap duration criteria, threshold levels and normalisation methods.

A gap duration of less than 1/2 s, and threshold level ≈0.3% MVE for gap frequency, and ≈0.5% MVE for muscular rest, were the criteria that optimised sensitivity to task differences. Minimal sensitivity to tasks and a high sensitivity to individuals was obtained using gap frequency with a threshold level of ≈1% MVE. Normalisation to RVE, rather than MVE, improved sensitivity to differences between tasks, and reduced undesirable variability. Muscular rest was more sensitive to task differences than APDF percentiles. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Electromyography; Trapezius muscle; Normalisation; Exposure; Musculoskeletal disorders; Occupational work; Repetitive work

1. Introduction

Surface electromyography (EMG) has a long tradition, and broad applications, for measuring muscular activity [6,13–15]. In studies of occupational musculoskeletal disorders, EMG has been used to obtain quantitative measures of physical exposure. EMG reflects the internal load and is thus dependent on both the external load, implied by the task, and individual factors. Due to the high prevalence and localisation of neck and shoulder disorders, many studies have focused on the trapezius muscle. The trapezius muscle is superficial, and thus accessible for EMG. However, to obtain — and validate — high-quality EMG recordings, during whole-day measurements in field studies, methodological factors should be considered [10].

To compensate for the large (order of a magnitude) inter-individual variation in the derived EMG amplitude, normalisation to a reference contraction is usually performed [19]. This contraction — usually isometric — may be either maximal or submaximal and performed in a variety of postures, and, for the submaximal contraction, at various load levels. However, the effect of various methods of normalisation, on inter-individual and inter-task variability is not well known [4].

The characterisation of muscular activity in quantitative terms may be performed in a practically unlimited number of ways, e.g., [16–18,21,22,26]. The 10th, 50th

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and 90th percentiles of the amplitude distribution (APDF=amplitude probability distribution function) [16] are frequently used. However, these measures may not be the optimal ones for predicting risk of muscular disorders in repetitive work; work that is characterised by sustained, low level muscle activity [11,32]. Consequently, information in the muscle activity at low load levels, e.g., the occurrence of (short) periods of EMG silence, “gaps” [26], has attained an increasing interest. Gap frequency can predict the development of neck/shoulder disorders [28]. Moreover, subjects with neck/shoulder disorders displayed lower relative duration of muscular rest during work, as compared to subjects without disorders [9]. Both these findings are consistent with the “Cinderella hypothesis” [8]. However, the knowledge of the effects of normalisation methods, the selected threshold level and gap duration criterion, all of which are likely to have a strong influence on the summary measure of the EMG, is limited.

The aim of this study was to determine the sensitivity of trapezius EMG *gap frequency*, relative duration of *muscular rest* and various *percentiles* of the amplitude distribution, to differences between occupational tasks and between individuals. In investigating this aim, emphasis was placed on evaluating the role of changes in the criteria for defining gaps and muscular rest, and of normalisation methods.

2. Materials and methods

Data are from a cross-sectional study of hospital cleaners and office workers [22]. On a typical workday the subject’s tasks were continuously noted and bilateral trapezius EMG was recorded for the full day. The fundamental tasks (e.g., cleaning, office work and pauses) were synchronised with the EMG data.

2.1. Subjects

Fifty-eight subjects, 45 women and 13 men, were involved in this study. Twenty-four of the women worked as hospital cleaners and all the others (34) as office workers. Their mean age was 48 (SD 9, range 26–63) years. The height and weight of the women were 164 (SD 6, range 152–178) cm and 63 (SD 9, range 48–84) kg. The corresponding values for the men were 179 (SD 7, range 165–189) cm and 89 (SD 22, range 67–150) kg. Three of the cleaners and one male office worker were left-handed. However, as detailed information about how the various tasks were performed by the left-handed individuals, separation by dominant and non-dominant sides was not made. The study was approved by the Ethic’s Committee of Lund University, and all participants had given their informed consent.

2.2. Electromyography (EMG)

2.2.1. Recording and signal processing

Bilateral bipolar recordings were made from the descending parts of m. trapezius using Ag/AgCl electrodes with an active electrode diameter of 6 mm (E-10-VS, Medicotest A/S, Ølstykke, Denmark). The electrode pairs (centre-to-centre distance 20 mm) were placed, along the direction of the muscle, 2 cm lateral to the midpoint of the line between the seventh cervical vertebra and acromion. For details on skin preparation and recordings of noise level see [1].

The signals were amplified with DC-coupled preamplifiers, placed close to the recording site, and stored on a portable data logger, using 20 Mbytes exchangeable flash memory cards [3]. The logger had passive high-pass filters (cut-off frequency 10 Hz; 6 dB/octave) and eight-order Butterworth anti-aliasing filters (48 dB/octave), with a cut-off frequency of 400 Hz, and a 12-bit analogue-to-digital converter. The sampling rate was 1024 Hz.

After collection, the data were transferred to an IBM compatible personal computer for further processing. The EMG signals were digitally band-pass (30–400 Hz) and notch (mains frequency and all its harmonics) filtered. The root mean square (RMS) value was calculated for epochs of 1/8 s, and the recorded noise level was, in a power sense, subtracted from the RMS value. In addition, power spectrum, mean power frequency and an artefact index, modified from [2], were also derived. These data were, in combination with the raw EMG, used for identifying and excluding data with movement artefacts and electromagnetic interference. For details on procedures and algorithms see [10].

2.2.2. Normalisation

The RMS values were normalised to both the maximal voluntary electrical activity (MVE) obtained during isometric maximal voluntary contractions (MVCs), and a reference voluntary electrical activity (RVE) obtained during an isometric submaximal reference voluntary contraction (RVC). During both test contractions, the subject was standing, with one arm at the time abducted to 90° in the scapular plane and the elbow was held straight, with the back of the hand facing upwards. Three MVCs, each lasting for ≈3 s, were performed as arm abductions against a strap applied just proximal to the elbow. The strap was connected to a strain-gauge force transducer anchored to the floor. The exerted force was recorded and displayed to the subject, and verbal encouragement was also given. For recording of RVE, a weight of 1 kg was held in the hand for ≈15 s [1,10]. Thus, MVC and RVC represent the maximum and reference torques about the glenohumeral joint and include the weight of the arm.

2.2.3. EMG measures

Gap frequency and *muscular rest* were calculated from the RMS values [22,26]. A gap was defined as ≥1, ≥2 or ≥4 consecutive samples (corresponding to *gap duration criteria* of ≥1/8, ≥1/4 and ≥1/2 s, respectively) which were below a predefined amplitude level (*threshold level*) preceded by ≥1 RMS value above this threshold level. This definition, which is well motivated for physiological reasons, becomes "asymmetrical" for gap duration criteria of ≥1/4 and ≥1/2 s. For example, for a gap duration criterion of ≥1/8 s, the repeated pattern of one epoch above and one epoch below the threshold level, will generate the highest possible gap frequency (240 min^{-1}), while, for a gap duration criterion of ≥1/2 s, the pattern of one epoch above, followed by four epochs below the threshold level, will generate the maximal gap frequency (96 min^{-1}). Muscular rest was defined as the summed duration of the gaps, relative to the total duration of the recording. Therefore, in the above examples, muscular rest is 50 and 80%, respectively. Gap frequency and muscular rest were calculated for various combinations of threshold levels, related to both MVE and RVE, and gap duration criteria of ≥1/8, ≥1/4 and ≥1/2 s. In addition, the 10th, 50th, 90th and 99th *percentiles* of the APDF of the RMS values were derived for the two normalisation methods. These percentiles represent the activity level, which is exceeded for 90%, 50%, 10% and 1% of the recording time, respectively.

2.3. Work tasks

During the EMG recordings, an observer continuously noted the time (estimated synchronisation error 1 s) of the beginning of each new task, at a detailed level. These were categorised into eight items: *cleaning*, *materials handling*, *transportation*, varied *office work*, *work with keyboard*, mobile *meetings* (standing and walking ones), *pauses* (e.g., for smoking) and *scheduled breaks* for breakfast, lunch and coffee (Table 1). The number of subjects performing each task ranged from 16 to 56 (overlap cleaners/office workers for transportation, meetings, scheduled breaks and pauses). Each subject performed, on average, 5.2 of the tasks set (range 2–6). Thus, recordings for 303 out of the 464 (58 subjects by eight tasks) possible combinations were obtained. Prior to the analyses, the tasks were rank ordered by estimated trapezius muscle load, by an ergonomist familiar with the task definitions.

2.4. Statistics

General linear models (GLMs) were used for evaluation of the variance explained by (1) tasks, (2) individuals and (3) the combination of tasks and individuals (all adjusted for random contribution; R^2_{adj}). A GLM attributes the fraction of variation in an EMG measure (e.g., gap frequency at specific criteria), that is not caused by random, to one or more factors (e.g. tasks and/or individuals). For the combined model, homogenous subsets of tasks and individuals were identified, according to the Tukey honestly significant test.

The Statistical Package for the Social Sciences (SPSS Inc., Chicago, IL, USA) was used.

3. Results

3.1. Noise level and reference contractions

For the right trapezius muscle the mean noise level was 0.95 (SD 0.27, range 0.41–1.55) μV, mean MVE activity 863 (SD 356, range 123–1988) μV, and the mean RVE value 17.9% (SD 6.7%, range 7.1–38.3%) of MVE. The mean noise to MVE ratio was 0.13% (SD 0.095%, range 0.04–0.69%), and the mean noise to RVE ratio was 0.78% (SD 0.45%, range 0.27–3.0%). The corresponding values were similar for the left side: 1.03 μV, 860 μV, 18.0% MVE, 0.13% and 0.83%, respectively.

Table 1
Number of recordings (*n*) and their duration (mean, SD, range and total) for the various work tasks for the 58 subjects

Work task	*n*	Duration				
		Mean (min.)	SD (min.)	Min (min.)	Max (min.)	Total[a] (h)
Cleaning	24	222	53	46	331	89
Materials handling	24	37	18	15	83	15
Transportation	56	27	20	1.1	72	25
Office work	34	213	79	40	381	121
Keyboard work	16	55	54	3.0	154	15
Meetings	41	40	42	0.9	191	27
Pauses	52	31	20	0.9	100	27
Scheduled breaks	56	69	27	18	133	64
Total	303	76	81	0.9	381	382

[a] Calculated from *n* and precise numbers of mean.

3.2. Numeric values of gap frequency, muscular rest and percentiles of the amplitude distribution

The numeric value of the *gap frequency* (as the mean value of the 303 measurements) was highly dependent on the gap duration criterion (Fig. 1a). For example, for the right m. trapezius, gap frequencies, at 1% MVE, were 11.7, 6.2 and 3.0 min^{-1}, for gap duration criteria of ≥1/8, ≥1/4 and ≥1/2 s, respectively. Hence, at 1% MVE, the frequency of gaps with duration ≥1/8–<1/4 s and ≥1/4–<1/2 s were 5.5 (11.7–6.2) and 3.2 (6.2–3.0) min^{-1}, respectively. Gap frequency displayed a pronounced peak, and, by definition, approached zero at low and high threshold levels. For a gap duration criterion of ≥1/8 s, the values of these peaks were, on average for the right and left side and the two normalisation methods, 35 min^{-1}. The threshold level for these peaks approximately coincided with the 50th percentiles of the APDFs (cf. Table 2). With an increasing gap duration criterion, the peaks occurred at higher threshold levels; this is a probable effect of the "asymmetrical" definition for the longer gap duration criteria, favouring this phenomenon. Gap frequency was also dependent on threshold level, especially at threshold levels less than 0.3% MVE (1.5% RVE) or greater than 1% MVE (5% RVE). In the ranges 0.3–1% MVE (1.5–5% RVE) gap frequency showed a plateau, i.e., gap frequency had a low sensitivity to changes in threshold level within these ranges. The plateau was higher for the left m. trapezius, as compared to the right one. This fact indicates a denser distribution of muscular activity at low levels, i.e., a lower load, for the left side, as compared to the right one.

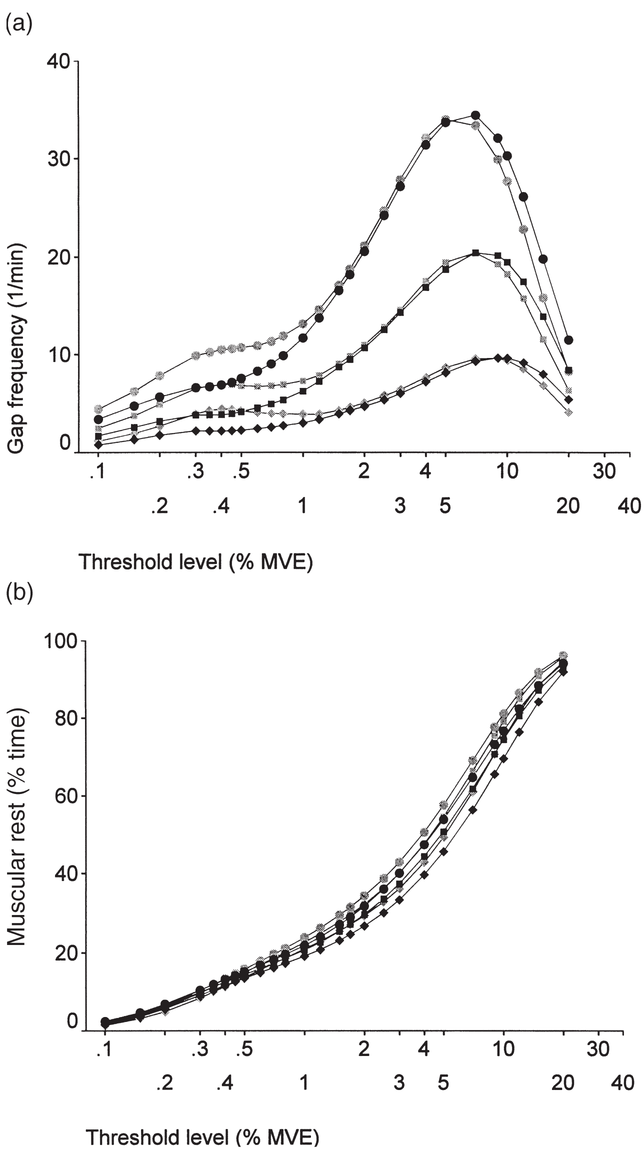

Fig. 1. Mean value of *gap frequency* (a) and *muscular rest* (b), for 303 recordings, performed by 58 subjects in eight possible tasks, as a function of the threshold level (as % MVE) and the gap duration criterion [≥1/8 (○), ≥1/4 (□) and ≥1/2 s (◇)] for both the right (black) and the left (grey symbols) m. trapezius.

Muscular rest was a monotonically increasing function of threshold level, with a value approaching 0% at low threshold levels and 100% at high levels (Fig. 1b). This function is, for a single recording (and a gap duration criterion of ≥1/8 s), by definition identical to the APDF, i.e., the threshold level that gives a muscular rest of *nn*% is identical to the value of the *nn*th percentile of the APDF. Although the above relation, for mathematical reasons, is not true for the *average* over the 303 measurements, it is still an approximation, and the error can be deducted from Fig. 1b in combination with Table 2. The slightly lower values, seen for the longer gap duration criteria, were caused by the "loss of rest events with short durations"; e.g., for a gap duration criterion of ≥1/2 s, the time spent below the threshold levels for shorter durations than half a second are not defined as muscular rest. The effect of the gap duration criterion, on muscular rest, was approximately an order of magnitude less than the effect of the gap duration criterion on gap frequency. The left m. trapezius had higher values of muscular rest than the right one, reflecting a lower load for the left side.

Gap frequency and muscular rest, as functions of RVE related threshold levels (not in figure), were very similar to the MVE related ones, both regarding shape and numerical values, when adjusted for the inverse of the mean RVE/MVE ratio (5.6=1/0.179 for the right m. trapezius, see above).

Regarding the APDF, the coefficient of variation values (CV=SD/mean) for the 303 measurements were, for all *percentiles*, smaller for RVE than for MVE normalised data (Table 2). The percentile values were, for the right m. trapezius, on average 5.5 times higher (deducted from Table 2) using RVE, as compared to MVE; this factor corresponds to the inverse of the mean RVE/MVE ratio (see above).

Table 2
Numeric values [mean and coefficient of variance (CV=SD/mean)] and explained variance (R^2_{adj}) by the factors work task (n=8) and individual (n=58), for four percentiles of the amplitude distribution of the EMG activity, for both the right and left m. trapezius. Data were based on 303 recordings, performed by 58 subjects in eight possible work tasks, and shown for normalisation to the electric activity at both the maximal voluntary contraction (MVE), and at a standardised submaximal reference contraction (RVE)

	Right m. trapezius								Left m. trapezius							
	Percentile (% MVE)				Percentile (% RVE)				Percentile (% MVE)				Percentile (% RVE)			
	10th	50th	90th	99th	10th	50th	90th	99th	10th	50th	90th	99th	10th	50th	90th	99th
Numerical value (% of reference)																
Mean	1.1	5.1	14	27	5.7	28	81	152	0.9	4.4	12	23	4.8	25	71	135
CV (%)	140	76	50	47	117	58	34	31	132	75	48	40	114	64	41	37
Explained variance (R^2_{adj}; %)																
Work task	8	13	15	16	10	17	16	15	11	11	6	5	14	16	8	5
Individual	50	64	81	81	44	46	62	63	21	50	81	84	18	45	73	76

3.3. Explained variance

The GLMs were valid for threshold levels between 0.15 and 9% MVE (0.75–45% RVE). Below and above these values, the residuals diverge from normal distributions. This finding was presumably caused by an increasing number of gap frequency values equal to zero, and, for the low threshold levels, muscular rest values of zero. Moreover, the threshold levels below 0.15% MVE (0.75% RVE) approached the noise level, as can be seen from the noise/MVE (noise/RVE) ratios (see above). The variance explained by the combined factor tasks and individuals, was, on average, only 1.8% R^2_{adj} greater than the sum of the variance explained, using tasks and individuals as separate factors. Hence, the evaluation of explained variance was performed separately for tasks and individuals.

The fraction of variance in *gap frequency*, which was explained by *tasks*, showed, as a function of threshold level, marked local minima for all gap duration criteria, for both sides, and for both normalisation methods (Fig. 2a, b). The mean value of these minima was 5% R^2_{adj}. For the shorter gap duration criteria ($\geq$1/8 and $\geq$1/4 s) these minima appeared at $\approx$1% MVE (5% RVE). Variance in gap frequency explained by tasks was, for the shorter gap duration criteria, greatest for threshold levels $<$0.4% MVC (2.0% RVE) and $>$4% MVC (20% RVE).

The variance in *gap frequency*, explained by *individuals*, showed prominent local maxima, for all gap duration criteria, both sides, and both normalisation methods (mean R^2_{adj}=53%; Fig. 2c, d). These maxima appeared at $\approx$1% MVE (5% RVE), for the shorter gap duration criteria. This location corresponded to the location of the minima in variance explained by tasks.

There was a difference, between the right and left sides, in the variance explained by tasks, as well as in the variance explained by individuals, when using MVE-related threshold levels (Fig. 2a, c). This difference was much less when using RVE (Fig. 2b, d).

For *muscular rest* the variance explained by *tasks* displayed, for all gap duration criteria, for both sides, and for both normalisation methods, flat maxima with a mean R^2_{adj} of 28% (Fig. 3a, b). These maxima were, for the shorter gap duration criteria, located at $\approx$0.5% MVE (3% RVE).

Variance in *muscular rest* explained by *individuals* showed, for all gap duration criteria, for both sides, and for both normalisation methods, relatively flat minima. As with *gap frequency*, the location of these minima corresponded to the location of the maxima in variance explained by tasks. The values of the minima were lower for RVE-related threshold levels (R^2_{adj}=21%; mean over gap duration criteria and sides) as compared to MVE-related threshold levels (R^2_{adj}=29%; Fig. 3c, d). Moreover, the locations and values of these minima were least sensitive to gap duration criteria and body side, when using RVE normalisation.

The variance in the *percentiles* of the APDF explained by *tasks* and by *individuals* are presented in Table 2. For the lower (10th and 50th) percentiles, normalisation to RVE led to a slight increase in variance explained by tasks, as compared to normalisation to MVE. However, even for normalisation to RVE, R^2_{adj} was still low (13%; mean over percentiles and sides). Normalisation to RVE also, for all percentiles, led to a decline in variance explained by individuals, which, however, was still high (R^2_{adj}=53%).

One female office worker — 52 years old, of normal height and weight and without any neck or shoulder complaints — displayed high muscle activity for the right side, regarding the 10th and the 50th percentiles (not for the higher percentiles, gap frequency or muscular rest). Her exerted force during MVC was normal, and a careful examination of her EMG indicated no artefacts. If her data were excluded from the analysis, as expected, the variance explained by tasks increased (by 6% R^2_{adj}) at the expense of that explained by individuals. This strong effect of one individual was not seen for the left side, and did not change the overall conclusions.

3.4. Rank order and homogenous subsets of EMG measures for tasks and individuals

Another approach to evaluating the sensitivity of an EMG measure to differences between tasks or individuals is to determine how well the measure differentiates tasks or individuals; i.e., how many homogeneous task subsets are formed, and is the ranking of tasks, based on estimated muscular load reasonable? A rank ordering of the tasks that is consistent with an ergonomist's opinion is desirable, although not necessary.

For both *gap frequency* and *muscular rest*, use of MVE vs. RVE related threshold levels had little effect on the task mean values, the rank order of the tasks, and the number of homogeneous subsets (Table 3).

The ratios between the MVE and RVE normalised *percentile* values, within each of the eight tasks (5.5; average over all tasks and percentiles) were similar to that found in the whole material (see above). The rank order of the tasks differed at the higher (90th and 99th) percentiles, as compared to both the ranking at the lower percentiles and by the ergonomist; the peak loads were lower during keyboard work than during any other task. This reflects that low and high percentiles represent different aspects of muscular load, a fact that is not covered by one general ranking by an ergonomist.

At 1% MVE (5% RVE) *gap frequency* was (for a gap duration criterion of $\geq$1/8 s), insensitive to differences between tasks; i.e., the numeric values were similar for all tasks, the ranking capability was low and inconsistent, and there were few homogeneous task subsets

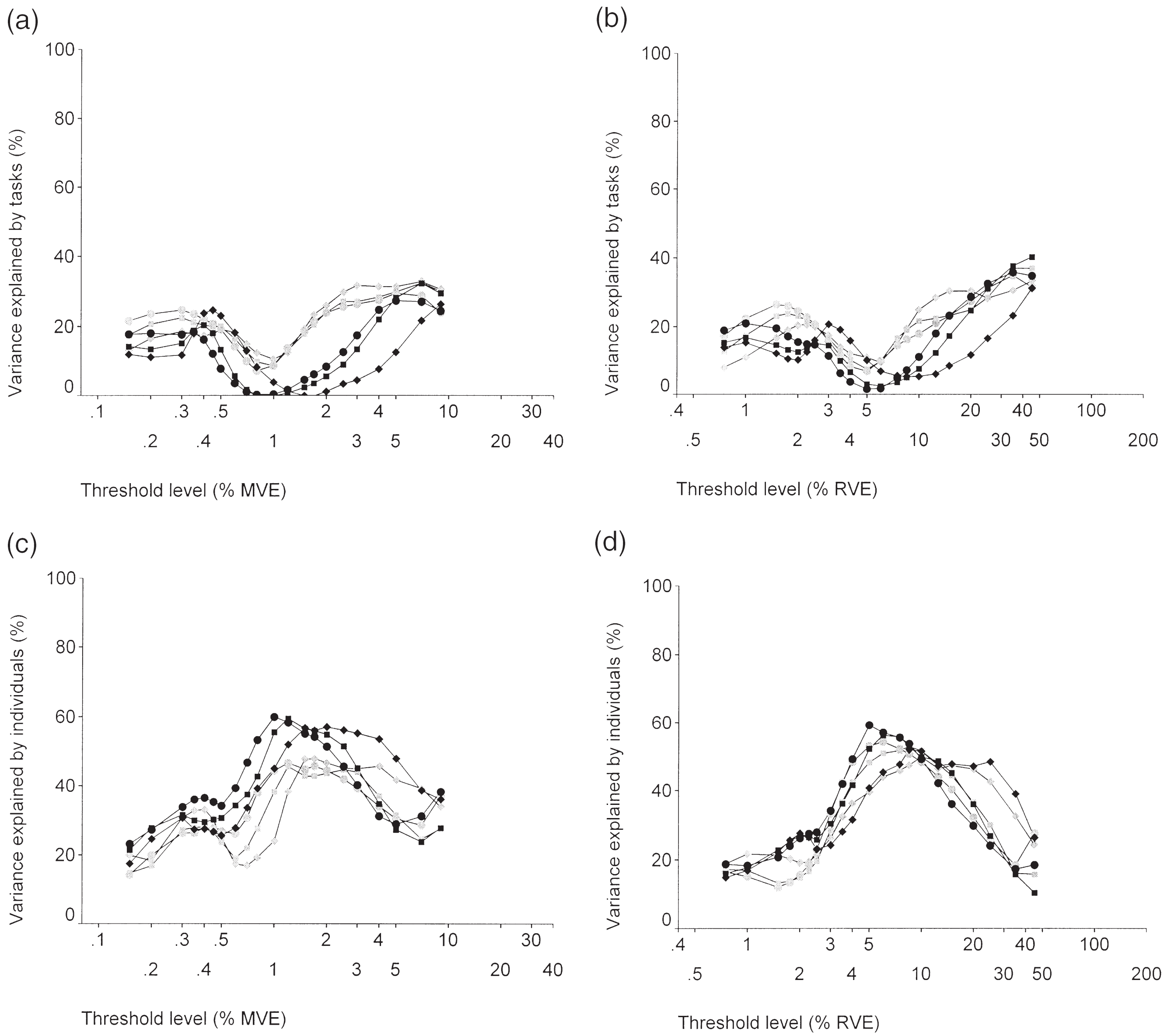

Fig. 2. Variance in *gap frequency*, explained by tasks (a, b) and by individuals (c, d), as a function of threshold level [both as % MVE (a, c) and % RVE (b, d)] and gap duration criterion [≥1/8 (○), ≥1/4 (□) and ≥1/2 s (◇)] for both the right (black) and the left (grey symbols) m. trapezius. Data were based on 303 recordings, performed by 58 subjects in eight possible tasks.

(Table 3). At the lower threshold level of 0.3% MVE (1.5% RVE), the tasks were rank ordered similarly to the order estimated by the ergonomist. At the higher threshold level of 3.0% MVE (15% RVE), gap frequency, surprisingly, rank ordered the tasks in reverse to the order of the ergonomist. The results were similar for the longer gap durations, as well as for the left m. trapezius (not in table).

On the other hand, for *muscular rest*, the ranking of the tasks was relatively insensitive to the threshold level. Across the threshold levels tested, 0.3–3.0% MVE (1.5–15% RVE), the rank order was in accordance with the ergonomist, and there were, in general, four subsets (Table 3). Despite the wider relative ranges of the numeric values of muscular rest at 0.3% MVE and 1.5% RVE (16 and 18, respectively), the ranking capacity of work tasks at these levels was not better, as compared to 1% MVE and 5% RVE, both with a smaller relative range of four.

The capability of *gap frequency*, as a function of threshold level, to rank *individuals* into subsets demonstrated, for all gap duration criteria, and both the right

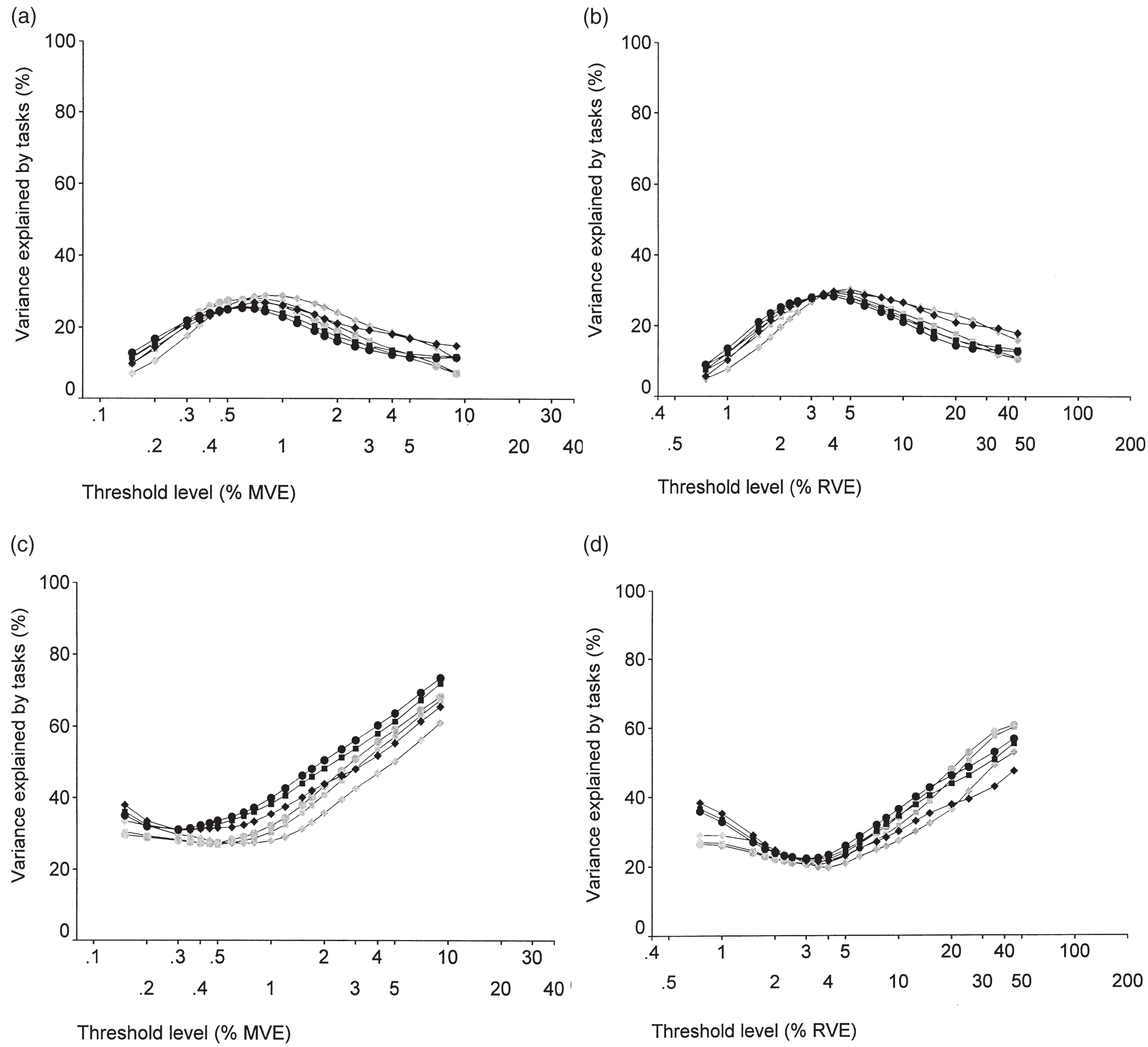

Fig. 3. Variance in *muscular rest*, explained by tasks (a, b) and by individuals (c, d) as a function of threshold level [both as % MVE (a, c) and % RVE (b, d)] and gap duration criterion [≥1/8 (○), ≥1/4 (□) and ≥1/2 s (◇)] for both the right (black) and the left (grey symbols) m. trapezius. Data were based on 303 recordings, performed by 58 subjects in eight possible tasks.

and left sides, flat and wide maxima, of about 15 subsets (not in figure or table). For the shorter gap duration criteria, these maxima occurred at 1–5% MVE (5–20% RVE). Regarding *muscular rest*, the number of subsets of individuals was similar for all gap duration criteria, and both sides. At 0.5% MVE (3% RVE) there were, on average, seven subsets.

3.5. Relations between various EMG measures

Muscular rest is, by definition, limited to 0–100% time, and *gap frequency* (at a gap duration criterion of ≥1/8 s) to 0–240 min^{-1}. Moreover, at muscular rest of 0 and 100% time, gap frequency must be 0 min^{-1}, and to obtain the maximum value of 240 min^{-1}, muscular rest must be 50% time. Considering these limitations, and the very specific patterns of muscular activity that must be at hand to obtain very high gap frequencies, and very low frequencies at muscular rest different from 0 or 100% time, these two measures were basically independent and reflected different aspects of muscular load (Fig. 4a). A very similar pattern, to that in Fig. 4a, was obtained when using the corresponding RVE-related threshold level.

Of course, *muscular rest* and the various APDF *percentiles* were also interrelated. For example, for muscular rest (at a gap duration criterion of ≥1/8 s and a threshold level of 1% MVE) and the 10th percentile, a percentile value of 1% MVE corresponds to 10% time of muscular rest (Fig. 4b). Moreover, for 10th percentile

Table 3

Number of recordings (n), mean value and homogeneous subsets of eight work tasks for various EMG measures, for the right m. trapezius[a]. Gap frequency and (relative duration of) muscular rest for three threshold levels as well as four percentiles of the amplitude distribution, are shown for normalisation to the electric activity at both the maximal voluntary contraction (MVE), and at a standardised submaximal reference contraction (RVE). Data are shown for gap duration $\geq$1/8 s, and the work tasks were a priori rank ordered, according to muscle load, by an ergonomist

Work task	n	Gap frequency (min^{-1})			Muscular rest (% time)			Percentile (% MVE)			
		Threshold level (% MVE)						10th	50th	90th	99th
		0.3	1.0	3.0	0.3	1.0	3.0				
Cleaning	24	1.5^{a}	12^{ab}	33^{c}	1.1^{a}	8^{a}	25^{a}	1.8^{a}	8.1^{a}	21^{a}	37^{a}
Materials handling	24	2.4^{ab}	12^{ab}	31^{bc}	1.8^{a}	10^{a}	27^{a}	1.7^{a}	7.7^{a}	20^{a}	38^{a}
Transportation	56	2.8^{ab}	13^{b}	37^{c}	3.4^{ab}	12^{ab}	33^{ab}	1.6^{ab}	6.1^{b}	15^{b}	28^{b}
Office work	34	6.2^{bc}	9^{a}	22^{a}	9.6^{bc}	20^{bc}	37^{bc}	1.0^{bcd}	5.2^{bc}	13^{cd}	22^{c}
Keyboard work	16	7.6^{cd}	10^{ab}	23^{a}	10.8^{cd}	21^{c}	43^{cd}	1.3^{abc}	4.2^{cd}	10^{e}	19^{d}
Meetings	41	8.7^{cd}	13^{b}	25^{ab}	13.4^{cd}	27^{cd}	47^{d}	0.8^{cd}	4.0^{cd}	12^{de}	22^{cd}
Pauses	52	9.1^{cd}	11^{ab}	25^{ab}	17.0^{d}	30^{d}	47^{d}	0.8^{cd}	4.1^{cd}	13^{bcd}	26^{b}
Scheduled breaks	56	10.3^{d}	12^{ab}	21^{a}	17.5^{d}	32^{d}	49^{d}	0.5^{d}	3.6^{d}	14^{bc}	27^{b}
		Threshold level (% RVE)						10th	50th	90th	99th
		1.5	5.0	15	1.5	5.0	15				
Cleaning	24	1.2^{a}	11^{bc}	32^{b}	0.8^{a}	7^{a}	24^{a}	8.9^{a}	41^{a}	106^{a}	188^{a}
Materials handling	24	1.8^{a}	11^{c}	30^{b}	1.4^{a}	9^{a}	25^{ab}	8.0^{ab}	38^{ab}	102^{a}	192^{a}
Transportation	56	2.4^{a}	9^{abc}	35^{b}	2.7^{a}	9^{ab}	27^{ab}	8.6^{ab}	33^{b}	83^{b}	159^{b}
Office work	34	5.1^{ab}	8^{ab}	19^{a}	6.5^{ab}	17^{bc}	30^{ab}	5.5^{cd}	31^{bc}	80^{b}	140^{bc}
Keyboard work	16	6.9^{bc}	7^{a}	23^{a}	8.8^{bc}	17^{bc}	33^{b}	7.3^{abc}	26^{cd}	63^{d}	118^{d}
Meetings	41	8.0^{bc}	12^{c}	22^{a}	10.1^{bcd}	24^{cd}	42^{c}	4.3^{cd}	22^{d}	68^{cd}	131^{cd}
Pauses	52	8.8^{bc}	11^{bc}	22^{a}	13.9^{cd}	28^{d}	43^{c}	3.9^{d}	22^{d}	73^{bc}	146^{bc}
Scheduled breaks	56	10.3^{c}	11^{bc}	20^{a}	14.7^{d}	30^{d}	45^{c}	2.6^{d}	20^{d}	79^{b}	150^{b}

[a], [b], [c], [d] and [e] indicate homogeneous subsets according to the Tukey honestly significant test. [a]Indicates the subset with the "highest" load (i.e., lowest gap frequency, lowest muscular rest and highest percentile values).

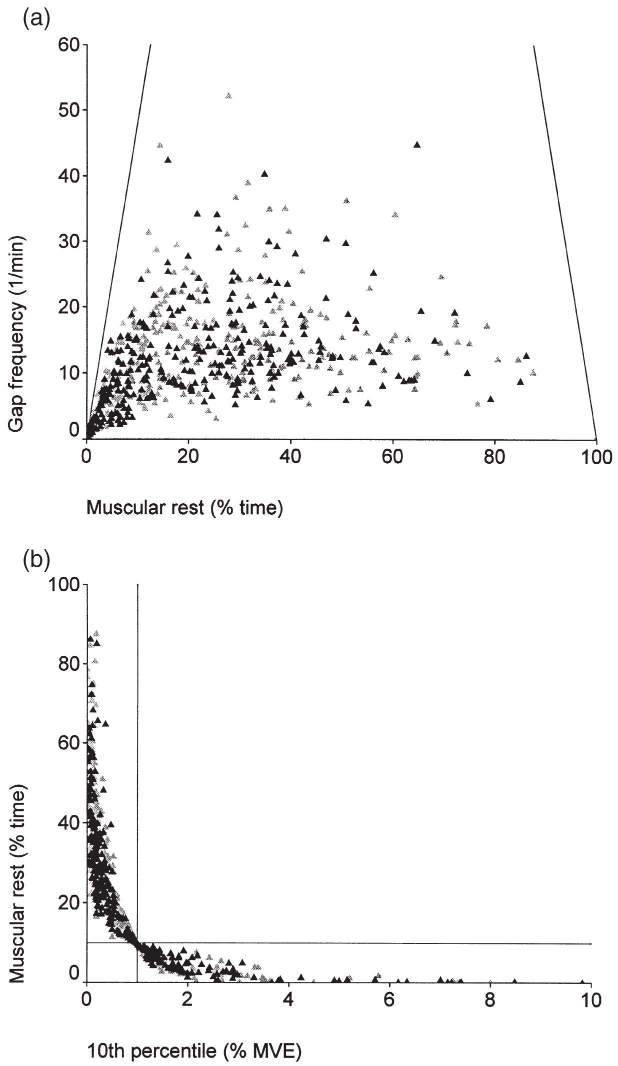

Fig. 4. Relations between various EMG measures, for 303 recordings, performed by 58 subjects in eight possible tasks, for both the right (black) and the left (grey symbols) m. trapezius. (a) Gap frequency vs. muscular rest; the two lines show the inherent limitation in gap frequency. (b) Muscular rest vs. 10th percentile of amplitude distribution; by the chosen definition, a 10th percentile of 1% MVE corresponds to 10% of muscular rest, and no measurement can obtain values in the upper right or lower left rectangles formed by the two lines. Gap frequency and muscular rest were calculated for a threshold level of 1% MVE, and a gap duration criterion of ≥1/8 s. The percentile values were normalised to MVE.

values <1% MVE, muscular rest is >10% time, and, correspondingly, for 10th percentile values >1% MVE, muscular rest is <10% time. Hence, for tasks performed at low load levels (10th percentile <1% MVE) the 10th percentile obtains small numeric values (0–1% MVE), while muscular rest has a wider range (10–100% time). Further, since the rank ordering obtained by these two measures were poorly related (Fig. 4b), muscular rest provided additional information about muscular load, not contained in the APDF *percentile*. The above reasoning is also valid for RVE-related threshold levels.

4. Discussion

This study demonstrates that the post-processing method used to analyse the trapezius EMG signal had an important effect on the derived summary measures. A short gap duration criterion and normalisation to RVE, rather than MVE, produced EMG measures with advantageous characteristics. For gap frequency, the selection of threshold level had a decisive effect on sensitivity to differences in tasks, as well as between individuals.

The present tasks represent common ones in modern working life. Moreover, since the prevalence of neck shoulder disorders is higher among cleaners than office workers [22], the ability of the EMG measures to differentiate work tasks is highly relevant in studies of exposure–response relations for work related musculoskeletal disorders.

4.1. EMG recording and processing

A prerequisite for performing EMG analyses is high quality recordings. These might be hard to obtain and validate, especially when characterising activity at low levels, or during field recordings of long duration, since EMG recordings are sensitive to artefacts (e.g., movements and electromagnetic interference).

We used pre-amplifiers in combination with electrodes with short leads, to reduce the artefacts. Moreover, we inspected the power spectra, and the simultaneous pattern of the muscle activity, the mean power frequency and the artefact index, and — when necessary — the raw EMG, to be able to exclude any remaining artefacts from the recordings in a reliable way. In addition, interference from the power line, which might be a major source of artefact, was effectively suppressed by the present notch-filter. Since the filter was implemented in the frequency domain, the stop bands could easily be kept narrow (1.0 Hz) and, hence, only a minor fraction of the EMG power was rejected.

From the shape of the power spectra we estimate that 20–30% of the total EMG power was rejected, by choosing a digital high-pass filter with a cut-off frequency of 30 Hz, instead of 10 Hz. The relatively high cut-off frequency was selected to exclude the ECG signal, since an elevated heart rate might otherwise be interpreted as an increased muscular activity [23]. An additional advantage of this filter was that it reduced the influence of possible movement artefacts, which also have their major power contained below 30 Hz [7].

4.2. Normalisation

The RVE/MVE ratio of 18% is in accordance with studies of dentists (17%; [1]) and industrial workers (20%; [4]). The higher value (29%) reported in a study of assembly line workers [5] might be due to the fact that the resistance during MVC in that study was applied at the wrist, not proximal to the elbow [25]. The ratio between the RVE/MVE ratio and the RVC/MVC ratio is approximately 0.5 [1], i.e., the mechanical load is about twice as high as the muscular activity at loads below approximately 20% MVE.

The activity recorded during the reference contraction, independent of whether it is maximal or submaximal, has itself a random variation, and, thus, introduces variation in the normalised EMG measures. Thus, for repeated measurements of the same task, on the same individual, un-normalised values might give better reproducibility, than normalisation to MVE or RVE [31]. The CV of repeated MVEs has been estimated to be 0.20–0.25 [33]. The magnitude of the variation, introduced by normalising to RVE, is similar to the value obtained by using MVE [20,29].

Any variation caused by the lack of reproducibility of the reference contractions will, due to the design of the present study, appear as “variance explained by individuals”. For example, the individual differences in gap frequency, which might represent an underlying individual factor, is, to a lesser or greater extent, contaminated by this lack of reproducibility of the test contractions.

Using RVE, as compared to MVE, had advantages. For both gap frequency and muscular rest, the variance explained (both by tasks and by individuals) became more congruent between the right and left sides. Moreover, for all the percentiles, normalisation to RVE decreased the sensitivity to individual differences. This is in accordance with a decrease in inter-individual variability when using RVE in stead of MVE for normalisation, which has been observed for women performing a standardised task [4]. These findings suggest that the inter-individual variance, and the side-to-side differences, were reduced with the use of RVE, and the EMG was instead more influenced by the performed task. This is consistent with a probable relation between the individual’s RVE/MVE ratio and strength.

Although RVE-normalisation is preferable for describing and comparing work tasks, it may be that the load relative to the maximal capacity constitutes the risk for an individual to develop disorders. If so, MVE-normalisation would be preferable [12].

4.3. Gap frequency

The properties of *gap frequency* were very dependent on threshold level. The optimal level for differentiating tasks was ≈0.3% MVE (1.5% RVE). This value is close to that (0.5% MVE) used in other studies [9,27,29]. At these low levels rank order and number of homogeneous groups were similar to those obtained for muscular rest [at their optimal level of ≈0.5% MVE (3.0% RVE)]. Our findings suggest that the two measures, at very low levels, reflected the same properties and, thus, are interchangeable.

For tasks that can be modelled by a Gaussian process, i.e., the load varies randomly round a mean level, the number of level crossings (which corresponds to gap frequency) will have its maximum, when the threshold level is set to this mean. Hence, tasks performed at low activity are expected to display their highest gap frequency at low threshold levels, and vice versa. This is in accordance with the findings in Table 3, and is the probable explanation of the high sensitivity of gap frequency to threshold level, and the transition in ranking order of the tasks at about 1% MVE (5% RVE).

For a specific task that is performed at the same mean activity level by a group of individuals, gap frequency will reflect the individual, possibly neuro-muscular mediated, differences in activity, which has been shown to be related to the development of disorders [27]. For a mixture of work tasks, as in the present study, gap frequency, at a suitable threshold level [in this study 1% MVE (5% RVE)], was predominantly sensitive to individuals and only minimally to tasks. Hence, at this threshold level, gap frequency may be applicable for characterising individuals, but not tasks.

For threshold levels above 1% MVE (5% RVE) the interpretation of gap frequency becomes complex, and the physiological relevance is not obvious.

4.4. Muscular rest and percentiles of the APDF

Muscular rest was, in contrast to gap frequency, a measure with relatively consistent properties over a wide range of threshold levels for gap durations of both ≥1/8 s and ≥1/4 s. However, the optimal threshold level for differentiating tasks was ≈0.5% MVE (3% RVE). For example, at this threshold level, muscular rest (for a gap duration criterion of ≥1/8 s) had the highest ratio between sensitivity to tasks (R^2_{adj}=27 and 28%, for 0.5% MVE and 3% RVE, respectively) and individuals (R^2_{adj}=31 and 22%, for 0.5% MVE and 3% RVE). Moreover, normalisation to RVE was advantageous, since the above ratio was higher for RVE (1.3=28/22), as compared to MVE (0.9=27/31).

Regarding APDF *percentiles*, the CVs decreased, and sensitivity to variations in tasks was substantially improved for the lower percentiles, when normalisation was performed to RVE rather than to MVE. Of the percentiles, the 50th displayed the highest sensitivity to tasks (R^2_{adj}=17%), but was still highly sensitive to individuals (R^2_{adj}=46%). Also regarding other aspects, muscular rest and the percentiles did not provide the same information. Thus, muscular rest seems generally suitable and more relevant than any of the percentiles for characterising work tasks with low level sustained load.

From a physiological point of view, the selecting of gap duration criterion and threshold level should operationalise the concept of muscular rest. Thus, the gap duration criterion should be set long enough to be insensitive to the fluctuations in the EMG, emanating from a continuously firing single motor unit, but simultaneously short enough to detect a single missing action potential. For the trapezius muscle, the dominant firing rate is 8–12 Hz [30], advocating a gap duration criterion of ≥1/8 s. This is in accordance with the present study, which demonstrated optimal properties for both muscular rest and gap frequency for 1/8 and 1/4 s, but for 1/2 s, the properties were degraded.

The contribution to the surface EMG amplitude from one single motor unit is, in general, small [24]. Thus, from a physiological point of view, the threshold should be set at a very low level. However, this level will, although we eliminated the main effect of the noise of the EMG signal (by subtraction of its RMS value), still be limited by the noise, since we cannot compensate for the random variation of the noise (which increases with an increasing noise level). Due to the distance dependence of the derived EMG amplitude, a decrease in the threshold level corresponds to an increase in the detection range of active motor units. Thus, the obtained levels, which in our study were based on statistical criteria regarding explained variance — rather than physiological ones — probably indicated the optimal trade-off between detection range and noise level of our total recording and processing system.

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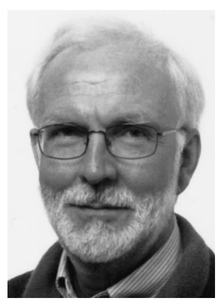

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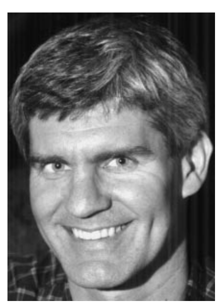

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