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Quantitative assessment of upper limb muscle fatigue depending on the conditions of repetitive task load

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Abstract

The aim of this study was to discriminate fatigue of upper limb muscles depending on the external load, through the development and analysis of a muscle fatigue index. Muscle fatigue is expressed by a fatigue index based on an amplitude parameter (calculated in the time domain) and a fatigue index based on a frequency parameter (a parameter calculated in the frequency domain). The fatigue index involves a regression function that describes changes in the EMG signal parameter, time elapsing before muscle fatigue and the probability of specific trends in changes in EMG parameters for the population under study.

The experimental study covered a group of 10 young men. During the study, they exerted force at a specific level and for a specific time in 12 load variants. During the study, EMG signals from four muscles of the upper limb were recorded (trapezius pars descendents, biceps brachii caput breve, extensor carpi radialis brevis, flexor carpi ulnaris). For each variant and for each examined muscles, the value of the fatigue index was calculated. Values of that index quantitatively expressed fatigue of a specific muscle in a specific load variant.

A statistical analysis indicated variation in the fatigue of the biceps brachii caput breve, extensor carpi radialis brevis, and flexor carpi ulnaris muscles depending on the external load (load variant) according to the task performed with the upper limb.

The study demonstrated usefulness of the fatigue index in expressing quantitatively muscle fatigue and in discriminating muscle fatigue depending on the external load.

Keywords: Electromyography; Handgrip; Upper limb; Fatigue; Repetitive task

1. Introduction

Jobs that require repetitive operations performed with upper limbs are very common. They usually involve spine and lower limb positions that are static for extended periods with simultaneous manipulations that are done with upper limbs, often at a fixed repetition rate.

This kind of upper limb activity—called cyclic work or repetitive task—consists of sequences of tasks. The length of the cycle, its duration and the relative external force of each cycle period determine the conditions of the external workload while repetitive tasks are performed [46]. It has been proved that repetitive tasks make work particularly hazardous [4,55,60].

The relationship between the external workload characterised by the abovementioned parameters of a repetitive task and musculoskeletal load or fatigue has been evidenced in numerous studies, in which individual authors discussed various indices of load and fatigue of the musculoskeletal system [12,14,27,33–35,44,46,56].

One of the most often applied methods of assessing local muscular fatigue is an analysis of the EMG signal. Processes occurring as an effect of fatigue are visible in the recorded EMG signal as a change of values of selected EMG parameters. Those parameters are obtained as a result of processing the EMG signal in the time and frequency domains. Muscle fatigue causes a shift of the EMG power spectrum into lower frequency [28,41]. Mean power frequency (MPF) and median frequency (MF) are indicators of the power frequency shift. A decrease in values of parameters

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analysed in the frequency domain is correlated with an increase in values of parameters analysed in the time domain (the amplitude of the EMG signal) [15,30,42].

Muscle fatigue is not the exclusive reason for changes in the values of EMG parameters. Many studies confirmed changes in the values of those parameters which result from changes in the value of the external force [5–7,19,49]. Recovery, which causes a decrease in the value of the amplitude and an increase in MPF or MF, can be another reason [38]. Therefore, it is generally agreed that muscle fatigue is documented by the EMG signal only if there is both a decrease in a parameter analysed in the frequency domain and an increase in the parameter analysed in the time domain [25,26,29,37,38,42,48,50,54,57].

Many studies documented that changes in EMG parameter values under study depended on the external load. Not all of the several studies that evidenced a decrease in values of parameters analysed in the frequency domain and an increase in parameter values in the time domain described parameter changes quantitatively; instead, they just indicated trends of changes [20,42,43]. In those studies in which changes were described with a regression equation, in most cases, it was assumed that a change in the analysed parameter of the EMG signal in time corresponded to a linear relationship and the slope coefficient or a change in the parameter value in time were taken as fatigue indices [13,36,45,51]. However, in many cases changes in EMG signal parameters in time corresponded more to an exponential or logarithmic curve than to a linear relationship [8,17,20,23,42,58]. That means changes in parameter values in time can be described by different regression functions.

In an analysis of an upper limb repetitive task, it is important to express muscular fatigue quantitatively. This makes it possible to distinguish differences in muscle fatigue depending on the conditions of the external load both for continuous static loads and for repetitive ones. In an analysis aimed at a quantitative assessment of muscle fatigue, in addition to a regression function equation, a few other factors should be considered as changes in EMG signal parameters depend not only on the external load [13,16,43] but also on other factors such as the composition of fibres of a particular muscle that is studied [3,21,25,26,39]. This means that during the same level of muscle contraction, fatigue in different muscles can be characterised by different changes in values of EMG parameters [3,21,25,26,36,39,40].

In our opinion a regression function equation, determined for the analysed muscle and describing changes in the analysed parameter in time, is the most important factor describing muscular fatigue. The regression function equation is influenced by the time in which changes in EMG signal parameters are considered. Therefore, it is necessary to consider how that time should be determined. In studies on muscle fatigue, the time of fatigue is subjectively determined by study participants (maximum holding time) [13,15,35,43,45,46,58] or the time is imposed: the same for each participant [36,42,46,47,52]. However, neither maximum holding time nor time imposed by experimental conditions characterises the time of fatigue of muscles involved in performing the task.

Participants, even when performing the same upper limb activity, activate muscles in different ways [32]. What is more, the necessity to sustain a determined force level for the longest possible time causes changes in muscle fiber activity [59], which influences values of EMG parameters. The time of sustaining a load imposed by experiment conditions does not take into consideration individual capabilities of participants and it can be either too short or too long considering the process of muscle fatigue. Maximum holding time considers general fatigue of the engaged body part, not of the analysed muscle from which the EMG signal is detected. Additionally, maximum holding time is also influenced by factors which do not depend on objective fatigue, like motivation or sensitivity to pain. This can lead to inaccuracies in EMG signal analysis, which can be avoided when the time of fatigue is determined independently for each examined muscle.

Fatigued muscle fibers can be switched off and exchanged by others, not fatigued [11] and upper limb load can still be sustained. A phenomenon like that is illustrated by EMG parameter values determined in the frequency domain, which show a decrease and then an increase in parameter values in time. This phenomenon can be caused by recruitment of new, not fatigued, muscle fibers [28,59] and is an evidence of a change in an activity caused by muscle fatigue. This phenomenon is very obvious when values of parameters are presented as a function of time and it makes determining the time of fatigue possible (time before there is an unexpected change in parameters). Even if switching occurs to prevent exhaustion in motor units, in our opinion, it can indicate muscle fatigue.

Lack of expected changes in EMG parameters in each participant is an additional obstacle when fatigue is assessed [1,10,22,49,57].

Consequently, it can be assumed that three factors are of particular importance in assessing muscle fatigue, that is, changes in the value of a particular EMG signal parameter in time (described by a regression function), time after which muscle fatigue takes place and the number of participants who exhibit expected trends in changes in the parameter in relation to the total number of participants. Thus, muscle fatigue should be assessed with an index enabling quantitative assessment of muscle fatigue, which includes the three factors mentioned above.

The aim of this study was to discriminate fatigue of upper limb muscles depending on the external load through a fatigue index, which involves a regression function describing changes in the EMG signal parameter in time, time before there is muscle fatigue and the probability of the occurrence of particular trends in changes for the population under study.

2. Muscle fatigue index

Assessed according to a standard algorithm, the fatigue index for an EMG parameter—a function of a regression function equation, the time of fatigue and the number of participants who show expected tendencies of changes in relation to all participants—makes it possible to quantitatively assess muscle fatigue in both static and repetitive tasks (Fig. 1).

Changes in EMG parameters describe muscle fatigue only when there is both a decrease in parameters calculated in the frequency domain and an increase in parameters calculated in the time domain. Therefore, in assessing fatigue two parameters must be considered: one calculated in the time domain and the other one calculated in the frequency domain. Selecting those parameters involves taking into consideration advantages and disadvantages of each EMG parameter that describes muscle fatigue. The next step, after parameters of muscle fatigue have been selected, consists in conducting calculations of values of the chosen parameters, according to standard procedures, on the basis of fragments of the signal registered during an isometric contraction of a muscle. Values of the analyzed parameters of the EMG signal for determined time sequences are a result of this step.

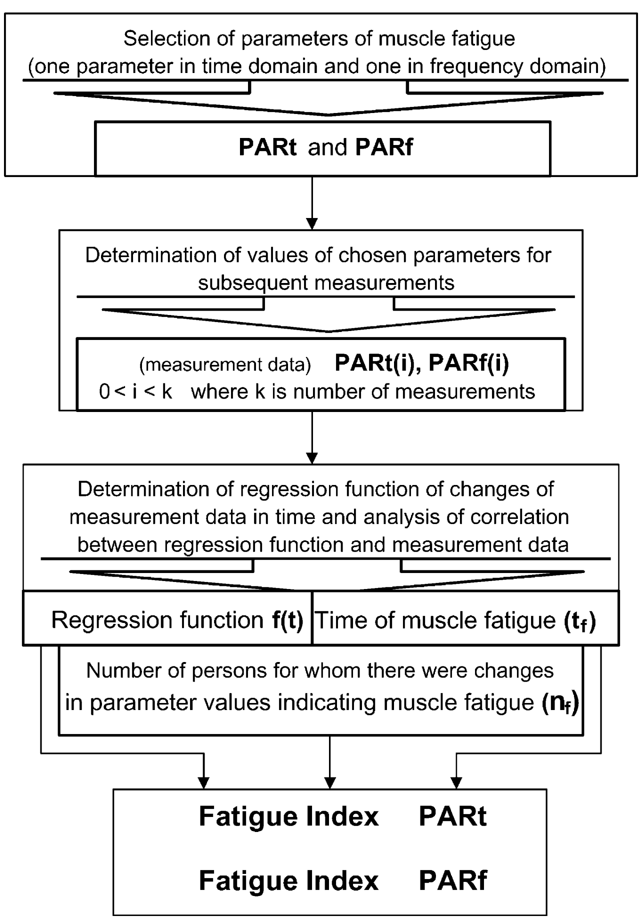

Fig. 1. An algorithm for assessing the muscle fatigue index.

Changes in values of the analyzed parameter in time can be determined in different ways, for example, with the difference or decrement from the first to the last. However, in our opinion, regression analysis is the most reliable way of expressing changes of the parameter in time. Regression analysis makes it possible to determine the regression function $f(t)$, which describes changes in the analyzed parameter in time. In the developed fatigue index any function can be applied. However, it should be a function that best fits experimental data. It is also required that it is the same one for all participants. The mathematical equation of the regression function changes depending on the adopted time of muscle fatigue. Because the parameter which expresses the time of fatigue is of considerable importance in a quantitative analysis of muscle fatigue, the question arises as to the way that time should be determined.

The time of fatigue is different for each of the involved muscles; therefore, it cannot be defined arbitrarily. In the proposed algorithm, it should be determined through an analysis of the correlation coefficient for successive time points (values of EMG parameters) and the regression function. Determination of the regression function and the coefficient of correlation between the regression function and measurement data in determined time sequences (for example, every minute) makes it possible to determine the regression function equation for which the correlation is strongest. The time for which the value of the correlation coefficient, that shows the relationship between measurement data and the regression curve is highest, is taken as the time of fatigue (t_f).

Parameter t_k expresses the duration of the experiment, which is the same for all participants. Parameter t_f depends on muscle fatigue, like maximum holding time, which is commonly used in such studies. However, it is assessed objectively and it relates the examined muscle only.

Load imposed by experimental conditions does not cause fatigue in all participants. That is why the number of valid trials (n_f) obtained for each variant and for each analysed muscle can be lower than the number of participants (n_n). The ratio of those two numbers is important for overall assessment of fatigue. Presence of fatigue is described by a coefficient of correlation between measurement data and the regression function for successive time points. In the present study, the threshold of fatigue was set—on the basis of statistical considerations—at 0.45 [31]. In those cases in which the value of the coefficient of correlation was lower than 0.45, measurement data were not approximated with any mathematical relationship and the value of the fatigue index was assumed to be zero.

On the basis of the equation of the regression function $f(t)$, fatigue time (t_f), the number of valid trials (n_f), the fatigue index for a parameter in the time domain and a parameter in the frequency domain is calculated according to the relationship (1):

$$\mathrm{FI} = \left|\frac{f(t_2) - f(t_1)}{f(t_1)}\right| \times \frac{t_k}{t_f} \times \frac{n_f}{n_n} \tag{1}$$

where FI, fatigue index; t_1, initial time for a parameter analysed in the frequency domain and final time for a parameter analysed in the time domain; t_2, final time for a parameter analysed in the frequency domain and initial time for a parameter analysed in the time domain; $f(t_1)$, value of regression function at time t_1; $f(t_2)$, value of regression function at time t_2; t_k, time of sustaining a load; t_f, time elapsing before muscle fatigue equalling (t_1–t_2) for a parameter analysed in the time domain or (t_2–t_1) for a parameter analysed in the frequency domain; n_f, the number of people in whom there are parameter changes indicating muscle fatigue; n_n, the number of participants.

In the presented relationship, for a given study, two parameters are constant, that is, time of sustaining a load (t_k) and the number of participants (n_n). All other parameters change their value according to muscle fatigue, which influences the value of the fatigue index. More rapid changes in the regression function cause a higher value of the fatigue index, as do lower fatigue time and a higher number of participants with signs of muscle fatigue.

Assuming that the regression function—in studies in which 10 participants took part (n_n) and the time of load was set at 10 min (t_k)—is expressed by the equation $f(t) = -8\ln(t) + 92$, then if fatigue occurred after 8 min (t_f) and was present in seven participants (n_f), FI equals 0.47. If fatigue occurred after 5 min (t_f), the value of FI would change and it would equal 0.69.

The last stage of the analysis consists in discriminating fatigue indices depending on the variant of the external load.

3. Experimental study

3.1. Participants

Ten male students of the Academy of Physical Education, not professional sportsmen, participated in the study. The age of the students ranged from 22 to 25 (average: 24.8), body height from 174 to 180 cm (average: 176.7), body mass from 67 to 90 kg (average: 75.9). People covered with the study did not complain of musculoskeletal disorders and had had no injuries within the past 3 months.

The study was carried out with the approval of the Ethics Committee of the Academy of Physical Education. An informed consent was obtained before the experiment. The participants were financially compensated.

3.2. Variants of experiments

Fatigue of selected muscles of the upper limb was assessed for 12 different variants of the external load, characterised by repetitive task parameters, that is, cycle duration as well as duration and the external force of each cycle period. Each variant involved exerting handgrip force at a determined level, at a fixed position of the upper limb. Force level was determined in relation to the maximal force, which individualised load conditions and determined universal parameters irrespective of the participants' anthropometric dimensions and physical capabilities.

Attention was paid to selecting variants which would differ in the character of the load and which would consider static as well as cyclic loads. In 10 out of the 12 variants that characterised two-cycle repetitive work, cycles differing in both force levels and cycle length were chosen. Two variants with static load of a considerably different force level were also included. Since, according to Silverstein et al. [55], cycles shorter than 30 s are particularly likely to induce upper limb musculoskeletal disorders, cycles of 5–31 s were considered.

Cycle time (CT), duration of a cycle period (TA and TB) and external relative force value (FA and FB) in individual cycle periods are presented in Table 1.

3.3. Protocol

Exertion of handgrip force was performed with the right upper limb at a specific (so-called standard) upper limb posture, that is, the arm was positioned along the trunk, whereas the forearm was at the angle of 90° in relation to the arm (Fig. 2). While performing the exercise, participants not only kept the appropriate force level for the time determined by study conditions but

Table 1
Values of external force (FA—force exerted during period A, relative to maximum, FB—force exerted during period B, relative to maximum), duration of a cycle period (TA, TB) and cycle time (CT) for each variant of the experiment

	CT (s)	TA (s)	FA	TB (s)	FB
V1	5	4	0.50	1	0
V2	230	230	0.40	0	0
V3	7.8	1	0.50	6.8	0.13
V4	4	2	0.51	2	0.23
V5	3	1	0.31	2	0
V6	2	1	1	1	0
V7	31	7	0.70	24	0
V8	300	300	0.15	0	0
V9	10.5	1	0.30	9.5	0
V10	15.8	1	0.46	14.8	0.14
V11	7.4	5	0.30	2.4	0.10
V12	9	7	0.50	2	0

also maintained an appropriate posture: they sat with an erect spine. Their left upper limb rested freely.

Experimental sessions were performed on separate days with intervals of at least one day. An experimental session consisted of a preparatory phase and an experimental phase.

During the preparatory phase, maximum strength capabilities of handgrip was measured. Participants were familiarised with the dynamometer and with the testing procedure, so they were able to exert maximal value during the measurements. The maximal level of force was determined by choosing the greatest of three attempts at generating maximal voluntary effort. Each of those attempts lasted 3 s, and they were 2 min apart. Maximal force values were used to determine the level of the external relative force corresponding to phases of cycles.

Fig. 2. Body posture during experiments.

During the preparatory phase, participants were also familiarised with a randomly-ordered variant of the experiment. They were encouraged to try to perform the experimental task, which gave them skills to perform the experimental task properly.

After a half- hour relaxation, participants performed the experimental phase of the session, during which they performed tasks determined by a given variant.

The duration of the experimental phase differed among variants. Intermittent load tasks were performed for up to 10 min, whereas constant load tasks lasted for up to 4.5 or 5 min, participants were not able to sustain the load longer time.

3.4. Strength measurement

Measurement of handgrip force—both while exerting maximal force and during tests under specific load conditions—was performed at a test stand equipped with a computerised muscle force measuring system (CMFMS), produced by JBA Zb. Staniak (Poland). The system made it possible not only to measure and record the value of the exerted force, but also to visualise it. The system consisted of a hand dynamometer connected to a PC (RS232C interface) via a 12-bit analog–digital converter with a sampling rate of 2 kHz, and an amplifier. A full Wheatstone bridge was used.

The measuring range of the hand dynamometer was 1200 N, and the maximum linear error of all measurement devices was below 0.5%.

3.5. EMG signal measurement

The EMG signal was recorded during isometric muscle tension, that is, while handgrip-type force of a constant value was exerted at a specific limb position.

The myoelectric signal was picked up with bipolar disposable Ag–AgCl (Blu Sensor Medicotest, Ølstykke, Denmark) electrodes, whose active area is 5 mm× 5 mm. The electrodes were applied to the skin with an inter-electrode distance of 20 mm, above and parallel to the assumed direction of the fibers in the central part of the muscles. The skin was properly prepared (including shaving if necessary, slight abrasion and cleaning with an alcohol solution) to obtain inter-electrode resistance below 2 kΩ. To ensure consistent electrode placement for each of the test sessions, the participant's skin was marked around the electrodes.

An ME3000P (Mega Electronics, Finland) device was used for the measurements and analysis: it enables observation and recording of a raw signal and its subsequent analysis following procedures of muscle fatigue analysis. Preamplifiers mounted close to the electrodes made it possible to register the non-artefact signal.

The EMG signal was amplified with a differential amplifier and a Butterworth filter (−3dB bandwidth: 8–500 Hz). Input impedance was 10 GΩ and CMRR 110dB. The signal-to-noise ratio was −75 dB. The EMG signal was sampled through a 12 bit A/D converter with a sampling rate of 1 kHz.

All tasks involve muscles, which play different roles and which determine fatigue of the entire upper limb. This study considered muscles which support the upper limb in a determined posture and those involved in handgrip force exertion. It is generally accepted that the trapezius muscle is crucial for supporting an upper limb posture. Another muscle considered for analysis was one expected to be activated as a result of supporting the upper limb and as a result of hand activity: biceps brachii caput breve. M. extensor carpi radialis, m. extensor digitorum communis, m. flexor carpi ulnaris and m. flexor digitorum superficiallis were considered in an analysis of muscle fatigue involved in exerting handgrip force.

During pilot studies, tests were performed which confirmed that an activity like flexion, extension of hand or fingers as well as handgrip activates both considered flexors and/or both considered extensors. During maximum handgrip, amplitude of both analysed flexors and both analysed extensors was similar, which can be for two reasons: (a) both muscles are involved in performing handgrip (activation of m. flexor carpi ulnaris and m. extensor carpi radialis was probably mainly caused by the need for stabilization); (b) possible crosstalk. Because in the examined participants m. flexor carpi ulnaris was better recognizable—by palpation—than m. flexor digitorum superficiallis, and m. extensor carpi radialis was better recognizable than m. flexor digitorum superficiallis, the electrodes were placed over m. extensor carpi radialis brevis and m. flexor carpi ulnaris. Usually crosstalk is possible, between either forearm flexors or forearm extensors. However, care was taken to ensure that there was no crosstalk between m. flexor carpi radiali and m. extensor carpi ulnaris.

4. Analysis

Two EMG signal parameters were analysed: the AEMG parameter (averaged amplitude of the EMG signal) and the MPF parameter (median power spectrum frequency of the EMG signal). In order to perform a quantitative assessment of fatigue, the fatigue index for the AEMG parameter and the fatigue index for the MPF parameter were determined.

The first step to determine the fatigue index was to calculate values of the AEMG and MPF parameters for each cycle and for each case (for each participant and for each muscle in 12 load variants). Those parameters were calculated for a fragment of the EMG signal recorded during the period of a higher level of relative force (period A), whereas for variants V2 and V8 (characterised by a constant level of force throughout the whole trial) the EMG signal was analysed in equal time intervals (every 15 s). Successive epochs of over 0.5 s were multiplied by a flat-topped window. As a result of that process, numerical values of the AEMG and MPF parameters were obtained for each cycle.

For each case, the regression function equation for parameters AEMG and MPF was determined. Because in the great majority of cases the relationship between AEMG or MPF and time was best described with a logarithmic equation, a mathematical relationship in the form $f(t) = a{*}\ln(t){+}b$ was adopted as the regression function.

In all cases, time of sustaining the load (t_k) was set at 10 min. According to the procedure of the fatigue index analysis, the time of fatigue was determined independently for each participant, each of the four muscles studied and each load variant.

The time of fatigue was determined in an analysis of the coefficient of correlation between measurement data (MPF parameters for successive time points) and the estimated regression function. In some cases, the MPF parameter decreased and then increased in value (Fig. 3). That situation made the analysis easier as it indicated the time for which the coefficient of correlation between measurement data (MPF parameters for successive time points) and the estimated regression function was largest, which meant it recognised the time of muscle fatigue.

Statitica 6.1 (Statsoft) was used for statistical analysis.

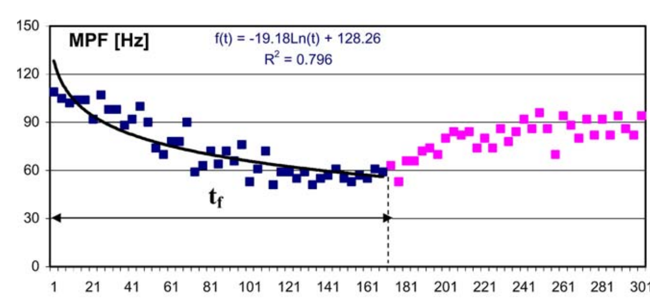

Fig. 3. An example of MPF (mean power frequency) changes in time for the extensor carpi radialis brevis muscle in variant V4 (t_f—time of fatigue).

5. Study results

As muscle fatigue is evidenced by changes in both the parameter calculated in the time domain and the parameter calculated in the frequency domain, it is important to analyse not only values of the fatigue index in the subsequent variants of the experiment but also if trends in the changes in the MPF fatigue index and the AEMG fatigue index are in step. For this purpose, correlation analysis was done.

Mean values and standard error for the AEMG fatigue index and the MPF fatigue index for the trapezius pars descendents muscle in individual load variants are presented in Fig. 4.

Trends in changes in the value of the AEMG fatigue index in relation to the load variant are similar to trends in changes in the MPF fatigue index. Spearman's correlation coefficient between those indices equals 0.98. For two study variants (V2 and V9) no valid cases were obtained, which meant that changes in AEMG and MPF parameters in time did not display relationships that made determining the regression function possible.

Fig. 5 presents mean values and standard error of the AEMG fatigue index and the MPF fatigue index for the biceps brachii caput breve muscle in relation to the load variant.

The mean value of the fatigue index for the V5 variant (for all participants $r < 0.45$) equalled zero for both MPF and AEMG parameters.

The coefficient of correlation between the AEMG fatigue index and the MPF fatigue index for the biceps brachii caput breve muscle equalled 0.95.

An analysis of the AEMG fatigue index and the MPF fatigue index for the extensor carpi radialis brevis muscle in two load variants (V7 and V9) did not evidence valid cases, which indicates that fatigue was not present in those variants (Fig. 6). Also in this muscle,

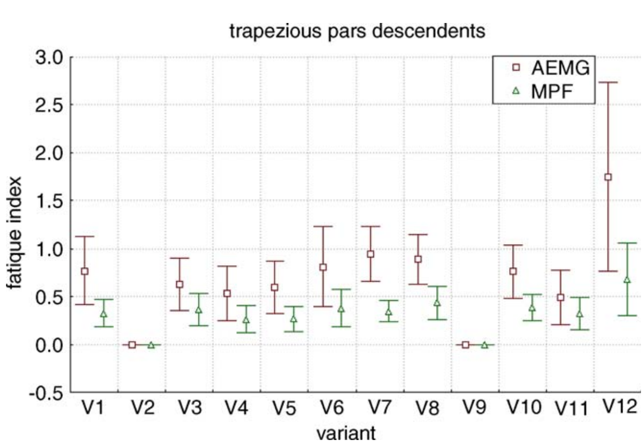

Fig. 4. Mean and standard error of AEMG fatigue index and MPF fatigue index for the trapezius pars descendents muscle in variants of the experiment.

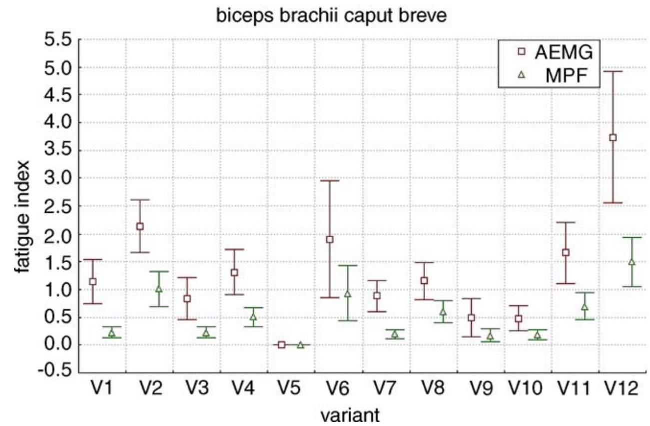

Fig. 5. Mean and standard error of AEMG fatigue index and MPF fatigue index for the biceps brachii caput breve muscle in variants of the experiment.

the coefficient of correlation between the AEMG fatigue index and the MPF parameter fatigue index was high and equalled 0.89.

Fig. 7 presents mean values and standard deviations for the AEMG and MPF fatigue indices for the flexor carpi ulnaris muscle.

In the case of the flexor carpi ulnaris muscle, similarly as in the case of the extensor carpi radialis muscle, mean values of the AEMG fatigue index and the MPF fatigue index for two study variants (V7 and V9) equalled zero.

The coefficient of correlation between the AEMG fatigue index and the MPF fatigue index for the flexor carpi ulnaris muscle equalled 0.84.

In order to analyse grounds of muscle fatigue in the examined muscles, (does it come from supporting upper limb posture or from exerting handgrip force?) the values of the correlation coefficients and the probability levels for the fatigue indices (AEMG and

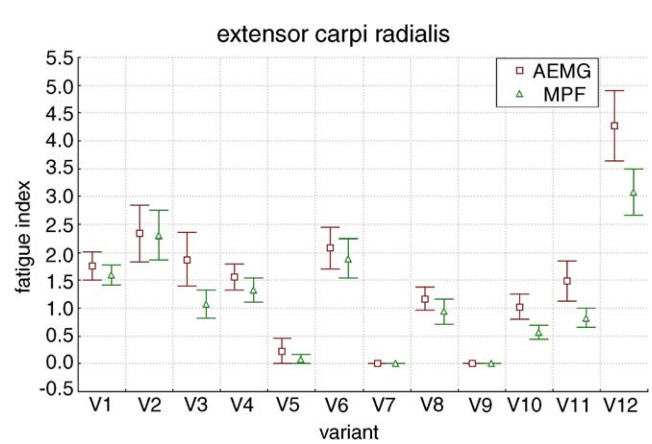

Fig. 6. Mean and standard error of AEMG fatigue index and MPF fatigue index for the extensor carpi radialis muscle in variants of the experiment.

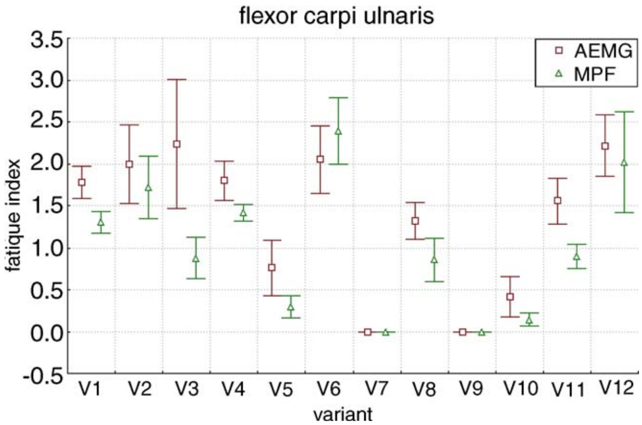

Fig. 7. Mean and standard error of AEMG fatigue index and MPF fatigue index for the flexor carpi ulnaris muscle in variants of the experiment.

MPF) obtained for individual muscles were examined (Table 2).

AEMG and MPF fatigue indices displayed statistically significant correlation between the biceps brachii caput breve muscle and the other three muscles. Correlation between the extensor carpi radialis and flexor carpi ulnaris muscles was the strongest.

The non-parametric ANOVA Friedman test showed significant differentiation in both the MPF fatigue index and the AEMG fatigue index in three out of the four examined muscles (Table 3).

The non-parametric post hoc for the Friedman test was used to find out between which load variants there were differences in muscle fatigue. Differences were recognised as statistically significant at $p < 0.05$.

As regards the biceps brachii caput breve muscle, statistically significant differences in both the MPF fatigue index and the AEMG fatigue index between individual study variants were found in one case.

In the case of the extensor carpi radialis brevis muscle, an analysis of the differences in the MPF fatigue index showed there were statistically significant differences in 13 cases, whereas for the AEMG fatigue index statistically significant differences were recorded in 10 cases. In nine cases, statistically significant differences between individual study variants were recorded for both the MPF fatigue index and the AEMG fatigue index.

In the course of the analysis of the MPF fatigue index and the AEMG fatigue index for the flexor capi ulnaris muscle, it was shown that statistically significant differences between study variants for the MPF fatigue index occurred in 20 cases, whereas for the AEMG fatigue index they occurred in 12 cases. In 10 cases, statistically significant differences between individual study variants were recorded for both the MPF fatigue index and the AEMG fatigue index.

Mean and root mean square of indices of all examined muscles were considered an indicator of total upper limb fatigue, called the summary fatigue index. The risk of musculoskeletal disorders can increase twofold—due to an increase in total fatigue of the upper limb (all the involved muscles) and due to excessive fatigue of one of the muscles involved. Accepting the summary fatigue index as the root mean square of indices for all examined muscles ensures that a high value of the index, even for one of the examined muscles, causes a higher value of the index than if it were expressed by a mean value.

Table 4 presents absolute differences between the average rank between individual study variants for the summary fatigue index obtained as a result of the post hoc for the Friedman test. The table presents only those cases for which there were statistically significant differences.

6. Discussion and conclusions

Fatigue index involves a change in the parameter value in time expressed by the regression function, time after which the analysed muscle is fatigued as well as the probability that expected changes will occur in the examined population.

The fatigue index was applied in experimental studies, whose aim was to differentiate muscle fatigue due to the external load characterised by repetitive task parameters. In some cases, the participants did not dis-

Table 2
Spearman correlation coefficients and probability levels for AEMG fatigue index and MPF fatigue index. Statistically significant differences at $p \leq 0.05$ are shown in bold

Muscle	Biceps brachii caput breve		Extensor carpi radialis brevis		Flexor carpi ulnaris	
	AEMG	MPF	AEMG	MPF	AEMG	MPF
Trapezius pars descendents	**0.247** ***p = 0.007***	**0.231** ***p = 0.011***	0.035 $p = 0.375$	0.355 $p = 0.723$	0.0215 $p = 0.234$	0.013 $p = 0.885$
Biceps brachii caput breve			**0.218** ***p = 0.016***	**0.295** ***p = 0.000***	**0.327** ***p = 0.000***	**0.329** ***p = 0.000***
Extensor carpi radialis					**0.666** ***p= 0.000***	**0.714** ***p = 0.000***

Table 3
Results of a non-parametric ANOVA Fridman test indicating differences in the muscle fatigue index between variants of experiments

	AEMG		MPF	
	Chi^2	*p*	Chi^2	*p*
Trapezius pars descendents	17.97	0.0823	15.51	0.1603
Biceps brachii caput breve	25.94	0.0066	25.56	0.0075
Extensor carpi radialis	61.29	0.0001	75.52	0.0001
Flexor carpi ulnaris	53.15	0.0001	75.53	0.0001
Summary fatigue index	59.06	0.0001	79.13	0.0001

Table 4
Results of a non-parametric post hoc for the Friedman test indicating differences between AEMG summary fatigue index and MPF summary fatigue index for variants with the statistically significant differences with $p < 0.05$ (marked as bold)

	AEMG	MPF
V1 × V7	4.6	**5.8**
V1 × V9	**5.65**	**6.35**
V2 × V7	3.85	**6.65**
V2 × V9	4.9	**7.2**
V4 × V7	4.4	**5.6**
V4 × V9	**5.45**	**6.15**
V5 × V12	**8.15**	**8.25**
V6 × V9	**5.65**	**8.05**
V6 × V10	4.05	**5.85**
V7 × V12	**8**	**8.7**
V9 × V12	**9.05**	**9.25**
V10 × V12	**7.45**	**7.05**

play typical changes indicating muscle fatigue (an increase in the value of the AEMG parameter and a decrease in the value of the MPF parameter). The number of people for whom the above phenomenon was recorded differed depending on the external load variant and the muscle studied. It is a commonly known fact that in some people no fatigue is observed or even changes opposite to expected ones take place; a phenomenon like that was recorded in several studies [9,29]. Differences between results related to muscle fatigue, obtained for individual people, might be a consequence of a change in muscle temperature [18], differences in fibre types or differences in muscle fibre recruitment pattern [24,40].

The results of the presented study showed differences between individual study variants. At the same time, the influence of cycle duration and the length of individual cycle periods as well as the relative force during cycle periods turn out to impact the value of the fatigue index. This is consistent with the results of other studies that suggest a clear relationship between fatigue and not only the value of the relative external force but also the duration of individual periods and cycle length [8,46].

The values of the fatigue index were high for the V6 variant for all muscles under study, whereas for variant V7 in three muscles there were no changes in EMG signal parameters, which suggests no fatigue in those muscles and at the same time the two variants were characterised by the highest force level at period A. However, they considerably differed in cycle length. The cycle of the V7 variant was 10 times as long as that of the V6 variant and the ratio of the load period to the relaxation period was similar in both study variants. This proves the influence of cycle length on the value of the parameter characterising muscle fatigue, which is consistent with Silverstein et al.'s [55] findings.

There is correlation of fatigue indices between muscles under study. The strongest correlation was recorded between forearm muscles, that is, m. extensor carpi radialis and m. flexor capi ulnaris. Fatigue indices for those muscles were also correlated with the fatigue index for the biceps brachii caput breve muscle. However, there was no such correlation with the trapezius pars descendents muscle. This can suggest that factors causing fatigue of forearm muscles differed from those that caused fatigue of the trapezius muscle. Statistically, significant correlation of the biceps brachii caput breve muscle both with the trapezius muscle and the forearm muscles indicated the intermediate role of that muscle, close both to the tasks performed by the trapezius muscle and the tasks of the extensor carpi radialis and flexor capi ulnaris muscles. The role of the biceps brachii caput breve muscle in handgrip exercise was evidenced also in other studies [2,53].

The developed fatigue indices (AEMG and MPF) evidenced quantitative variation in the fatigue of the biceps brachii caput breve, extensor carpi radialis brevis, and flexor carpi ulnaris muscles depending on the parameters of the repetitive task performed with the upper limb.

The fatigue index enabled quantitative assessment of fatigue of a specific muscle depending on the load, also of the repetitive task.

Values of the fatigue index reflect, in part, fatigue of the muscle under analysis, which occurs as a result of the external load in individual study variants. This study has proved that the fatigue index makes it possible to quantitatively express muscle fatigue with consideration of the factors which play a meaningful role in assessing fatigue, like the time of fatigue or the number of cases in which there was fatigue. It was also shown that by using that index it was possible to discriminate muscle fatigue depending on the external load.

Dynamic or repetitive loads predominate in current jobs. This type of load is more difficult to study than static load due to some limitations, particularly in spectral analysis, which can be used for analysing stationary fragments of the EMG signal only. Therefore, two approaches are taken in analysing non-isometric loads: (a) implementing isometric tests between the main work tasks, and (b) recording EMG signal during cycle phases with isometric muscle contraction, which can be applied only in repetitive tasks in which there are long enough periods of isometric muscle contraction. The developed fatigue index relies on an analysis of fragments of the EMG signal registered during isometric muscle contractions repeated in determined time sequences. Therefore, it can be applied in both kinds of studies of repetitive tasks.

Limitations in the application of the index are connected mostly with the requirements applying to spectral analysis. In the case of dynamic work, when the test is applied, or in the case of a repetitive task with variations in movements, repeatability of posture in which measurements are performed is extremely important. Another limitation occurs when intervals between loads that are long enough for the renewal process to start, lead to an increase in the values of the MF and MPF parameters and to a decrease in the value of the amplitude. That phenomenon indicates a limited use of electromyography for analysing muscle fatigue during repetitive work.

It should be also stressed that although the index expresses fatigue quantitatively, most information can be derived from comparing at least two different indices, describing two different work conditions.

The index can have broad application in upper limb muscles fatigue differentiation according to external load described by repetitive task parameters. The fatigue index is particularly useful in comparative studies. However, in cases where comparative analysis is performed the same regression function should be applied for each participant and study variant. Due to the fact that this index is relatively independent of the conditions of the conducted studies, it makes a sound comparison of fatigue for different variants of the external load possible. It can be a good tool for assessing muscle fatigue and thus for assessing work conditions.

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References

[1] W. Ament, G.J.J. Bonga, A.L. Hof, G.J. Verkerke, EMG median power frequency in an exhausting exercise, J. Electromyogr. Kinesiol. 3 (1993) 214–220.

[2] F. Aoki, Activity patterns of upper arm muscles in relation to direction of rapid wrist movement in man, Exp. Brain Res. 83 (1991) 679–682.

[3] M. Badier, C. Guillot, F. Lagier-Tessonnier, H. Burnet, Y. Jammes, EMG power spectrum of respiratory and skeletal muscles during static contraction in healthy man, Muscle Nerve 16 (1993) 601–609.

[4] S. Barnahart, P.A. Demers, M. Miller, W.T. Longstreth, L. Rosenstock, Carpal tunnel syndrome among ski manufacturing workers, Scand J. Work Environ. Health 17 (1991) 46–52.

[5] M. Bernardi, F. Felici, M. Marchetti, F. Montellanico, M.F. Piacentini, M. Solomonow, Force generation performance and motor unit recruitment strategy in muscles of contralateral limbs, J. Electromyogr. Kinesiol. 9 (2) (1999) 121–130.

[6] M. Bilodeau, B. Arsenault, D. Gravel, D. Bourbonnais, Influence of gender on the EMG power spectrum during an increasing force level, J. Electromyogr. Kinesiol. 2 (3) (1992) 121–129.

[7] M. Bilodeau, M. Cincera, S. Gervais, A.B. Arsenault, D. Gravel, Y. Lepage, P. McKinley, Changes in the electromyographic spectrum power distribution caused by a progressive increase in the force level, Eur. J. Appl. Physiol. 71 (2–3) (1995) 113–123.

[8] S.E.G. Bystrom, S.E. Mathiassen, C. Fransson-Hall, Physiological effects of micropauses in isometric handgrip exercise, Eur. J. Appl. Physiol. 63 (1991) 405–411.

[9] H. Christensen, A. Fuglsang-Frederiksen, Quantitative surface EMG during sustained and intermittent submaximal contractions, Electroencephalogr. Clin. Neurophysiol. 70 (1988) 239–247.

[10] H. Christensen, K. Sogaard, B.R. Jensen, L. Finsen, G. Sjogard, Intramuscular and surface EMG power spectrum from dynamic and static contractions, J. Electromyogr. Kinesiol. 5 (1995) 27–36.

[11] P. Christova, A. Kossev, Motor unit activity during long-lasting intermittent muscle contractions in humans, Eur. J. Appl. Physiol. 77 (4) (1998) 379–387.

[12] T. Cook, J. Rosencrance, C. Zimmermann, D. Gerleman, P. Ludewig, Electromyographic analysis of a repetitive hand gripping task, Int. J. Occup. Saf. Ergonomics 4 (2) (1998) 185–200.

[13] A.G. Crenshaw, S. Karlsson, B. Gerdle, J. Friden, Differential responses in intramuscular pressure and EMG fatigue indicators during low- vs. high-level isometric contractions to fatigue, Acta Physiol. Scand. 160 (4) (1997) 353–361.

[14] J.B. Dahalan, J.E. Fernandez, Psychophysical frequency for a gripping task, Int. J. Ind. Ergonomics 12 (1993) 219–230.

[15] J.H. Van Dieen, H.H.E.O. Vrielink, A.F. Housheer, F.B.J. Toussaint, H.M. Toussaint, Trunk extensor endurance and its relationship to electromyogram parameters, Eur. J. Appl. Physiol. 66 (1993) 388–396.

[16] J.H. van Dieën, B. Böke, W. Oosterhuis, H.M. Toussaint, The influence of torque and velocity on erector spinae muscle fatigue and its relationship to changes of electromyogram spectrum density, Eur. J. Appl. Physiol. 72 (1996) 310–315.

[17] J. Duchateau, K. Hainaut, Effects of immobilization on electromyogram power spectrum changes during fatigue, Eur. J. Appl. Physiol. 63 (1991) 458–462.

[18] J. Duchêne, F. Goubel, Surface electromyography during voluntary contraction: processing tools and relation to physiological events, Crit. Rev. Biomed. Eng. 21 (1993) 313–397.

[19] F. Esposito, D. Malgrati, A. Veicsteinas, C. Orizio, Time and frequency domain analysis of electromyogram and sound myogram in the elderly, Eur. J. Appl. Physiol. 73 (1996) 503–510.

[20] F. Esposito, C. Orizio, A. Veicsteinas, Electromyogram and mechanomyogram changes in fresh and fatigued muscle during sustained contraction in men, Eur. J. Appl. Physiol. 78 (6) (1998) 494–501.

[21] A.J. Fugelvand, K.M. Zackowski, K.A. Huey, R.M. Enoka, Impairment of neuromuscular propagation during human fatiguing contractions at submaximal forces, J. Physiol. 460 (1993) 549–572.
[22] D. Gamet, J. Duchene, C. Garapon-Bar, F. Goubel, Surface electromyogram power spectrum in human quadriceps muscle during incremental exercise, J. Appl. Phys. 74 (1993) 2704–2710.
[23] B. Gerdle, M.L. Wretling, K. Henriksson-Larsen, Do the fibre-type proportion and the angular velocity influence the mean power frequency of the electromyogram? Acta Physiol. Scand. 134 (3) (1988) 341–346.
[24] B. Gerdle, K. Henriksson-Larsen, R. Lorentzon, M.L. Wretling, Dependence of the mean power frequency of the electomyogram on muscle force and fiber type, Acta Physiol. Scand. 142 (1991) 457–465.
[25] B. Gerdle, M. Edström, M. Rahm, Fatigue in the shoulder muscles during static work at two different torque levels, Clin. Physiol. 13 (1993) 469–482.
[26] B. Gerdle, S. Karlsson, The mean frequency of the EMG of the knee extensors is torque dependant both in the unfatigued and the fatigued states, Clin. Physiol. 14 (1994) 419–432.
[27] M. Hagberg, Work load and fatigue in repetitive arm elevations, Ergonomics 24 (7) (1981) 543–555.
[28] G.M. Hägg, Interpretation of EMG spectral alterations and alteration indexes at sustained contraction, J. Appl. Phys. 73 (1992) 1211–1217.
[29] G.A. Hansson, U. Strömberg, B. Larsson, K. Ohlsson, L. Moritz, U. Moritz, Electromyographic fatigue in neck/shoulder muscles and endurance in women with repetitive work, Ergonomics 35 (11) (1992) 1341–1352.
[30] V. Hermans, A.J. Spaepen, Muscular activity of the shoulder and neck region during sustained and intermittent exercise, Clin. Physiol. 17 (1997) 95–104.
[31] P.A. Herzberg, Relationship between two variables, in: E. Robert (Ed.), Principles of Statistics, Krieger Publishing Company, Malabar, Florida, 1989, pp. 156–186.
[32] E. Johanson, M. James, S. Skinner, Forearm muscle activation during power grip and release, J. Hand. Surg. [Am] 23A (1998) 938–944.
[33] C.H. Kim, J.E. Fernandez, Psychophysical frequency for a drilling task, Int. J. Ind. Ergonomics 12 (1993) 209–218.
[34] M.G. Klein, J.E. Fernandez, The effects of posture, duration, and force on pinching frequency, Int. J. Ind. Ergonomics 20 (1997) 267–275.
[35] U. Kobryn, B. Hoffmann, G. Küchler, Effects of repeated fatiguing rhythmical hand work, Eur. J. Appl. Physiol. 47 (1981) 271–297.
[36] L.S. Krivickas, A. Taylor, R.M. Maniar, E. Mascha, S.S. Reisman, Is spectral analysis of the surface electromyographic signal a clinically useful tool for evaluation of skeletal muscle fatigue?, J. Clin. Neurophysiol. 15 (2) (1998) 138–145.
[37] C. Krogh-Lund, K. Jorgensen, Changes in conduction velocity, median frequency, and root mean square-amplitude of the electromyogram during 25% maximal voluntary contraction of the triceps brachii muscle, to limit of endurance, Eur. J. Appl. Physiol. 63 (1) (1991) 60–69.
[38] C. Krogh-Lund, K. Jorgensen, Modification of myo-electric power spectrum in fatigue from 15% maximal voluntary contraction of human elbow flexor muscles, to limit of endurance: reflection of conduction velocity variation and/or centrally mediated mechanisms? Eur. J. Appl. Physiol. 64 (4) (1992) 359–370.
[39] C. Krogh-Lund, K. Jorgensen, Myo-electric fatigue manifestations revisited: power spectrum, conduction velocity, and amplitude of human elbow flexor muscles during isolated and repetitive endurance contractions at 30% maximal voluntary contraction, Eur. J. Appl. Physiol. 66 (2) (1993) 161–173.
[40] E.J. Kupa, S.H. Roy, S.C. Kandarian, C.J. DeLuca, Effects of muscle fiber type and size on EMG median frequency and conduction velocity, J. Appl. Phys. 79 (1) (1995) 23–32.
[41] W.H.J.P. Linssen, D.F. Stegeman, E.M.G. Joosten, M.A. van horst, R.A. Binkhorst, S.L.H. Notermans, Variability and interrelationship of surface EMG parameters during local muscle fatigue, Muscle Nerve 16 (8) (1993) 849–856.
[42] W.N. Löscher, A.G. Cresswell, A. Thortensson, Electromyographic responses of the human triceps surae and force tremor during sustained sub-maximal isometric plantar flexion, Acta Physiol. Scand. 152 (1994) 73–82.
[43] M. Lowery, P. Nolan, M. O'Malley, Electromyogram median frequency, spectral compression and muscle fibre conduction velocity during sustained sub-maximal contraction of the brachioradialis muscle, J. Electromyogr. Kinesiol. 12 (2) (2002) 111–118.
[44] R. Marley, J. Fernandez, Psychophysical frequency and sustained exertion at varying wrist postures for a drilling task, Ergonomics 38 (2) (1995) 303–325.
[45] K. Masuda, T. Masuda, T. Sadoyama, M. Inaki, S. Katsuta, Changes in surface EMG parameters during static and dynamic fatiguing contractions, J. Electromyogr. Kinesiol. 9 (1) (1999) 39–46.
[46] S.E. Mathiassen, The influence of exercise/rest schedule on the physiological and psychophysical response to isometric shoulder–neck exercise, Eur. J. Appl. Physiol. 67 (1993) 528–539.
[47] R. Merletti, S. Roy, Myoelectric and mechanical manifestations of muscle fatigue in voluntary contractions, J. Orthop. Sports Phys. Ther. 24 (6) (1996) 342–353.
[48] R. Merletti, L.R. Lo Conte, Surface EMG signal processing during isometric contractions, J. Electromyogr. Kinesiol. 7 (1997) 241–250.
[49] S. Nagata, A.B. Arsenault, D. Gagnon, G. Smyth, P.A. Mathieu, EMG power spectrum as a measure of muscular fatigue at different levels of contraction, Med. Biol. Eng. Comput. 28 (4) (1990) 374–378.
[50] B.R. Neibuhr, R. Marion, S.M. Hasson, Electromyographic analysis of effort in grip strength assessment, Electromyogr. Clin. Neurophysiol. 33 (1993) 149–156.
[51] M. Nussbaum, L.L. Clarc, M.A. Lanza, K.M. Rice, Fatigue and endurance limits during intermittent overhead work, Am. Ind. Hyg. Assoc. J. 62 (2001) 446–456.
[52] D. Roman-Liu, T. Tokarski, J. Kamińska, Assessment of musculoskeletal load of trapezius and deltoid muscles during activity of hand, Int. J. Occup. Saf. Ergonomics 7 (2) (2001) 179–193.
[53] D. Roman-Liu, T. Tokarski, EMG arm and forearm muscle activities with regard to handgrip force in relation to upper limb location, Acta Bioeng. Biomech. 4 (2) (2002) 33–47.
[54] Rose, L., 1992. Development of a model to estimate physical load, pause need and production time in different working situations. Thesis for the Degree of Licentiate of Engineering Department of Injury Prevention, Goteborg.
[55] B. Silverstein, L.J. Fine, T.J. Armstrong, Hand wrist cumulative trauma disorders in industry, Brit. J. Ind. Med. 43 (1986) 779–784.
[56] S.H. Snook, D.R. Vaillancourt, V.M. Ciriello, B.S. Webster, Psychophysical studies of repetitive wrist flexion and extension, Ergonomics 38 (7) (1995) 1488–1507.
[57] G. Sundelin, M. Hagberg, Electromyographic signs of shoulder muscle fatigue in repetitive arm work paced by the methods–time measurement system, Scand J. Work Environ. Health 18 (1992) 262–268.

[58] W. West, A. Hicks, L. Clements, J. Dowling, The relationship between voluntary electromyogram, endurance time and intensity of effort in isometric handgrip exercise, Eur. J. Appl. Physiol. 71 (1995) 301–305.
[59] R.H. Westgaard, C.J. De Luca, Motor unit substitution in long-duration contractions of the human trapezius muscle, J. Neurophysiol. 82 (1) (1999) 501–504.
[60] V.L. Young, M.K. Seaton, C.A. Feely, C. Arfken, D.F. Baum, C.M. Baum, S. Logan, Detecting cumulative trauma in workers performing repetitive tasks, Am. J. Ind. Med. 27 (1995) 419–431.

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