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EVALUATION OF THE MEAN POWER FREQUENCY OF THE EMG SIGNAL POWER SPECTRUM AT ENDURANCE LEVELS DURING FATIGUING ISOMETRIC MUSCLE CONTRACTIONS

VREDNOTENJE NAJNIŽJE SREDNJE FREKVENCE MOČNOSTNEGA SPEKTRA EMG SIGNALA MED UTRUJAJOČIM IZOMETRIČNIM MIŠIČNIM NAPREZANJEM

Abstract

Surface electromyographic (EMG) signals of the triceps brachii muscle during three consecutive long-lasting isometric muscle contractions at a maximum effort level were recorded and then analyzed. The decrease of the mean frequency of an EMG power spectrum (MNF) as a function of time during sustained isometric contraction was efficiently modelled using the exponential model. Criteria to decide whether the sustained isometric contraction was sufficiently long for the reliable determination of the so called *endurance level* (MNF_p) were tested. It was shown that if the maximal voluntary muscle contraction is sustained for long enough so that the fitted exponential curve fulfils certain predefined derivative criteria as described in the text, the data could be used for reliable estimation of the MNF_p without the experimental MNF data actually reaching the plateau level. Using these criteria, it was found that there are no differences in the MNF_p values of the two consecutive series of maximal voluntary isometric muscle contractions. This might also indicate that MNF_p could be used as the normalization criteria for the extent of muscle fatigue in frequency domain.

Keywords: muscle fatigue, surface EMG, mean frequency, endurance level

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Povzetek

Posneli in analizirali smo površinske EMG signale mišice triceps brachii pri treh zaporednih dalj časa trajajočih največjih hotenih mišičnih naprezanjih. Zmanjševanje srednje frekvence močnostnega spektra (MNF) smo prikazali v odvisnosti od časa in vrednostim prilagodili eksponentno krivuljo. Preizkusili smo različne kriterije na podlagi katerih smo poskušali ugotoviti ali je mišično naprezanje trajalo dovolj dolgo, da so se vrednosti MNF ustalile pri nekih konstantnih najnižjih vrednostih - na tako imenovanem *platoju vzdržljivosti* (MNF_p). Ugotovili smo, da pri dovolj dolgo trajajočem mišičnem naprezanju, kjer krivulja, prilagojena MNF vrednostim, zadovoljuje določene kriterije opisane v tekstu, lahko zanesljivo ocenimo vrednost MNF_p. Ocene so do določene mere zanesljive tudi v primerih, ko se mišično naprezanje konča prej preden vrednosti MNF pridejo do platoja. Kriterij določanja MNF_p smo uporabili pri primerjavi dveh zaporednih izometričnih mišičnih naprezanj in ugotovili, da se vrednosti MNF_p ne razlikujejo. Ugotovitve kažejo, da je MNF_p možno uporabiti kot kriterij za normalizacijo vrednosti MNF med mišičnim utrujanjem.

Ključne besede: mišična utrujenost, površinski EMG, močnostni spekter, srednja frekvenca

INTRODUCTION

Muscle fatigue can be monitored using surface electromyography (sEMG). Electromyographic signs of fatigue are presented by the increase of the sEMG amplitude and by the shift of the mean (MNF) or/and median (MDF) frequency of the sEMG signal power spectrum density (PSD) estimate to lower frequencies. The amplitude of the sEMG during sustained muscle contraction increases due to the synchronisation of the recruited MU and the activation of new ones (Lowery, Nolan & O'Malley, 2002; Masuda et al., 1999; Merletti, Rainoldi & Farina, 2004); recruited motor units (MU) are becoming fatigued and new MU must be activated in order to sustain set levels of output (force, torque, power, speed).

However, for the evaluation of muscle fatigue, the EMG signal is usually analysed in the frequency domain (Gerdle, Eriksson & Hagberg, 1988; Gerdle et al., 1997; Komi & Tesch, 1979; Merletti & Roy, 1996). The power spectral density (PSD) of the EMG signal is estimated and the mean and/or median frequency are calculated and used as measures of central frequency of the PSD. MNF (and MDF) shifts to lower frequencies during the progression of muscle fatigue when a continuous isometric contraction of the muscle is performed. This decrease of MNF has been predominantly attributed to the decrease in muscle fibre conduction velocity even though there are also other possible causes (Masuda et al., 1999; Lowery, Nolan & O'Malley, 2002; Merletti & Roy, 1996). The results of several studies indicate that the observed shift of MNF to lower frequencies is mostly due to biochemical changes during fatiguing contraction in the type II muscle fibres (Gerdle et al., 1997)

MNF decreases in two phases: the initial steep linear decrease which has been labelled as *fatigue phase,* followed by a plateau with very small or no further decrease which has been labelled as an *endurance level* (Gerdle et al., 1988; 1992). The two-phase MNF decrease has been observed during repeated maximum isometric contractions (Štirn, 2006), isokinetic contractions (Lindstrom et al., 1997, Lundblad, Elert & Gerdle, 1998, Gerdle et al., 1988, 1992), dynamic contractions (Wretling et al., 1997), during treadmill uphill running (Ament, 1993) and cycling (Strojnik, Jereb & Colja, 1997).

The decrease of MNF as a function of time during long-lasting sustained isometric contraction can be efficiently modelled using the exponential model according to equation (Merletti, Rainoldi & Farina, 2004):

$$f_{MNF}(t) = f_{MNF_p} + a \cdot e^{-\frac{t}{\tau}} \text{ (Equation 1)}$$

In Equation 1 where f_{MNFp} is the so-called plateau level of MNF sometimes referred to as the *endurance level* [8]. It has been hypothesized that both the initial level of MNF at the beginning of the muscle contraction (corresponding to f_{MNFp+a} in equation 1) and especially the final plateau level reached after a long-time sustined isometric contraction (f_{MNFp}) may be relatively insensitive to the actual intensity of muscle contraction over a wide range of intensities. In contrast, the rate of MNF decrease (time constant τ) and therefore the time needed to reach the plateau depends greatly on the intensity of muscle contraction (Merletti, Rainoldi & Farina, 2004).

With the progression of the fatigue, the MNF is getting closer to its endurance level represented by f_{MNFp}. If the value of this parameter in the model described by Equation 1 can be estimated reliably and if it exhibits a high degree of repeatability over various levels of intensity of contraction, it could be used as the normalization criteria for the extent of muscle fatigue.

In order to reach the plateau level of MNF (the endurance level), the muscle in question has to be subjected to long sustained contractions. However, the endurance level may also be estimated by f_{MNFp} from the model in Equation 1 without the muscle actually reaching the endurance level, which is less exhaustive for the subject. The main question then is how long EMG has to be recorded during sustained isometric contraction in order to arrive at the accurate estimate of the endurance level based on the fitted model.

The goal of the present study was to reliably estimate the MNF_p at the endurance level by comparing the MNF_p estimate with the measured MNF_p and to discover whether the MNF_p estimates of the three consecutive trials differs or not. If MNF_p shows repeatable values, it might present a stable physiological parameter and could therefore be used as the normalization criteria for the extent of muscle fatigue.

METHOD

Participants

Eleven healthy male students (22.3 +/- 2.7 years of age) volunteered for this preliminary study. For two days prior to the experiment, they were requested to refrain from any intensive strength training. Prior to the experiment they were given a full explanation of the study and they all signed a form of consent to participate in the study.

Procedures

Testing protocol

The protocol consisted of a series of three consecutive isometric contractions of the triceps brachii muscle at the maximum voluntary effort level. The idea was to approach the endurance level as quickly as possible based on the assumption that the endurance level (the plateau level of MNF) does not depend on the actual intensity level used to reach it (Merletti, Rainoldi & Farina, 2004). The duration of each bout of muscle contraction was 75 seconds followed by 60 seconds of rest. A specific body position emphasizing the functional role of the triceps muscle was chosen for the study. The subject was positioned horizontally and face down on a cushioned table with the upper arm abducted by 90 degrees. The forearm was left to hang down off the table freely and a soft hand cuff connected to a fixed length of rope was attached to the wrist. The isometric contraction of the triceps muscle was performed with the forearm flexed by 30 degrees at the elbow.

Collection of the EMG data

EMG signals from m. triceps brachii (TB) were collected during an isometric contraction. The electrodes on the long head of TB muscle were placed in accordance with the SENIAM recommendations. The skin was shaved, rubbed with sandpaper and cleaned with alcohol so that inter electrode resistance did not exceed 5 kOhm. Bipolar Ag-AgCl skin electrodes (9 mm diameter, Hellige, Freiburg, Germany) with an inter-electrode distance of 20 mm, were used.

The ground electrode was positioned on the elbow. Data was recorded using Dasy Lab (Dasytec, Amherst, NH) with a sampling frequency of 1,000 Hz and afterwards analysed with MATLAB (The MathWorks, Inc., Natick MA).

Data analysis

The raw EMG signals were first filtered using a 5th order Butterworth band pass filter with lower and upper cut off frequencies set to 10 and 500 Hz respectively. The length of data window used for frequency analysis was set to 250 ms (250 samples).The data length of 250 ms was chosen as the optimum value based on the literature (Farina & Merletti, 2000) and our own experience. In one previous study (Štirn, 2006), we compared data window lengths between 125 to 1,000 ms on data recorded during prolonged isometric contraction and found no significant effect on frequency parameters under investigation. Furthermore, in our analysis of data recorded during dynamic exercise (swimming), the length of the active phase during each stroke was roughly between 125 and 250 ms. Therefore 250 ms was chosen as a compromise. Zero padding was not necessary but we used it simply for convenience to increase the frequency resolution (without zero padding the frequency resolution – delta f - would be very coarse: 4 Hz).

Power spectral density was estimated using the periodogram method on non-overlapping segments of 250 ms derived from the filtered EMG signal. Before the calculation of the Fourier transform, the segments were zero-padded to the total length of one second. Mean frequency of the PSD (MNF) was calculated for each data segment according to equation:

$$f_{MNF} = \frac{\int_0^{f_s/2} f \cdot P(f) df}{\int_0^{f_s/2} P(f) df} \quad \text{(Equation 2)}$$

Where *P(f)* represents the PSD estimate and *fs* is the sampling frequency. By default, the MNF values belonging to the initial 5 seconds of the contraction were discarded to avoid the part of the signal where the maximum muscle force was being established. The remaining MNF values were plotted as a function of time for visualization of the results. A model according to Equation 1 was fitted to the whole MNF sequence thus obtained and the value of parameter f_{MNFp} was used as the estimate of the endurance level and was labelled MNF_{p0}.

Ten sets of MNF data, where the plateau level of MNF was clearly reached, were selected for further analysis. The model in Equation 1 was then fitted to three progressively shortened versions of the original sequence of MNF values and three new values of f_{MNFp} were thus obtained. The cut off points for truncated MNF sequences were arbitrary set based on the value of derivative of the fitted curve from the original non-truncated MNF sequence; these values were 0.03, 0.05 and 0.1 Hz/s. The estimates of endurance level obtained by fitting the exponential model to the truncated MNF sequences were labelled $MNF_{p0.03}$, $MNF_{p0.05}$ and $MNF_{p0.1}$. The error in the estimation of endurance level based on truncated MNF sequence was therefore defined as (for example):

$$err_{p0.05}(\%) = \frac{MNF_{p0.05} - MNF_{p0}}{MNF_{p0}} \cdot 100 \quad \text{(Equation 3)}$$

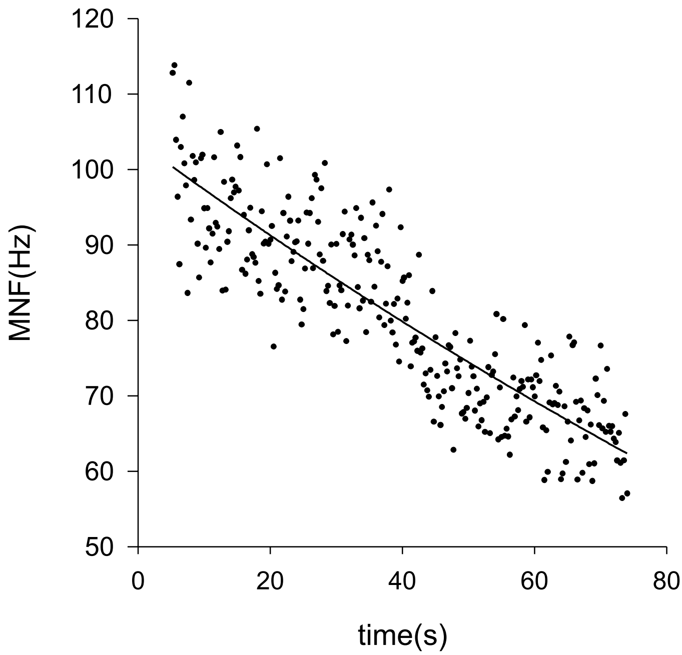
Finally, MNF_p values, obtained in three consecutive isometric contractions and with respect to the different criterion of selection of the analyzed data, were tested for the repeatability.

Statistical methods: Differences between endurance level estimates obtained by different methods and repeatability of the results were evaluated using the paired *t*-test. The correlations were evaluated by Pearson's correlation coefficient.

RESULTS

MNF values plotted as a function of time and a model fitted according to Equation 1 to the whole MNF sequence are presented in Figure 1 and 2a. The example where 75 seconds of sustained isometric contraction of the m. triceps brachii at maximum voluntary effort level was not enough to reach stable plateau level (MNF_{p0}) is presented in Figure1.

Figure 1: MNF of the 75-second isometric contraction of m. triceps brachii. Note that the plateau was not achieved.



In Figure 2a, an example is shown where the 75 seconds of sustained isometric contraction at maximum voluntary effort level was enough to reach a relatively stable plateau level for the mean frequency of the PSD. Examples of the original and truncated MNF estimate sequences along with the corresponding fitted curves are shown. The value of the plateau, the so-called endurance level MNF_{p0} was estimated from the fitted curve of the original signal (Figure 2a) and was considered to be the reference (true) endurance level for this subject. Fitting the same exponential model to truncated MNF sequences (according to the derivative criteria described in the text) in Figures 2b to 2d resulted in different curves and thus in different estimates of the endurance level. The comparison of the fitted curves is shown in Figure 3.

Figure 2: MNF of the 75-second isometric contraction of m. triceps brachii: original signal (a), note that the plateau was achieved and truncated data at dy(t)/dt ≤ 0.03 (b), ≤ 0.05 (c) and ≤ 0.1 (d)

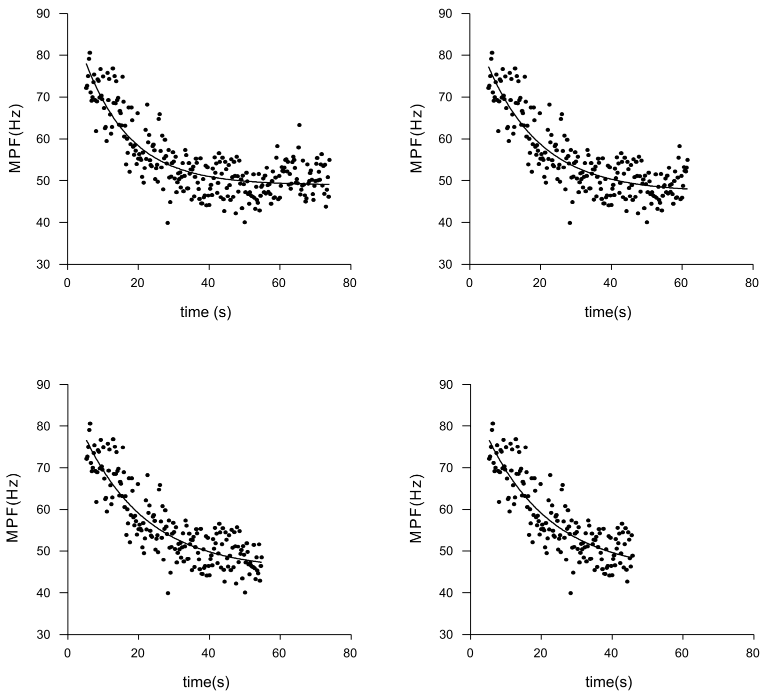


Figure 3: Comparison of the fitted curves of the original data (the longest) and the truncated data.

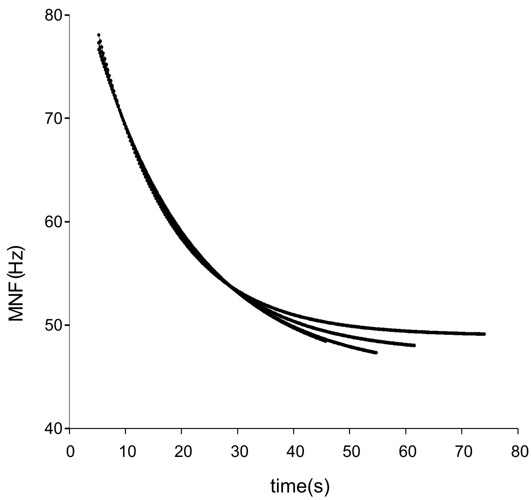


Table 1 contains the reference values MNF_{p0} and the error in the estimate of endurance level based on progressively truncated MNF sequences for 10 subjects. Note that the estimate of the endurance level deviates from the true value and this deviation becomes greater with further reduction of the experimental data. MNF_p values of the truncated data are lower in comparison to the original data (MNF_{p0}) in almost all cases.

Table 1: Differences in MNF_p with respect to the original signal. S1-S10 selected curves. MNF_{p0} – original fitted curve, MNF_{003}- cut off data at dy(t)/dt ≤ 0.03, err_{003}-error with respect to MNF_p, MNF_{005} -cut off data at dy(t)/dt ≤ 0.05, err_{005}-error with respect to MNF_p MNF_{01}-cut off data at dy(t)/dt ≤ 0.1, err_{01}-error with respect to MNF_p.

	MNF_{p0} (Hz)	MNF_{003} (Hz)	$err_{0.03}$ %	MNF_{005} (Hz)	$err_{0.05}$ %	MNF_{01} (Hz)	$Err_{0.1}$ %
S1	75.3	74.0	-1.61	73.8	-1.91	68.9	-8.49
S2	48.9	46.1	-5.56	39.7	-18.83	33.5	-31.36
S3	49.8	50.3	0.97	49.4	-0.83	33.7	-32.33
S4	41.7	41.7	0.11	42.6	2.31	44.6	6.99
S5	53.0	53.1	0.21	51.5	-2.95	50.0	-5.78
S6	65.5	64.4	-1.79	64.0	-2.28	64.7	-1.35
S7	60.7	60.4	-0.51	58.0	-4.38	52.6	-13.38
S8	49.0	47.3	-3.50	45.4	-7.38	44.9	-8.29
S9	50.5	47.4	-6.18	42.7	-15.5	45.1	-10.74
S10	53.3	50.5	-5.32	50.0	-6.17	51.0	-4.39
Mean	54.8	53.5	2.58	51.7	6.25	48.9	12.31
SD	9.8	9.9	2.36	10.7	6.14	11.5	10.81
P			0.016		0.014		0.013

Table 2 contains the results of correlation analysis of the endurance level estimates. All correlations showed high statistical significance ($p<0.01$). The correlation to an original MNF_p estimate is the highest (0.991) for the less truncated data (dy(t)/dt ≤ 0.03)

Table 2: Correlation matrix between the MNF_p values of the cut off data. MNF_p – original fitted curve, MNF_{01}-cut off data at dy(t)/dt ≤ 0.1, MNF_{005}-truncated data at dy(t)/dt ≤ 0.05, MNF_{003}-cut off data at dy(t)/dt ≤ 0.03

	MNF_p	MNF_{01}	MNF_{005}
MNF_{01}	.852(**)	1	
MNF_{005}	.956(**)	.880(**)	1
MNF_{003}	.991(**)	.846(**)	.980(**)

Table 3 shows the comparison of MNF_{p0} values for the second and third 75-second muscle contractions. Note that the first series of contractions was not considered due to the fact that most subjects did not reach the plateau level of MNF during the first contraction. This prevented a reliable estimation of the endurance level (Figure1) Significant differences were found between the MNF_p values obtained during the 2^{nd} and 3^{rd} series of contractions if contractions (without any restrictions) of all 11 subjects were analyzed. After subjects (contractions) for further comparison of the MNF_p were selected according to the derivative criteria described above (dy(t)/dt < 0.1, 0.05, 0.03 Hz/s), the number of appropriate contractions (n) considered in the analyses was reduced. Significant differences between the MNF_p were no longer found, showing that the MNF_p values of the two consecutive series of contractions were not different. Note that the difference of the average absolute values of MNF_p of the two series in Hz is progressively smaller as the derivative criterion is more severe.

Table 3 The comparison of MNF_p (Hz) of the 2nd (SE2) and 3rd (SE3) consecutive series of isometric contractions between the original data and truncated data. $dy(t)/dt \leq 0.1, 0.05, 0.03$, av - average, DS – standard deviation, n – number of analyzed contractions, p - statistical significance

	av	SD	n	p
SE2	57.3	9.5	11	0.044
SE3	62.9	11.5		
$SE2_{01}$	59.3	9.4	9	0.077
$SE3_{01}$	62.1	12.3		
$SE2_{005}$	55.3	6	7	0.314
$SE3_{005}$	56.8	7.7		
$SE2_{003}$	56.5	5.6	6	0.422
$SE3_{003}$	57.9	7.8		

DISCUSSION

In the present study, the MNF_p at the endurance (plateau) level during three consecutive long-lasting isometric muscle contractions were evaluated and compared. We have shown that if the muscle contraction is sustained for long enough so that the fitted exponential curve fulfils certain predefined derivative criteria as described in the text, the reliable estimation of the MNF_p with the low error with respect to the original (true) MNF_p can be achieved. Doing so, the differences in MNF_p after 2nd and 3rd consecutive 75-second isometric contractions at full level effort were not observed.

During maximal voluntary isometric contraction until exhaustion, the MNF of the EMG signal PSD estimate decreases due to muscle fatigue. According to the Lindstrom and Magnusson model (1977) the MNF decreases because muscular fibre conduction velocity (MFCV) is reduced. Action potential is slowed due to the metabolic changes in the muscle; lactate accumulates as the result of intensive muscle work and pH is reduced, which leads to the reduction of the propagation of an action potential. Studies have shown that the MNF decrease is actually greater than the MFCV, indicating that there are also some other possible reasons for the MNF decrease (Masuda et al., 1999; Lowery, Nolan & O'Malley, 2002; Merletti & Roy, 1996).

MNF decreased in two phases. According to Gerdle, Eriksson, & Hagberg (1988), the linear decrease in the beginning of the muscle contraction has been labelled the *fatigue phase.* As the contraction is being sustained for some time, the MNF values approached a level that has been labelled the *endurance level.* Since the *endurance* is a very broad term, *plateau* seems to be a better term describing the MNF at this stabilised level.

It can be seen in Figure 2 that there was a relatively large variability in data which is commonly observed in these types of measurements. The variability can be reduced by using longer data windows but it was shown that in the case of non-stationary signals (such as in our study) lengthening of the data window results in poorer model parameter estimates (Farina & Merletti, 2000) which is not acceptable. In contrast, it was shown that data windows between 250 and 4000 ms result in virtually indistinguishable parameter values in the case of stationary signals.

The plateau level is not reached if muscle contraction is not sustained long enough (Štirn, 2006). Such contractions should be prolonged or repeated after a short fragmentary rest in order to reach the endurance level as a result of the exhaustion of the muscle. Our results show that plateau is rarely reached during the first 75-second contraction of triceps brachii. MNF_p of only four of eleven subjects could be reliably estimated in accordance to the derivative criterion described (data not shown).

In the 2nd and 3rd series of contractions, MNF has approached the plateau. When the fitted curves included in the analysis were selected in accordance with the most strict criteria (0.05 and 0.03) the comparison between the MNF_p showed no differences.

Assuming that the exercise used is of the same type (e.g. isometric contraction), we suggest that the plateau level is at least to a certain degree an absolute quantity independent of the intensity of the exercise used to reach it and of the initial state of the muscle under observation (e.g. fully recovered versus partially fatigued muscle). Comparisons of the plateau values reached in the 2nd and 3rd set of repeated isometric contraction in our study as well as the results of some other studies (Merletti & Roy, 1996) support this suggestion.

These results indicate that plateau might present a stable measure of the lower limit of the MNF_p decrease during the sustained isometric contraction. If so, this parameter could be used as the normalization criterion for the muscular fatigue. The muscle which approaches the plateau MNF value more shows more fatigue. The question is whether this decrease refers only to the selective fatigue of fast twitch muscle fibres. Specifically, the MNF decrease has been found greater in the muscles composed of a greater portion of type II muscle fibres. Nevertheless, the same muscles or subjects can be compared and analysis of different fatigue protocols within such samples can be made.

By using the described method of evaluating the MNF_p, this phenomenon can be further studied. Can a stable and reliable MNF_p estimation be made during fatiguing dynamic contractions or even functional movement? Are the MNFp estimates detected during isometric contractions equivalent to the estimates detected during dynamic contractions? Further, in our study electrodes were fixed at the same spot for the whole fatiguing protocol. Would the same results be obtained if the electrodes have been removed and latter replaced due to the day-to-day analyses? The detected sEMG depends on the positioning of the electrodes on the muscle. Shifting the electrodes while repositioning them could cause that different populations of MU are measured and consequently different results (with respect to the initial ones) would be obtained (Dimitrova & Dimitrov, 2003) These questions still need to be answered in further studies.

CONCLUSIONS

Prescribing the time of the duration of the long-lasting maximal voluntary muscle contraction in advance does not assure that the endurance level MNF will be reached. However, if the muscle contraction is sustained for long enough so that the fitted exponential curve fulfils certain predefined derivative criteria as described in the text, the reliable estimation of the MNF_p with a low error rate with respect to the original (true) MNF_p can be achieved. Such an estimate, when performed on-line, may significantly reduce time needed to achieve fatiguing condition and be more convenient and user-friendly to the subject. With the estimates, differences in MNF_p after 2nd and 3rd consecutive 75-second isometric contractions were no longer observed. Therefore, we believe that MNF_p could be used as the normalization criteria for the extent of muscle fatigue in the frequency domain. As the muscle is exposed to a greater fatigue, it reaches closer to its plateau (endurance level) value.

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