Muscle Fatigue during Dynamic Contractions Assessed by New Spectral Indices

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[1]*Centre of Biomedical Engineering, Bulgarian Academy of Sciences, Sofia, BULGARIA;* [2]*Sport and Exercise Research Centre, Academy of Sport, Physical Activity and Well-being, and* [3]*Institute of Primary Care and Public Health, Faculty of Health and Social Care, London South Bank University, London, UNITED KINGDOM*

ABSTRACT

DIMITROV, G. V., T. I. ARABADZHIEV, K. N. MILEVA, J. L. BOWTELL, N. CRICHTON, and N. A. DIMITROVA. Muscle Fatigue during Dynamic Contractions Assessed by New Spectral Indices. *Med. Sci. Sports Exerc*., Vol. 38, No. 11, pp. 1971–1979, 2006. **Purpose:** The aim of the present study was to test the applicability and sensitivity of new electromyography (EMG) spectral indices in assessing peripheral muscle fatigue during dynamic knee-extension exercise. **Methods:** Seven subjects completed 10 sets of 15 repetitions of right knee–extension exercise lifting 50% of their one-repetition maximum. Torque (T), knee-joint angle, and the interference EMG of rectus femoris muscle were recorded simultaneously. Maximal voluntary isometric contraction (MVC) was tested before and after exercise. Median spectral frequency (F_{med}) and new spectral indices of muscle fatigue (FI_{nsmk}) were calculated for each repetition. **Results:** The rate and range of FI_{nsmk}- and F_{med}-relative changes against the first repetition of the corresponding set increased gradually across successive repetitions within the set, reflecting accumulation of peripheral muscle fatigue. The maximal change of FI_{nsmk} observed in the present experiment was approximately eightfold, whereas that of F_{med} was only 32%. Significant between-subject variability in the range of FI_{nsmk} changes ($P < 0.0001$) was found, so a hierarchical cluster analysis of muscle fatigue indices was conducted. Three distinct subgroups of subjects were identified: high ($N = 1$, FI_{nsmk} change > 400%), medium ($N = 4$, 200% < FI_{nsmk} change < 400%), and low ($N = 2$, FI_{nsmk} change < 200%) muscle fatigability. The changes in muscle performance during (last vs first repetition peak T, $P = 0.03$) and after (post- vs preexercise MVC, $P = 0.012$) exercise were significantly different between clusters (one-way ANOVA). The rate of fatigue development was also significantly different between clusters (linear regression analysis of F_{med} and FI_{nsmk} changes). **Conclusions:** The new spectral indices are a valid and reliable tool for assessment of muscle fatigability irrespective of EMG signal variability caused by dynamic muscle contractions, and these indices are more sensitive than those traditionally used. **Key Words:** HUMAN, EMG, MEDIAN FREQUENCY, EXERCISE, MUSCLE STRENGTH AND ENDURANCE

Methods that allow reliable assessment of muscle strength and endurance are of great importance for studying human muscle function and motor control as well as for sports and clinical practice. Maximal voluntary contraction (MVC) and one-repetition maximum (1RM, weight successfully lifted once) are traditionally used to test for isometric and dynamic strength, respectively. These methods alone do not allow for a precise evaluation of the performance of a particular muscle or muscle group, and therefore they are often combined with simultaneous recording of muscle electrical activity (EMG) to evaluate muscle activation level and changes during different types of exercise.

Surface electromyography is a noninvasive method for assessing neuromuscular function. EMG amplitude (mean or root mean square) and spectral parameters (mean and median frequency of EMG power spectrum) are traditionally used to evaluate the pattern of motor unit activity as well as skeletal muscle fatigue. During isometric exercise, in healthy subjects, muscle fatigue development is associated with an increase in the surface EMG amplitude and with a shift of the EMG power spectrum toward lower frequencies (19).

Ratios between EMG power content in high and low frequency ranges have been adopted as indices of peripheral muscle fatigue by some researchers (4,5,7,25,26,30,32,36). However, the selection of boundary frequency and/or high- and low-frequency bands is subjective because there are no

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Submitted for publication October 2005.
Accepted for publication May 2006.

0915-9131/06/3811-1971/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/01.mss.0000233794.31659.6d

established criteria for an objective selection. This has led to wide variation across the literature (40 Hz (23), 30 Hz (7), or 64 Hz (32); 130–238 vs 20–40 Hz (30), 150–350 vs 20–46.7 Hz (5)). The establishment of objective criteria for selection of border frequency or frequency bands is problematic because the spectral power–density distribution depends not only on the development of muscle fatigue but also on the muscle fiber-to-electrode distances, electrode type, electrode longitudinal position, muscle fiber length, and volume conductor properties (12,22,27,31). These factors will vary between subjects and experimental set-ups.

To avoid the subjective selection of border frequency or frequency bands, the rate of changes of mean frequency (F_{mean}, the ratio between the spectral moments of order 1 and order 0 (25)) and median frequency (F_{med}, which is less sensitive to noise (36)) have been proposed as indices of localized muscle fatigue. However, F_{mean} and F_{med} have relatively low sensitivity. This may contribute to the conflicting data in the literature regarding EMG frequency changes during fatiguing exercise. Chesler and Durfee (8) found that RMS and F_{med} were unreliable indicators for predicting and tracking fatigue during functional electrical stimulation of quadriceps muscle. Mizrahi et al. (29) also found an extremely low correlation between force and F_{med} changes. Reviewing the methods used for measurement of human muscle fatigue, Vøllestad (37) concluded that the validity of the amplitude and spectral shifts of the EMG signal in assessment of fatigue is questionable because there is no straightforward relationship between them.

To overcome the problem of the relatively low sensitivity of F_{med} and F_{mean}, new highly sensitive spectral indices (FI_{nsmk}) have been recently proposed for quantifying the spectral changes of muscle EMG during fatigue (2,14). These indices are based on EMG spectral characteristics in the frequency domain obtained by the conventional FFT algorithm and have been constructed as the ratio between the signal spectral moment of order (-1) and normalizing spectral moment of order k = 2, 3, 4, or 5. Spectral moments represent the area under the spectral curve after multiplication by the frequency raised to the power of k (called order k of the moment) as the weighting function. Therefore, the spectral moments allow extraction of characteristic features and pattern recognition from the power–spectral density function. The applicability of spectral moments and their changes over time for monitoring of muscular fatigue has been previously explored in a great detail (26). The spectral moment of order (-1) emphasizes the increase in low and ultralow frequencies in EMG spectrum (26) attributable to increased negative afterpotentials during muscular fatigue (2,13). The spectral moment of order 2 and higher emphasizes the effect of decreases in the high frequencies attributable to the increased duration of the intracellular action potentials and decreased action potential propagation velocity (2). Therefore, FI_{nsmk} provide low to high frequency-ratio indices, which, in contrast to previous spectral ratio indices, are not dependent on the subjective selection of a separation point between high- and low-frequency regions. Mathematical simulations have demonstrated that FI_{nsmk} adequately reflect the changes in muscle fiber–conduction velocity and in the shape of the intracellular action potential observed during peripheral muscle fatigue (2). Qualitatively comparable changes in both traditional and new indices were observed when applied for analysis of M-waves detected noninvasively from human *m. biceps brachii* during repetitive, slightly above-threshold electrical stimulation (14), as well as during isometric voluntary contractions at 50% MVC (11). However, the sensitivity of the new indices was found to be up to 150 times greater than that of F_{mean} and F_{med} during electrically evoked contractions, and 50 times greater during voluntary isometric contractions.

The surface EMG signal can be assumed to be a wide-sense stationary stochastic process with Gaussian distribution during relatively low-level (20–30% MVC) and short-duration (up to 20–40 s) isometric contractions (28). However, higher-intensity contractions (50–80% MVC) cause more rapid muscle fatigue, and thus the EMG signal only behaves as a stationary process for very short periods of 0.5–1 s (28). In dynamic conditions, the surface myoelectric signal generated by the muscle may no longer be considered a steady-state process (4,19,28). The static-contraction paradigm should not be applied during dynamic contractions, for a number of reasons largely related to movement-induced confounding factors. First, the surface EMG signals are nonstationary because of the variations in joint angle. Fiber length (6,12,15,22,27) and electrode longitudinal positions strongly affect the EMG signal spectral characteristics (13,17,21,26,31). In addition, the spectral changes attributable to fatigue occur on a much slower time scale. Hence, EMG data that are collected during dynamic contractions will be nonstationary, which may affect the validity of using the fast Fourier transformation (FFT) (19,28). This may contribute to the questionable validity of using F_{med} and F_{mean} shifts in the assessment of fatigue (37). The aims of the present study were to test the applicability of the new spectral indices for assessing peripheral muscle fatigue during dynamic contractions and to compare their sensitivity to the level and the rate of muscle fatigue development versus the sensitivity of F_{med} and F_{mean}.

METHODS

Subjects

Seven healthy adults (N = 7: six male, one female; age, 28.7 ± 7 yr; height, 180 ± 10 cm; body mass, 78 ± 12 kg (mean ± SD)) with no previous motor disorders or current injuries, and taking no medication, gave their written informed consent to participate in this study. The study was approved by the university local ethics committee and was performed according to the Declaration of Helsinki. The subjects in this study were recreational athletes training three to four times per week: one subject emphasized strength training, two predominantly undertook endurance training, and the remainder undertook a mix of both endurance and resistance training.

Experimental Procedures

Before starting the trials, the subjects were familiarized with the protocol and equipment used. After 5-min standardized warm-up (cycling at 90 W, cadence-independent mode on a standard LODE ergometer (Groningen, The Netherlands)) and stretching, the subjects were seated on the knee-extension machine (TechnoGym UK Ltd). The backrest and the bar levels were adjusted for each subject and kept constant during the trial. A lapbelt restraint was used to exclude contribution from the hip musculature during the knee-extension exercise. The EMG electrode and the electrogoniometer were then attached to the right leg. Unilateral (right leg only) isometric MVC and dynamic knee-extension strength (1RM) of the subjects were tested. First, subjects performed three knee-extension MVC at a 90° knee angle, with their right leg only, separated by 2-min rest periods. Subjects were asked to push maximally for 3 s against a 120-kg weight, which could not be lifted, ensuring muscle contraction at constant fiber length (isometric). After 2 min of rest, the subject performed a standard ramp test to identify the 1RM (20). Each weight lift was assessed by the investigator and considered successful if performed with proper technique, within the metronome-guided time interval (2.5 s) and going through the full range of knee motion of the exercise (0.7 rad). The maximum weight lifted was identified as the 1RM. In all tests, verbal encouragement was given to each subject. After 2 min of rest, subjects completed 10 sets of 15 repetitions (with 2 min of rest between sets) of right knee–extension exercise lifting 50% of their 1RM. Subjects were instructed to extend their knee as far as possible during the concentric phase of the knee extension (range of motion between 90° flexion and 20° extension) and to control the descent of the leg during the eccentric phase (range of motion between 20° extension and 90° flexion). Subjects were also instructed to perform each phase at a constant rate (40 bpm on the metronome) so that each repetition would last approximately 2.5 s. MVC was tested again immediately after the last set of the exercise.

Data Collection

Force, knee-joint flexion/extension angle, and EMG activity of the right rectus femoris (RF) muscle were recorded throughout the exercise protocol (Fig. 1). EMG recordings were taken using standard active bipolar surface electrode (1-cm diameter, 2-cm interelectrode distance; B & L Engineering, Tustin, CA) secured onto the skin with antiallergic tape after exfoliation and cleaning of the skin with abrasive gel and alcohol. The electrode was positioned over the right RF muscle, midway between the motor end-plate zone and the quadriceps tendon to patella, and orientated longitudinally along the muscle fibers. The knee-extension force was measured continuously during the experimental protocol using an inline force transducer (MCL; RDP Ltd. Wolverhampton, United Kingdom). The transducer was calibrated in the range from 0 to 100 kg using standard weights, and the force was recalculated and

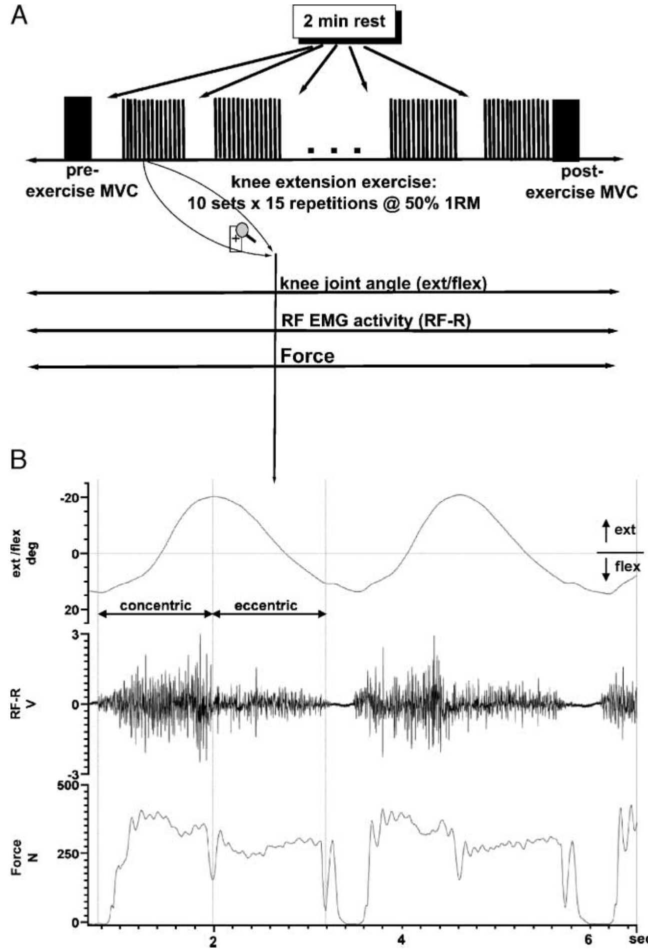

FIGURE 1—(A) Experimental protocol. (B) Expanded view of simultaneously recorded knee-joint angle, rectus femoris (RF) EMG muscle activity, and force during two consecutive repetitions of knee-extension exercise performed by a representative subject at a level of 50% of one-repetition maximum. Note considerably lower EMG amplitudes during eccentric than during concentric phases.

displayed online in newtons. Knee angular displacement profile was recorded via a preamplified electrogoniometer (Biometrics system, Gwent, United Kingdom), which was attached lateral to the patella of the right leg. The knee angle was set to zero, with a 110° angle between the femur and the fibula, which approximates neutral sitting position. All data were recorded and digitized simultaneously via an analog-to-digital converter (CED 1401 power, Cambridge, United Kingdom) using Spike2 data-acquisition software (CED, Cambridge, United Kingdom). Sampling frequency for EMG signal was 2 kHz and 200 Hz for knee-joint angle and torque. The EMG signal was preamplified (×330, B & L Engineering, Tustin, CA) and further amplified (×3000, 1902 amplifier, CED, Cambridge, United Kingdom) before being passed through the A/D converter.

Data Analysis

MVC determination. Offline data analysis was performed using a custom-written script developed in Spike2 (CED, Cambridge, United Kingdom). The force record was recalculated in torque measures (N·m) by multiplying the force (N) by the force moment arm (0.43 ± 0.02 m; range 0.4–0.44 m) for each subject. The force moment arm was measured as the distance between the tip of patella and the axis of the bar, positioned just above the ankle for each subject in the seated position. The MVC was calculated as the average torque over a 1-s period during the torque-plateau level of each MVC attempt (pre- and postexercise). The 1-s period used for MVC determination did not include the first segment of the contraction (lasting around 0.5 s), so that the period of developing force would be excluded. The highest of three MVC completed before the exercise was accepted as initial MVC value. The normalized percentage change between pre- and postexercise MVC was calculated as:

$$\Delta \mathrm{MVC} = \frac{\mathrm{MVC_{post}} - \mathrm{MVC_{pre}}}{\mathrm{MVC_{pre}}} \times 100, \% \qquad [1]$$

and was used to evaluate the change in muscle isometric strength attributable to the fatiguing exercise protocol.

Performance during exercise sets. Peak contraction torque (T) was calculated for each exercise repetition as a functional measure of muscle strength during the dynamic contractions. The normalized percentage change of the peak torque between the first and the last (150th) repetition during the exercise protocol (ΔT, %) was used to evaluate the level of fatigue-induced change in muscle dynamic strength and was calculated as:

$$\Delta \mathrm{T} = \frac{\mathrm{T_{last}} - \mathrm{T_{first}}}{\mathrm{T_{first}}} \times 100, \% \qquad [2]$$

Calculation of the spectral indices. Fifteen segments from the raw EMG signal for each set were extracted for subsequent processing. Each segment corresponded to a knee-extension repetition. The duration of the extracted segments (2 or 1 s) was dependent on the actual duration of each repetition; although guided by the metronome rhythm, the duration was not absolutely equal throughout the trial. The power–density spectrum was obtained using the conventional FFT algorithm for each extracted segment. The spectral resolutions obtained after corresponding zero padding in the extracted segments were about 0.3 and 0.6 Hz for segment durations of 2 and 1 s, respectively.

Spectral moments were used to extract the characteristic features of the EMG power–spectral density function and were calculated using the standard formula:

$$\mathrm{M_k} = \int_{\mathrm{f\,min}}^{\mathrm{f\,max}} \mathrm{f^k \cdot PS(f) \cdot df} \qquad [3]$$

where M_k is a spectral moment of order k, PS(f) denotes the EMG power-frequency spectrum as a function of frequency f, and f_{min} and f_{max} delineate the bandwidth of the signal (25,26). F_{mean} was calculated as the ratio between the spectral moments of order 1 and 0 (6,26), and F_{med} was calculated from:

$$\int_{\mathrm{f_1}}^{\mathrm{F_{med}}} \mathrm{PS(f) \cdot df} = \int_{\mathrm{F_{med}}}^{\mathrm{f_2}} \mathrm{PS(f) \cdot df} \qquad [4]$$

where PS(f) was the spectral power for the current frequency f, and f_1 = 5 Hz and f_2 = 500 Hz were the high- and low-pass frequencies of the amplifier filter, respectively. The FI_{nsmk} indices were calculated as the ratio between the spectral moments of order (−1) and order, k:

$$\mathrm{FI_{nsmk}} = \frac{\int_{\mathrm{f_1}}^{\mathrm{f_2}} \mathrm{f^{-1} \cdot PS(f) \cdot df}}{\int_{\mathrm{f_1}}^{\mathrm{f_2}} \mathrm{f^{k} \cdot PS(f) \cdot df}} \qquad [5]$$

where k was 2, 3, 4, or 5. The relative changes in values of each spectral fatigue index (F_{med}, F_{mean}, FI_{nsm2}, FI_{nsm3}, FI_{nsm4}, FI_{nsm5}) for different repetitions were calculated against the first repetition of the corresponding set: for instance, $FI^n{}_{nsmk}/FI^1{}_{nsmk} \times 100$, % (n = 1, 2, …, 15; repetition number in the set).

Preliminary investigations were conducted to test the sensitivity of the FI_{nsmk} indices to 1) the time position of the extracted segments; 2) the noise induced by the main power supply by comparing the indices calculated from the unfiltered EMG signals with those calculated from EMG filtered by a 50-Hz (48–52 Hz) notch filter; and 3) the order k (= 2, 3, 4, or 5) of the normalizing spectral moment. Three possibilities for selecting the actual position of the extracted segments in the time were considered. In the first, segments were allocated only during the concentric part of the contractions. In the second, the middle of each segment was selected to coincide with the maximal knee-extension angle during the repetition. Thus, the first half of each segment corresponded to concentric phase of the knee extension, whereas the latter half corresponded to the eccentric phase. As a result, changes in knee angle, lengths of the fibers, and electrode longitudinal position during the concentric and eccentric phases should be opposite in sign and almost the same in amplitude. In the third, segments were extracted only from the eccentric phase of knee-extension repetition.

Statistical Analysis

To determine the test–retest reliability of EMG spectral parameters as measures of muscle fatigability, the intraclass correlation coefficients (ICC) were calculated for F_{med} and FI_{nsmk} values from the first repetition of each set using one-way random-effects single-measure (1,1) model (33). Two-way repeated-measures ANOVA (set (10 levels) and repetiton (15 levels)) was used to test for main and interaction effects of exercise design on muscle fatigue indices (F_{med} and FI_{nsmk}) and between-subject variability. For each tested factor, the effect size statistic η^2 was calculated to evaluate the proportion of variance in the data that was attributable to the exercise design. ANOVA established significant between-subject variation in the fatigue-induced changes in FI_{nsmk} and F_{med} values ($P < 0.0001$). Therefore, a hierarchical cluster analysis of muscle fatigue indices was conducted to explore the feasibility of classifying subjects into groups based on their muscle fatigability. Hierarchical cluster analysis is widely used to group together homogeneous cases/subjects based on selected characteristics. In this case, the cluster analysis was applied separately to the F_{med}- and FI_{nsmk}-relative change data, which were calculated as muscle fatigue indices for each subject. The algorithm initially allocates each case/subject into a separate cluster and then sequentially combines clusters on the basis of their similarity until all cases are in a single cluster. Both single-linkage (nearest neighbor) and average-linkage (between groups) methods using Euclidian distance as the interval measure of dissimilarity were used, and both methods produced the same cluster results (16). Cluster dendrograms resulting from the application of the clustering procedure were drawn to optimize classification of cases/subjects into clusters based on the calculated similarity and distance matrices for each variable. A physiologically appropriate value for the cutoff level of similarity has not been established. Therefore, clusters whose members were similar to each other but distinct from the members of other clusters were differentiated by setting the threshold to 75%, as suggested in muscle functional MRI studies for subtle distinction in time series (10). The changes in EMG spectral indices within the sets (from repetition 1 to repetition 15) varied between subjects not only in magnitude of change but also in the rate of change across repetitions. Therefore, a linear regression analysis based on the least square errors method was performed on muscle fatigue indices (relative changes of F_{med} and FI_{nsmk}) for each cluster identified using the FI_{nsmk} data. The slopes of the regression lines were used to assess the differences in rates of fatigue development between clusters.

To test the physiological significance of the identified clusters, the data for MVC and T during the knee-extension repetitions were compared between clusters. The values for preexercise MVC (initial muscle isometric strength), ΔMVC (fatigue-induced percentage changes in isometric muscle strength), and ΔT (percentage changes in dynamic muscle strength) were averaged for each cluster established using the FI_{nsmk} data. These values were then analyzed for between-cluster differences using one-way ANOVA. The overall acceptable significance level of differences for all statistical tests was set at $P < 0.05$. The statistical analyses were performed in SPSS 10 (SPSS Inc., Chicago, IL) and Minitab Release 13.1 (Minitab Inc., State College, PA) package software.

RESULTS

The rate and range of changes in the fatigue index were similar irrespective of the position of EMG segment, but

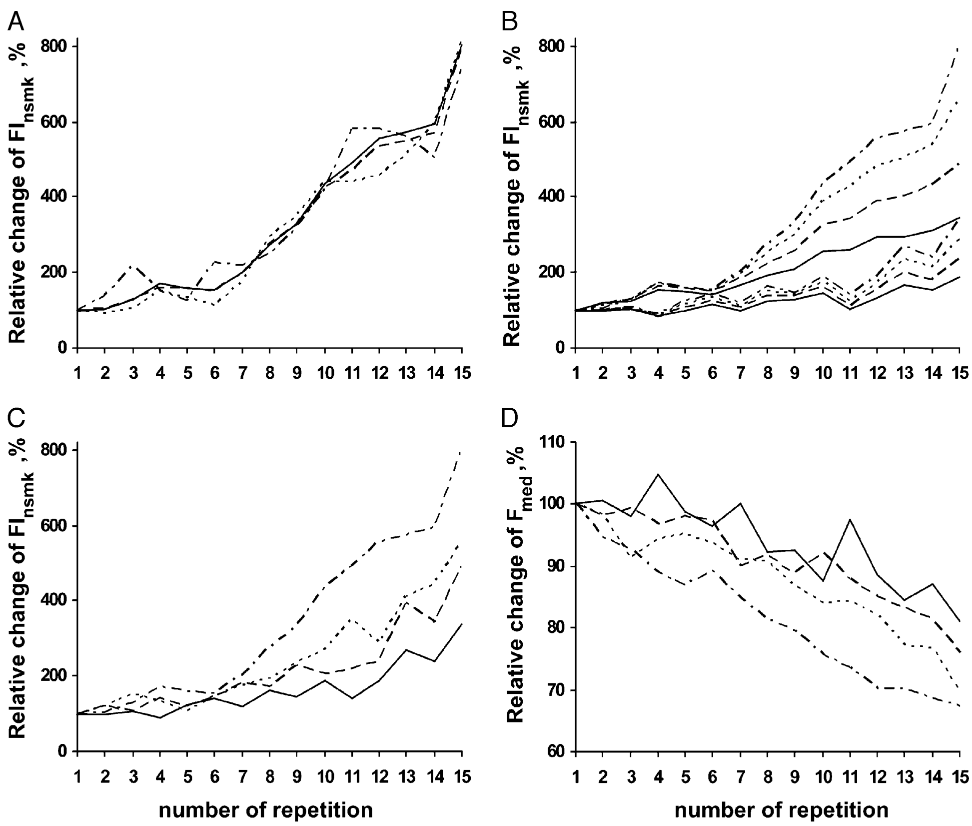

FIGURE 2—Theoretical considerations for calculation of muscle fatigability indices illustrated on the data collected from the same subject represented in Figure 1. Data for the spectral indices are represented as relative change against the corresponding index value for the first repetition of each set. (A) Changes in the spectral index (FI_{nsmk}), with order k = 5 of the normalizing spectral moment, when the analyzed segment of the signal was extracted from the concentric repetition phase only (*dotted line*), eccentric phase only (*dashed dotted line*), or when the first half of the segment was during concentric and the second half was during the eccentric phase under unfiltered (*solid line*) and filtered by 50-Hz notch filter (*dashed line*) EMG signals. (B) Effect of the order of the normalizing spectral moment, k, on the spectral index FI_{nsmk} changes. *Solid lines,* k = 2; *dashed lines,* k = 3; *dotted lines,* k = 4; *dashed dotted line,* k = 5. The upper four lines are calculated for the fourth set, and the lower four lines are for the first set of completed knee-extension repetitions. (C, D) Relative changes in the spectral index (FI_{nsmk}, k = 5) and in the median spectral frequency F_{med} during the first (*solid lines*), second (*dashed lines*) third (*dotted lines*), and fourth (*dashed dotted lines*) set of the exercise protocol.

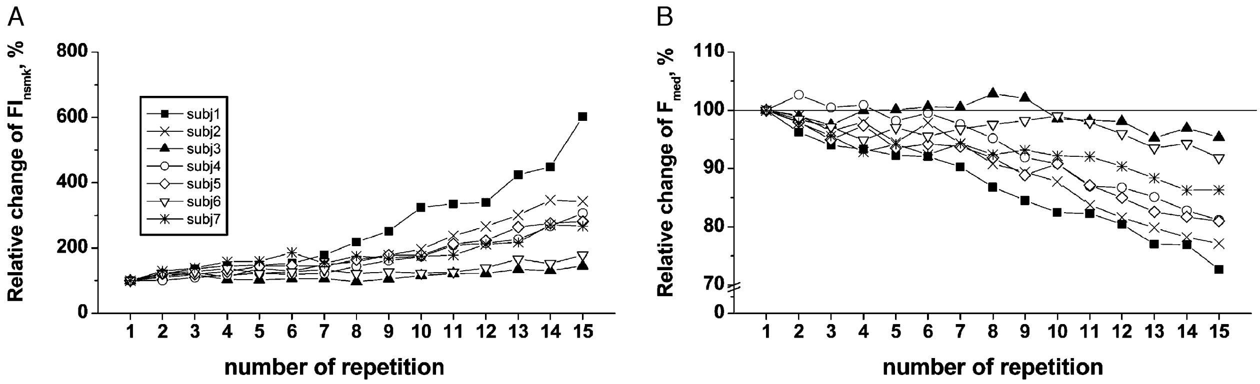

FIGURE 3—Relative changes of the calculated (A) spectral indices FI_{nsmk} with normalizing spectral moment of the fifth order and (B) median frequencies F_{med} averaged for all sets across repetitions for each subject (N = 7). Data are normalized against the corresponding value for the first repetition of each set.

index variability was greater when the segments were extracted during the concentric (Fig. 2A, dotted line) and especially during the eccentric phase only (Fig. 2A, dashed dotted line). Subsequently, data analysis was performed for signal segments whose first half corresponded to concentric phase and whose second half corresponded to the eccentric phase (Fig. 2A, solid line) of the contraction. The range of changes of the spectral fatigue index value during one set of repetitions for the filtered EMG signal (Fig. 2A, dashed line) was similar to that for the unfiltered signal (Fig. 2A, solid line). Thus, unfiltered EMG signals were used for the following data analyses. The range of changes in the spectral fatigue index value (calculated against the first repetition in the corresponding set) across the repetitions in a set tended to be greater when the order k of the normalizing spectral moment was higher (Fig. 2B). Therefore, fifth-order FI_{nms5} data were subsequently used for comparison with F_{med}. The rate and range of changes in the spectral index FI_{nsmk} (Fig. 2C) and F_{med} (Fig. 2D) increased gradually with the number of repetitions. The maximal change of the spectral index observed in the present experiment was about eightfold (Fig. 2C), whereas that of the F_{mean} (not shown) and F_{med} (Fig. 2D) was only 32%.

The ICC values for the F_{med} (0.78, P < 0.0001) and FI_{nsmk} (0.75, P < 0.0001) calculated from the first repetition of each set of the exercise protocol demonstrated fair to good reliability (24). There was a main effect of repetition number (N = 15) on both F_{med} and FI_{nsmk} changes during the exercise ($P < 0.0001$, $\eta^2 = 71$ and 74%, respectively). Because no significant main set number ($P > 0.05$, η^2 = 22 and 15%, respectively, N = 10) and no interaction set × repetition effects ($P > 0.05$, η^2 = 17% for both) were found, muscle fatigue indices were averaged for each subject across sets for each repetition (Fig. 3) before generating mean ± SEM data for the subject group. Statistical analysis of the spectral fatigue index (FI_{nsmk}) data averaged across repetitions indicated significant intersubject variability in the levels of FI_{nsmk} changes within the tested subject population (P < 0.0001, η^2 = 97%).

Dendrograms illustrating the stages of the hierarchical clustering process applied to both of the muscle fatigue indices are presented in Figure 4. The decision about final data partition into groups was made using 75% cutoff threshold based on the similarity and distance levels calculated at each grouping stage (solid horizontal line in Fig. 4). Three distinct groups were revealed: HF (N = 1, high FI_{nsmk} change, solid line), group MF (N = 4, medium

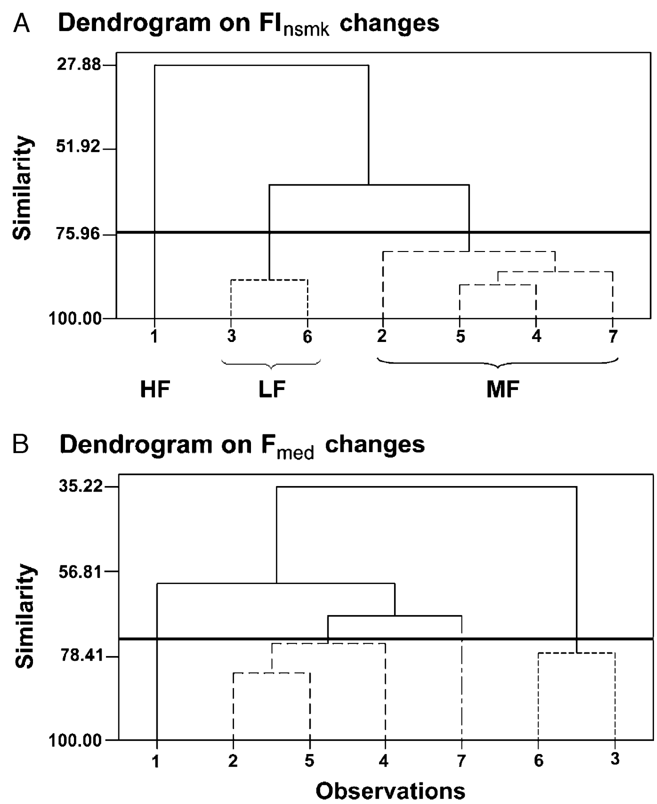

FIGURE 4—Dendrograms of the clustering procedures performed using individual relative changes of the spectral index FI_{nsmk} (A) and of the median frequency F_{med} (B). The results were grouped starting with the closest neighbor on the basis of their similarity. Resultant groupings are indicated as MF (medium fatigability, *dashed lines*), LF (low fatigability, *dotted lines*), and HF (high fatigability, *solid lines*). The *horizontal bold line* illustrates the cutting point of the clustering (optimal grouping point) determined at the 75% similarity level.

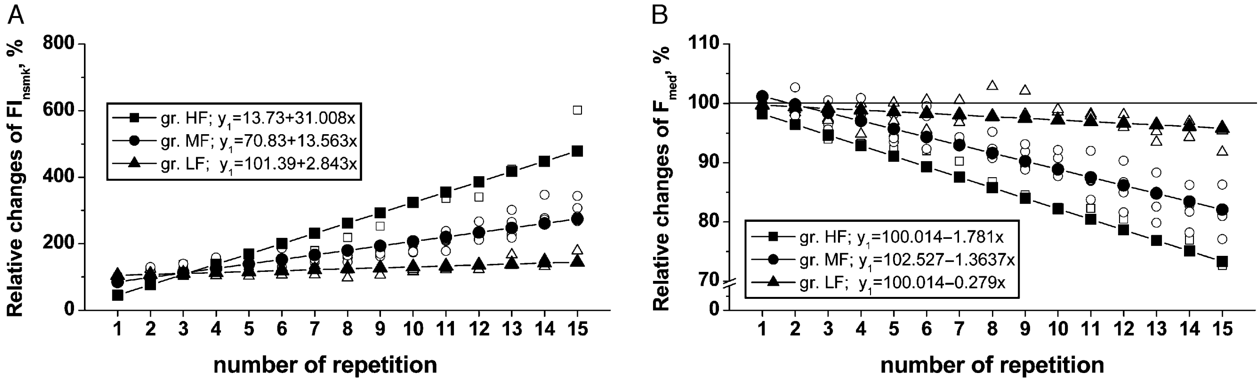

FIGURE 5—Linear regression analysis of the relative changes of spectral index FI_{nsmk} (A) and median frequency F_{med} (B) values for each subject cluster classified by the muscle fatigability: HF (high, *N* = 1), MF (medium, *N* = 4), and LF (low, *N* = 2). The slopes of the fitting lines were significantly different between the groups ($P < 0.05$) for both models.

FI_{nsmk} change, dashed lines), and LF (*N* = 2, low FI_{nsmk} change, dotted lines). The dendrogram constructed during the clustering procedure performed on F_{med} data was cut at the same similarity and distance levels as for FI_{nsmk} data, but it resulted in partition of the data into four classes (Fig. 4B; note the different line style for each cluster). Linear regression analysis revealed significantly different slopes of the lines fitting the data for each group (adjusted R^2 = 88.9% for FI_{nsmk} model; R^2 = 87.9% for F_{med} model; $P <$ 0.05 for both models; Fig. 5). The average maximal ΔFI_{nsmk} value for cluster HF was 602 ± 0%; for cluster MF, 300 ± 17%; and for cluster LF, 162 ± 16%. The average maximal ΔF_{med} value for cluster HF was 73 ± 0%; for cluster MF, 81 ± 2%; and for cluster LF, 94 ± 2%. There were no significant differences between the three clusters in initial MVC values corrected for body mass (Fig. 6A). Comparison of percentage change in peak contraction torque (last vs first repetition in the exercise, ΔT) and in MVC data (post vs preexercise, ΔMVC) using one- way ANOVA indicated that the ΔMVC ($P = 0.03$, Fig. 6B) and ΔT ($P = 0.012$, Fig. 6C) values were significantly different between clusters. Thus, cluster HF consisted of cases with the highest muscle fatigability, and cluster LF consisted of subjects with the highest muscle endurance.

DISCUSSION

The primary aim of this study was to establish the validity and the sensitivity of the new EMG spectral indices for muscle fatigue assessment in comparison with the traditionally used EMG median frequency. The qualitative changes in the new spectral indices mirror those of the characteristic EMG spectral frequencies (F_{med} and F_{mean}), as was found in previous theoretical (2,3) and experimental (11,14) studies. In the present study, we demonstrated that application of the new spectral indices on surface EMG data allowed a reliable assessment of peripheral muscle fatigue during dynamic contractions of the RF muscle. The larger range of change observed in the spectral index FI_{nsmk} across repetitions confers greater sensitivity than that provided by the characteristic frequencies (F_{mean} and F_{med}) traditionally used and allowed more precise evaluation and classification of muscle fatigability (Fig. 4). Therefore, the proposed spectral indices could be useful for monitoring training status, talent

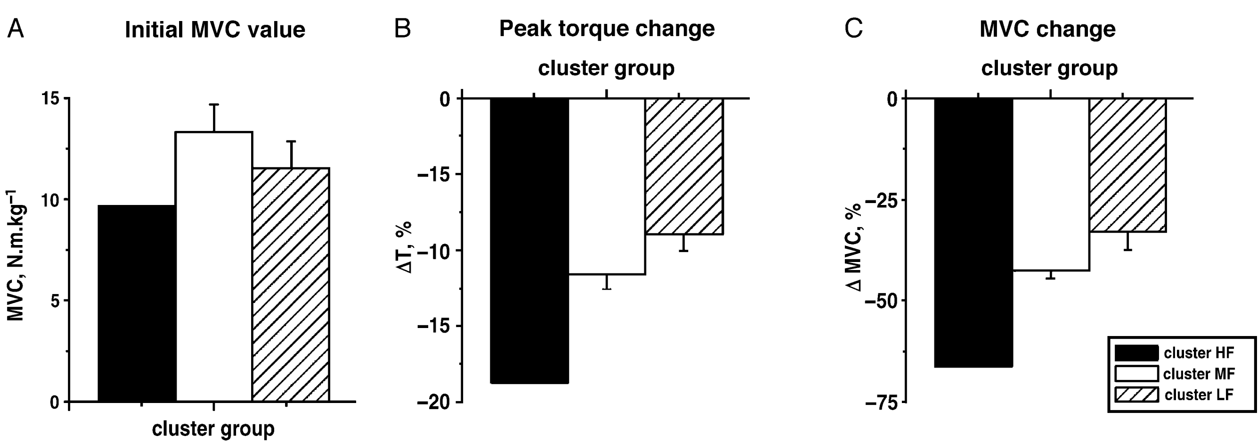

FIGURE 6—Average (± SEM) values of A) the initial maximal isometric contraction torque (MVC); B) the percentage changes of the peak knee-extension torque by the end of exercise; and C) the percentage changes of MVC after exercise for the established subgroups of subjects classified using a hierarchical cluster analysis: HF (high, *N* = 1), MF (medium, *N* = 4), and LF (low, *N* = 2). Initial MVC values are normalized by body mass (kg) for each subject. One-way ANOVA established significant differences in the peak torque and MVC changes but not in the initial MVC values between subgroups.

identification for endurance- versus strength-based sports, and evaluating the efficacy of interventions designed to delay fatigue onset. However, additional investigations are necessary to determine standard ranges of spectral index change for classification of fatigable, medium fatigable, and fatigue-resistant muscles. Such ranges will be specific to the muscle tested and the exercise protocol used.

As in the case of isometric voluntary contraction (11) or M-wave quantification (14), the range of changes in the spectral fatigue index value was greater when the order of the normalizing spectral moment, k, was higher (Fig. 2). The changes in the new spectral index (11) and F_{med} (6,34) are not sensitive to variation in motor unit firing rate, which is centrally controlled. Therefore, the increase of the spectral index (Fig. 3A) and F_{med} (Fig. 3B) with the number of exercise repetitions should reflect development of peripheral muscle fatigue.

Using the new, highly sensitive indices, we found that participants could be differentiated into distinct groups related to peripheral muscle fatigability. This was possible, irrespective of the changes in EMG data during dynamic contraction related to changes in the knee angle, length of the muscle fibers, and longitudinal electrode position. The classification was validated by the significant differences found between the clusters in the fatigue-induced changes in the peak contraction torque during the exercise and in the magnitude of the postexercise reduction in maximal isometric force. However, these differences must be treated with some caution because of the use of a parametric test with such small subject numbers. Differences in the intrinsic properties of individual subjects' RF muscle were the most likely cause of different fatigability, probably related to different training status and fiber-type composition. However, further work is required with a larger group of subjects to validate the use of FI_{nsmk} as a means of differentiating subjects on the basis of muscle fatigability. This study was designed to test the applicability of FI_{nsmk} for assessing peripheral muscle fatigue during dynamic contractions and to compare their sensitivity to the level and the rate of muscle fatigue development versus the sensitivity of F_{med} and F_{mean}. An important finding of the present work was the good reliability of both F_{med} and FI_{nsmk} during repetitive knee-extension (dynamic) contractions, which is in line with previously reported ICC values for EMG parameters during dynamic and isometric contractions (24). Therefore, the differences observed in EMG spectral parameters between subjects and between clusters cannot be attributed to data variability and are indicative of muscle function and fatigability.

EMG spectral analysis methods have been used in both ergonomic and clinical studies of muscular fatigue. However, no definitive clinical interpretation of spectral changes observed during prolonged exercise has emerged. It is not yet possible to reliably classify spectral measurement shifts as normal or abnormal or to define different ranges of muscle fatigability, because of the observed high variability and low sensitivity (lack of consistent differences between tested populations) of the existing spectral measures (35,37). Therefore, development of reliable, physiologically valid, and highly sensitive measurement is required. The sensitivity to the pattern of muscle fatigue development of the new spectral indices compared with the EMG median frequency was tested on the paradigm of dynamic knee-extension exercise. The higher sensitivity of the new spectral indices was evidenced by the greater magnitude of change (eightfold for FI_{nsm5} vs 32% for F_{med}) and further illustrated by the identification of three functionally distinct subject subgroups: high fatigable (Fig. 5A, group HF, range of FI_{nsm5} changes higher than 400%), medium fatigable (Fig. 5A, group MF, range of changes between 200 and 400%) and low fatigable (Fig. 5A, group LF, range of changes below 200%). These differences in the rate and degree of the development of the peripheral muscle fatigue most likely reflected differences between the individual characteristics of the subjects analyzed. The rate and range of changes for F_{med} could also be used to separate subjects into groups based on fatigability of their muscles (Fig. 5B; F_{med} decreased by more than 20% (group HF), by 10 to 20% (group MF), and by less than 10% (group LF)). However, because of the much smaller ranges of change between repetitions in F_{med} (100 to 68%) than in the spectral index FI_{nsm5} (100 to 600%), separation into groups based on the F_{med} parameter was more problematic (Fig. 4). Future work is necessary to investigate the dependence of the range and sensitivity of FI_{nsmk} changes on the exercise protocol, fitness level, gender, age, and other such characteristics of the tested subjects.

PRACTICAL IMPLICATIONS

The present study provides a new technique based on surface EMG measurement during prolonged submaximal dynamic exercise to assess skeletal muscle function and fatigue. Valid and reliable tests of muscular function that allow characterization of personal physical profile are important for sports talent identification and prescribing individualized training programs to maximize the response to strength training. In combination with traditional methods such as MVC and 1RM for functional testing of muscle strength and power, the spectral analysis of surface EMG activity using the new indices offers a powerful tool for the assessment of muscle fatigability. All of these developments are important in exercise science and in the field of rehabilitation of sports injuries. Peripheral muscle endurance is often impaired even in individuals with relatively normal physical activity and mild to moderate stage of disease or injury, resulting in muscle dysfunction and exercise intolerance. Muscle fatigability can be used as a diagnostic tool. Training programs to increase muscle endurance are often included in the rehabilitation or treatment of patients in all stages with polymyositis, including body myositis and dermatomyositis (1), patients recovering from surgical knee replacement (18), chronic obstructive pulmonary disease (9), and other conditions. Further studies are needed to fully establish the validity and reliability of the new spectral indices for testing muscle performance in the clinical, rehabilitation, and sports setting.

In summary, we have shown that the new spectral indices provide reliable evaluation of peripheral muscle fatigue during dynamic contractions comparable with the EMG spectral characteristics traditionally used as muscle fatigue indices. However, the new indices provide far greater sensitivity, which allows classification of the tested subjects into groups according to their muscle fatigability. This information could be useful for functional muscle testing during rehabilitation and in clinical practice and for monitoring athletic performance and training progress. Further research is necessary to develop protocols and grouping criteria customized to the specific testing conditions.

G. V. Dimitrov, T. I. Arabadzhiev, and N. A. Dimitrova were supported by the Bulgarian National Science Fund, Project 1530/05.

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