Original Article

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The effect of fatigue and heavy load on surface EMG variables during dynamic contraction

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ABSTRACT

Spectral surface electromyographic changes in the lower extremity muscles during dynamic contractions were studied to investigate the discrimination between fatiguing tasks and heavy load tasks. Twenty-six young female volunteers (15 for the fatigue task, 11 for the heavy load task) performed either a repetitive standing exercise until fatigued with the 2 sec rhythm, or an exercise repeated five times while carrying a weight of 20 kg with the 4 sec rhythm, which was so heavy that there was the possibility of the subjects falling over during the task. Electromyographic activity was recorded from the vastus lateralis, the long head of the biceps femoris, the tibialis anterior, and the lateral head of the gastrocnemius. Mean frequency (MNF) and median frequency (MDF) were analyzed using a wavelet transform, and the root mean square (RMS) of the electromyogram was calculated. Fatigue tasks reduced both MNF and MDF in the vastus lateralis, tibialis anterior, and gastrocnemius muscles, mainly at the beginning and end of muscle contractions. Compared with no load exercise without fatigue, heavy load tasks markedly increased RMS in all four muscles, with no alteration in MNF and MDF patterns. These results suggest that MNF and MDF are spectral parameters that are reduced by muscle fatigue but not by heavy load during dynamic contractions.

KEY WORDS

Lower extremity muscles, Standing exercise, Root mean square, Spectral parameters, Wavelet transform

Introduction

Fatigue during isometric contraction has frequently been studied using surface electromyography (EMG). It is commonly known that mean frequency (MNF) and median frequency (MDF) decrease while the root mean square (RMS) increases as a result of fatigue during voluntary contraction[1-3]. If static contraction is performed at stable torque, the algorithm of calculation for spectral parameters can be based on the Fourier transform. However, the majority of contractions during motion in our daily lives are dynamic contractions and new methods are therefore needed for evaluating fatigue or difficulty continuing motion in such dynamic tasks.

Recently, continuous wavelet transform has been reported as providing better accuracy in analyzing the power spectrum from surface EMG during dynamic contraction[4-6]. Wakeling et al[7]. showed a significant reduction in EMG intensity at low frequencies and a significant increase at high frequencies in the muscles of the lower extremities after 30 min of running. These findings are different from those with static fatigue contractions. Karlsson et al[4]. showed a significant positive correlation between MNF and force in knee extensors without fatigue, although another investigator reported increased amplitude in the lower frequency band during jumping in an altered gravity environment[8]. These reports, however, examined either fatigued or loaded conditions; the difference in response in spectral parameters accord-

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Table 1 Profiles of subjects in the two tasks

	age (y)	height (cm)	weight (kg)	number
fatigue task	21.9 ± 0.2	158.5 ± 1.7	50.3 ± 1.4	15
heavy load task	21.6 ± 0.4	158.4 ± 1.4	52.3 ± 1.5	11

Values are mean ± SE.

ing to conditions during dynamic contractions remains obscure.

The aim of the present study was to investigate the discrimination in spectral EMG changes between fatiguing tasks and heavy load tasks using wavelet transform. We examined a repetitive standing and sitting exercise for both kinds of tasks.

Methods

Subjects

Twenty-six healthy, sedentary female students volunteered to participate in the present study. Their profiles are shown in Table 1. Fifteen subjects completed the fatigue task and 11 subjects completed the heavy load task. Each subject gave informed consent to be studied.

Exercise protocol

For the fatigue task, the subjects sat on a stool 40 cm in height with their heels 10 cm from the front edge of the stool as the starting position. They were asked to stand up for 1 sec and sit down for 1 sec following a synthesized 1 Hz sound, and to repeat the exercise until they felt fatigue or difficulty continuing. Twelve stopped when they felt fatigue and three stopped when they felt unable to continue the motion. The EMG data for the initial five repetitions and the final five repetitions served for analysis of the effects of fatigue.

For the heavy load task, subjects sat on the same stool as used in the fatigue task, in the same starting position. The load was a 20 kg weight held around the trunk with a harness from the shoulders and fixed with a waist band to prevent slipping. Because this load was too heavy to repeat the exercise with the 1 Hz rhythm used in the fatigue task, subjects were asked to stand for 2 sec and sit for 2 sec. To avoid the effects of fatigue[9], they performed the exercise five times without the load, and then performed the exercise five more times with the load. These EMG data were analyzed for the effects of heavy load.

Surface electromyography

During the exercises, EMG signals were recorded continuously. Signals were obtained from the right vastus lateralis, the long head of the biceps femoris, the tibialis anterior, and the lateral head of the gastrocnemius. The skin was rubbed with a skin preparation gel (SkinPure, Nihon Kohden, Japan) to clean the sites for the electrodes. The bipolar disposable Ag/AgCl disc electrodes (Blue sensor M-00-S, Medicotest, Denmark) were attached parallel to the muscle fibers on the longitudinal midline of the muscle bellies with a center-to-center distance of 30 mm. The EMG signals were detected by the Holter EMG system (ME3000P, Mega Electronics, Finland) with differential amplifiers and 12-bit analog/digital conversion at a sampling rate of 1000 Hz. The range of band pass filtering was 8-500 Hz.

Data analysis was performed off-line using a personal computer (Prosignia Notebook 190, Compaq, USA). Because the sampling rate of the EMG signals was 1000 Hz, the frequency band up to 500 Hz by wavelet transform was divided into 512 ($=2^9$), about half the number of the sampling rate. Values of MNF, MDF, and RMS were extracted every 0.064 ($=2^6$E-3) sec from analyzed data to set the data time points; hence, one repetition for the fatigue task was about 31 points of data every 2 sec, and for the heavy load task about 62 points every 4 sec. As shown in Figure 1, representing sample EMG signals from the vastus lateralis muscle, the spectrogram and

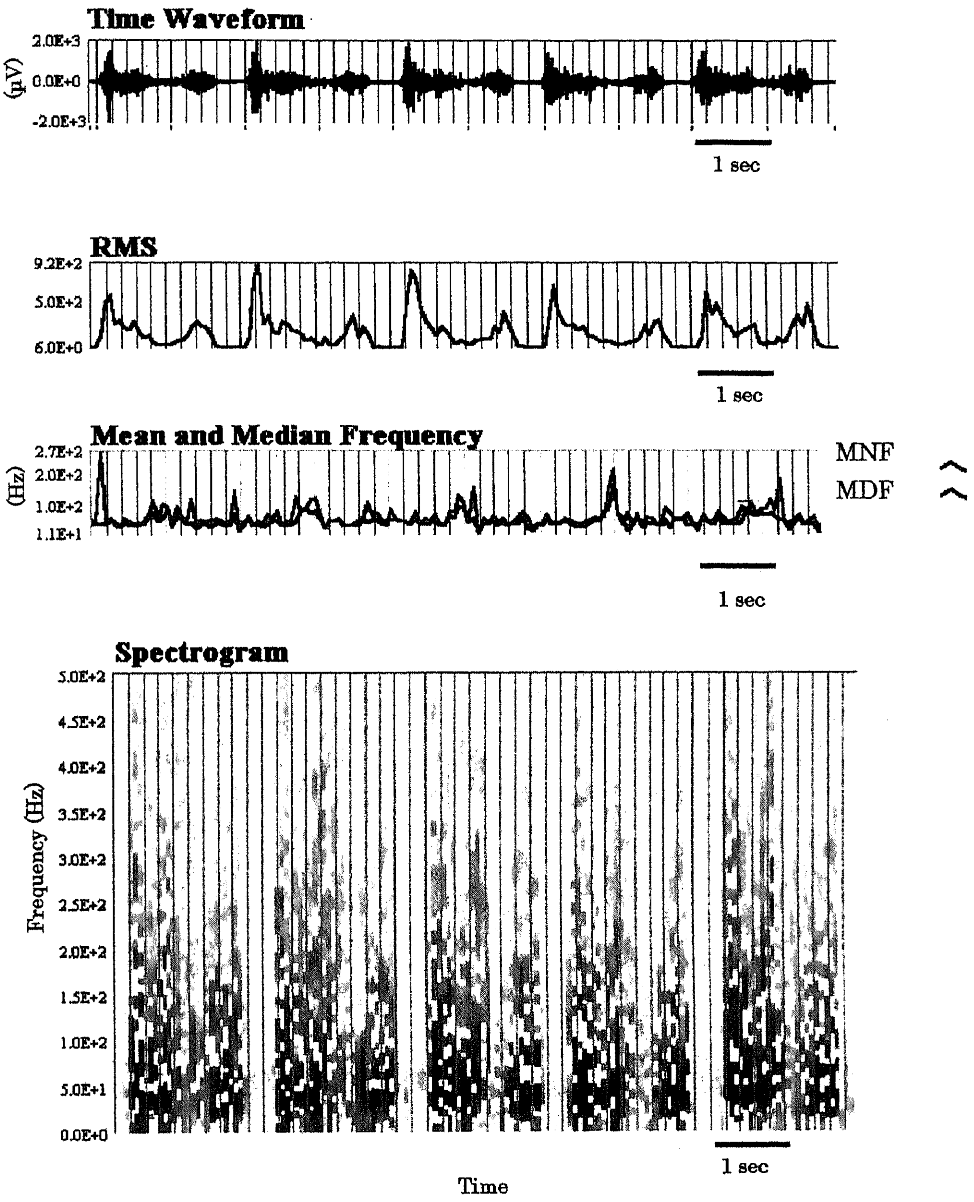

Fig. 1. Surface EMG signals, RMS, MNF, MDF, and power spectrogram by wavelet transform of the vastus lateralis muscle in one subject during the initial five repetitions of the fatigue task. In the spectrogram, the time width of band is 0.064 sec and the frequency up to 500 Hz is divided into 512 bands. Intensity of frequency is shown black by tone; a solid black band represents the high intensity of frequency, while a light grey band represents the low intensity of frequency during the analyzed period.

RMS varied in each repetition. At first, we selected the starting time point of a repetition when the RMS value of the vastus lateralis muscle began to increase in the standing motion. Therefore, there were 31 data time points in the fatigue task in one repetition. However, in the heavy load task, because of the longer time cycle, the identified starting time point did not appear punctually every 4 sec. Because the number of time points in one repetition, that is, from the starting time point to the next starting point, varied among trials, a minimum number of time points was employed for the data analyses. Consequently, the number of data time points in the heavy load task was reduced to 57. Then, the five-repetition values from EMG signals at each data time point were averaged.

Statistics

In the fatigue task, RMS values in each muscle were normalized by the largest RMS value during the initial repetition exercise for quantitative analysis of activity. In the heavy load task, RMS values were also normalized by the largest RMS value during the exercise without load. The normalized RMS, the MNF, and the MDF were each statistically compared using ANOVA between the initial and the final repetitions in the fatigue task and between no-load and loaded conditions in the heavy load task. As a post hoc test, the Bonferroni-Dunn method was used at each data point between nonfatigue and fatigue values or between no-load and loaded values. P<0.05 was considered significant in the statistical tests.

Results

Fatigue task

The normalized RMS in the vastus lateralis, biceps femoris, and tibialis anterior muscles showed two peaks, corresponding to muscle contractions during standing and sitting (Fig. 2). These peaks in the biceps femoris and tibialis anterior muscles were significantly reduced by fatigue. In the gastrocnemius muscle, continuous activity was shown during the period between the peaks made by the other muscles, and there was no statistical difference between the fatigue and nonfatigue conditions in the normalized RMS.

Changes in patterns of MNF and MDF appeared to be similar for the four muscles. Most of the significant reductions in both MNF and MDF by fatigue were seen during the periods when there was no peak of the normalized RMS, that is, at the beginning and end of muscle contractions. These reductions were clearly shown in the vastus lateralis, tibialis anterior, and gastrocnemius muscles, but not in the biceps femoris muscle.

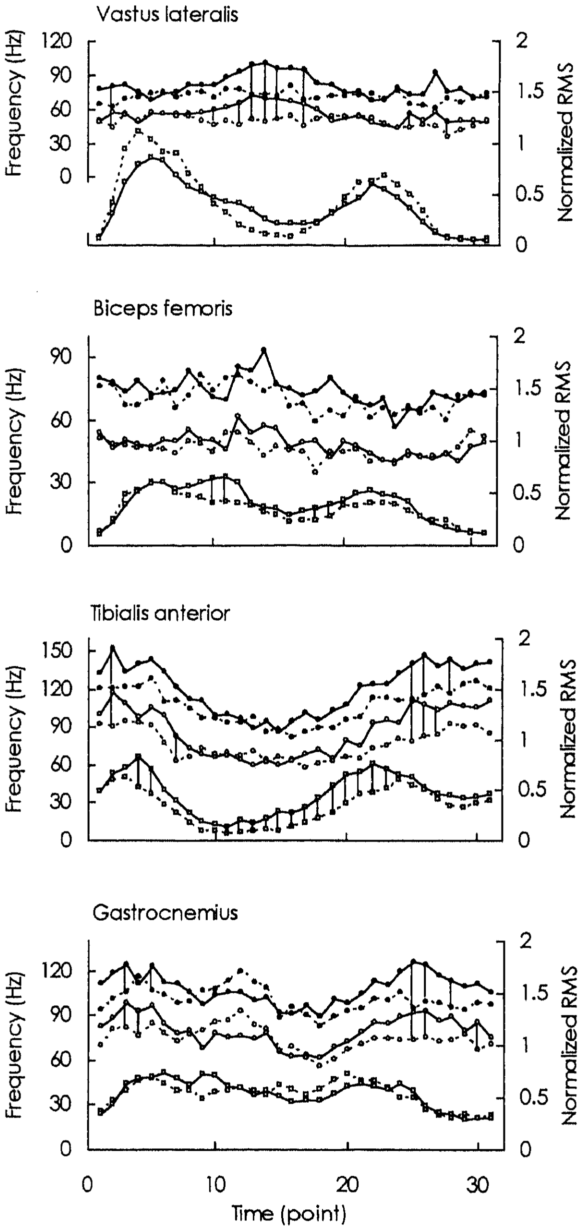

Fig. 2. Mean values of surface EMG parameters in 15 subjects during the fatigue task. The interval of time points is 0.064 sec. The solid line represents the initial repetition values of MNF (●), MDF (○), and normalized RMS (□), and the broken line represents the final repetition values. The vertical line between the initial and final values shows significant difference by Bonferroni-Dunn method after ANOVA (p<0.05).

Heavy load task

During exercise with the heavy load added, the normalized RMS in the four muscles significantly increased from the values of the no-load condition (Fig. 3). The normalized RMS pattern of two peaks in the vastus lateralis, biceps femoris, and tibialis anterior muscles, and the continuous contraction pattern in the gastrocnemius muscle were similar to that in the fatigue task. In the MNF and MDF data analyses, there were a few data points which showed significant reduction by heavy load compared with the

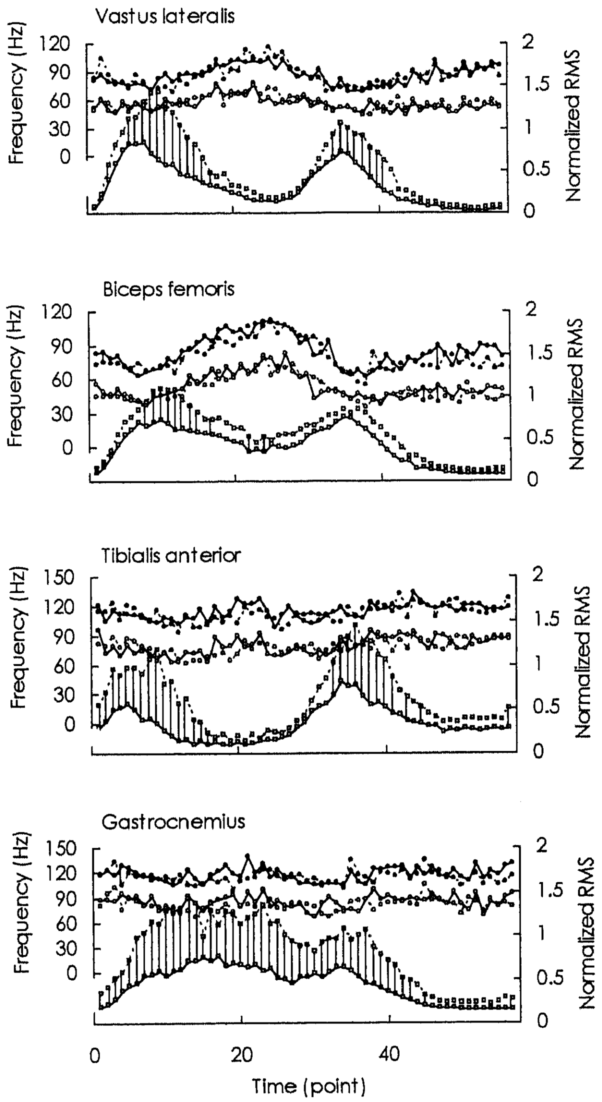

Fig. 3. Mean values of surface EMG parameters in 11 subjects during the heavy load task. The interval of time points is 0.064 sec. The solid line represents the no-load repetition values of MNF (●), MDF (○), and normalized RMS (□), and the broken line represents the heavy load repetition values. The vertical line between the no-load and heavy load values shows a significant difference by Bonferroni-Dunn method after ANOVA ($p<0.05$).

no-load condition. These reductions in MNF and MDF were seen at the end of the biceps femoris muscle contraction and the beginning of the gastrocnemius muscle contraction. However, the data points showing reductions in MNF and MDF from the no-load condition during the heavy load task were very scattered compared with reductions from the nonfatigue condition during the fatigue task.

Discussion

Repetitive exercises such as isokinetic knee extension and running have been applied in the study of muscle fatigue during dynamic contractions[7,10]. Because the purpose of the present study was to examine the discrimination in changes in EMG between fatigue and heavy load tasks, the subjects performed the same repetitive exercise of standing and sitting.

Investigators have previously reported on the effects of either fatigue or load on EMG results. For example, a repetitive knee extension exercise reduced MNF or MDF in the vastus lateralis muscle during fatigue[2,10-13]. A repetitive elbow flexion-extension task with a weight showed greater MNF reduction at shorter muscle lengths by fatigue accompanied by an increase in muscle activity[14]. The MNF and MDF in the shoulder muscles were also reduced from the nonfatigue condition during dynamic contractions[15]. However, a study of running for 30 min showed reductions in intensity of low-frequency components of EMG signals and increases in intensity of high-frequency components compared with levels in the initial period of running[7], while a study on back muscles during cyclical lifting showed a nonlinear decrease in MDF[16].

The present study showed that the fatigue condition reduced values in spectral parameters compared with the nonfatigue condition, and the reductions in MNF and MDF appeared to occur when there was no peak of RMS for each muscle. These results suggest that muscle contractions during peak periods of RMS are performed mainly by type 2 muscle fibers; however under the fatigue condition, type 1 fibers are recruited to contract or the number of contracting type 2 fibers is simply reduced, so there is no peak of RMS. Therefore, when type 2 fibers cannot contract sufficiently for the fast contraction during peak periods of RMS, the subjects cannot stand up any more or follow the 1 Hz rhythm. Morphological studies showing that the MNF negatively correlated with the area and proportion of type 1 fibers[13,17,18] during the state of fatigue supports that a large proportion of contracting type 1 fibers reduces the MNF compared with the

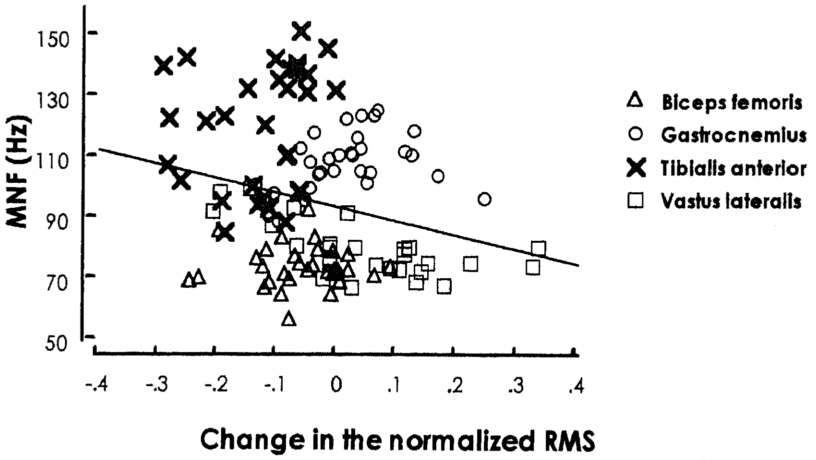

Fig. 4. Initial MNF values versus changes in the normalized RMS during the fatigue task for the four muscles. The regression line is y=94.2-47.3 x, r=-0.24 ($p<0.05$, by the simple linear regression test).

MNF of the nonfatigue condition.

Changes in RMS induced by fatigue were also different among the muscles; peaks of RMS decreased in the biceps femoris and tibialis anterior muscles, but were not changed in the vastus lateralis and gastrocnemius muscles. In the vastus lateralis muscle, it has been reported that RMS does not change with fatigue during maximum dynamic contraction[11, 13)], significantly increases during sub-maximal dynamic and static contractions[2)], or varies according to the individual[10)]. In addition, RMS in the shoulder muscles increased from fatigue during submaximum dynamic contraction[15)].

In the present study, RMS appeared to be decreased by fatigue at the data points when the values in the initial spectral parameters were high. Hence, to clarify this hypothesis extracted from result data we examined the correlation between the change in RMS due to fatigue and the initial MNF by using the test for significance of the simple linear regression. As shown in Figure 4, there was a significant negative correlation between the two parameters employing all 31 data points for the four muscles, where the change in RMS represents a difference in the normalized RMS (value at fatigue minus the initial value). This result suggests that muscle contraction with high frequencies easily diminishes RMS in the fatigue condition.

In isotonic contractions without fatigue, the MNF was demonstrated to be lower at a low torque level than at a high torque level[1)]. However, during dynamic contraction without fatigue, the relation between force or load and power frequencies has not been established. The relation has variously been reported as a significant positive correlation between MNF and force[4, 10)], as decreased MNF during muscle contraction[19)], and as various individual changes in MPF during incremental bicycle ergometer exercise[20)]. In the present study, both fatiguing tasks and heavy load tasks showed that MNF and MDF in the vastus lateralis muscle appeared to be lower during peak periods of RMS than during periods when there was no peak of RMS in the nonfatigue condition. This means that high muscle activity reduces MNF and MDF, which is contrary to the result shown in the isotonic contraction study. However, in the tibialis anterior muscle, which also had two peaks of RMS in this study, the initial repetition data on MNF and MDF were lower when subjects were standing, that is, when there was no peak of RMS, in the fatigue task. Thus, the relation between muscle activity and power frequencies during dynamic contraction in the nonfatigue condition is still obscure because of the different responses by the muscles in EMG parameters. These differences among the muscles might be due to the composition of the muscle fiber and the type of contracting muscle fiber during the exercise.

Moreover, the higher muscle activity due to heavy load, in this study, did not influence the spectral parameters, except at a few data points. For this reason, a 20 kg weight might not be heavy enough to change the patterns of MNF and MDF, even though the differences in RMS were distinctly greater in the heavy load task than the fatigue task. Consequently, it is suggested that extra load has little effect on MNF and MDF compared to the muscle contraction cycle during motion.

In conclusion, MNF and MDF were significantly reduced by fatigue during dynamic contraction. The reductions were usually found during lower activity periods in each muscle. The differences in the reduced pattern among muscles are thought to depend on the degree of fatigue of each muscle caused by the designated motion and also by the proportion of contracting fibers by type. Without fatigue, heavy load significantly increased RMS, although it did not affect MNF and MDF. When either fatigue or heavy load is utilized for dynamic exercise, there was discrimination in surface EMG changes.

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動的収縮において疲労と高負荷が表面筋電図の測定値に与える影響

染矢富士子，三秋　泰一

要　　旨

疲労と高負荷が表面筋電図の周波数に及ぼす影響の違いを下肢筋の動的収縮において検討した。26名の本学女子大生を，15名と11名に分けて，それぞれ疲労あるいは高負荷の条件で椅子からの立ち上がり動作を施行させた。疲労条件は２秒のリズムで疲労困憊するまで立ち上がり動作を繰り返し，高負荷条件は20kgの錘を負荷して４秒のリズムで５回の立ち上がり動作をさせた。表面筋電図は外側広筋，大腿二頭筋，前脛骨筋，腓腹筋より導出し，ウェブレット変換による平均周波数（MNF）と中央周波数（MDF），また交流実効値（RMS）を求めた。疲労条件では動作の１周期の中でMNFとMDFが外側広筋，前脛骨筋，腓腹筋の収縮し始めと終わりの時に有意に低下したが，高負荷条件では負荷をしない場合と比較してRMSは増大しても周波数に差は認められなかった。以上より，筋電周波数は疲労により変化するが，高負荷では変わらないことが分かった。