Original Article

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Correlation between perceived muscular fatigue and EMG values during bicycle ergometry

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ABSTRACT

This study examined the correlation between perceived muscular fatigue and surface electromyogram values during bicycle ergometry in order to determine the values of median frequency (MDF) and root mean square (RMS) for the lower extremity muscles ; the vastus lateralis, the biceps femoris, the tibialis anterior and the gastrocnemius, that corresponded with perception of fatigue.

Nine healthy female subjects who performed 5-min constant-load ergometer exercises with 70 and 100-watt workload, avoiding individual differences of physical strength, rated perception of muscular fatigue using a 10-point graded scale of Borg, resulting in significant negative correlation between MDF in the vastus lateralis and the biceps femoris, but not in the tibialis anterior and the gastrocnemius. When subjects perceived an increase in muscular fatigue of "greater than heavy", MDF in the vastus lateralis showed significant decrease individually but not in the other three muscles. RMS did not show significant correlation between ratings for perceived muscular fatigue. In the pre- and post-peak periods of RMS during cycle motion, the final MDF values of 5-min-exercise in the vastus lateralis and the biceps femoris were significantly lower than the initial values of exercise.

It was concluded that MDF in the vastus lateralis correlated to perceived muscular fatigue during bicycle ergometry. In especial, significant decrease in MDF with exercise was observed before and after peak muscular contraction.

KEY WORDS

muscle fatigue, Borg scale, MDF, RMS

INTRODUCTION

Bicycle ergometer exercise is widely applied, with users including rehabilitation patients and athletes. During this form of exercise, people perceive muscular fatigue and exertion. Although the correlation between intensity of exercise based on heart rate or oxygen consumption and the rating of perceived exertion has been well documented[1,2], few studies have focused on the correlation between perceived muscular fatigue and objective values. Gerdle and Karlsson[3] rated the perception of muscular fatigue during isometric muscle contraction using a 10-point graded scale, and high perception of fatigue was found at the end of a low-torque test where the mean frequency (MNF) of the power spectrum of the electromyogram (EMG) was less decreased than in a high-torque test.

During incremental bicycle ergometer exercise, it has been shown that both surface EMG activity and oxygen consumption increase and the linearity of increase for each disappear at the same workload[4,5]. This finding implies a probable correlation between EMG signals and perceived muscular fatigue similar to the correlation between oxygen consumption and perceived exertion. As a dynamic exercise with constant workload, a repetitive knee extension exercise showed reduced MNF or median frequency (MDF) in the vastus lateralis muscle during fatigue[6-10]. In con-

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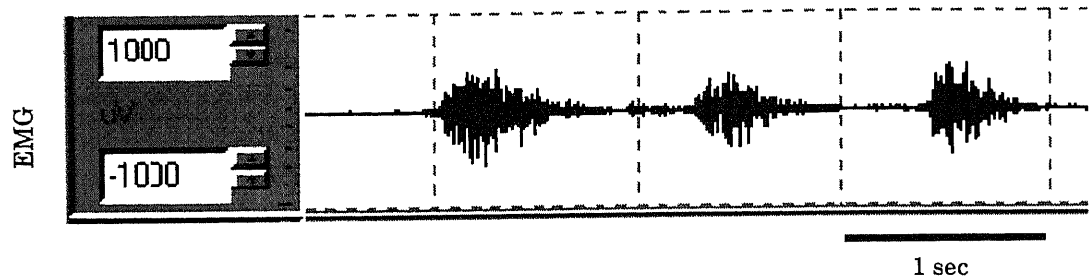

Figure. 1 Surface EMG signals of the vastus lateralis muscle in one subject during the initial three cycles with a 100-watt workload.

trast, in the same muscle, the root mean square (RMS) value has been shown to not change during maximum dynamic contraction[6,10], but to increase significantly during submaximal dynamic contractions[9], or to vary according to the individual[7].

The present study investigated the correlation between perceived muscular fatigue and EMG values in order to determine the values of MDF and RMS for the lower extremity muscles that corresponded with perception of fatigue during bicycle ergometry. We therefore monitored EMG signals of the lower extremity muscles to evaluate RMS and MDF during bicycle ergometer exercise. Two constant workloads, of 70 and 100 watts, were set for the subjects to perceive two differing degrees of muscular fatigue. Avoiding individual differences of physical strength, we also examined individual changes in EMG parameters and fatigue perception.

METHODS

subjects and procedure

Nine healthy sedentary female students, aged 21 to 23 years, volunteered to participate in the present study. Each gave informed consent to participate. The subjects completed 5 min of bicycle ergometer exercises twice, with each of the different workloads, on separate days. The first exercise was performed with the 100-watt workload and the second with the 70-watt workload at about 50 cycles per min (cpm). The mean interval of the two exercises was 14.7 days.

The rating scale for perceived muscular fatigue in the lower extremity utilized the 0-10 scale of Borg[11], and subjects' verbal reports of muscular fatigue at the beginning and end of the exercises were assigned by the examiner to this scale.

EMG 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 cleaned with a skin preparation gel before placement of electrodes. Bipolar disposable Ag/AgCl disc electrodes (blue sensor M-00-S, Medicotest, Denmark) were attached on the longitudinal midline of the muscle bellies with a center-to-center distance of 30 mm. The EMG signals were sampled at a rate of 1000 Hz by a Holter EMG system (ME3000P, Mega Electronics, Finland) with differential amplifiers and 12-bit analog/digital conversion. The range of band pass filtering was 8-500 Hz.

Data was analyzed using a personal computer (Compaq Prosignia Notebook 190, USA). The frequency band up to 500 Hz was divided into 512 ($=2^9$) by wavelet transform, about half the sampling rate. Values of MDF and RMS were extracted every 0.032 ($=2^5$E-3) sec from the analyzed data to set data time points : hence, one cycle of leg motion on the ergometer during exercise gave about 37 data points every 1.2 sec (50 cpm). As shown in Figure 1, EMG signals varied for each cycle motion, and we therefore selected the start time point of a cycle motion as the time when the RMS value of the vastus lateralis muscle began to increase. As the identified start time point did not appear punctually every 1.2 sec, the number of time points in one cycle, that is, from one start time point to the next, varied between cycles. Consequently, the number of time data points employed for the data analyses in one cycle was reduced to 36. The values from EMG signals in the initial and the final five cycles of exercise at each

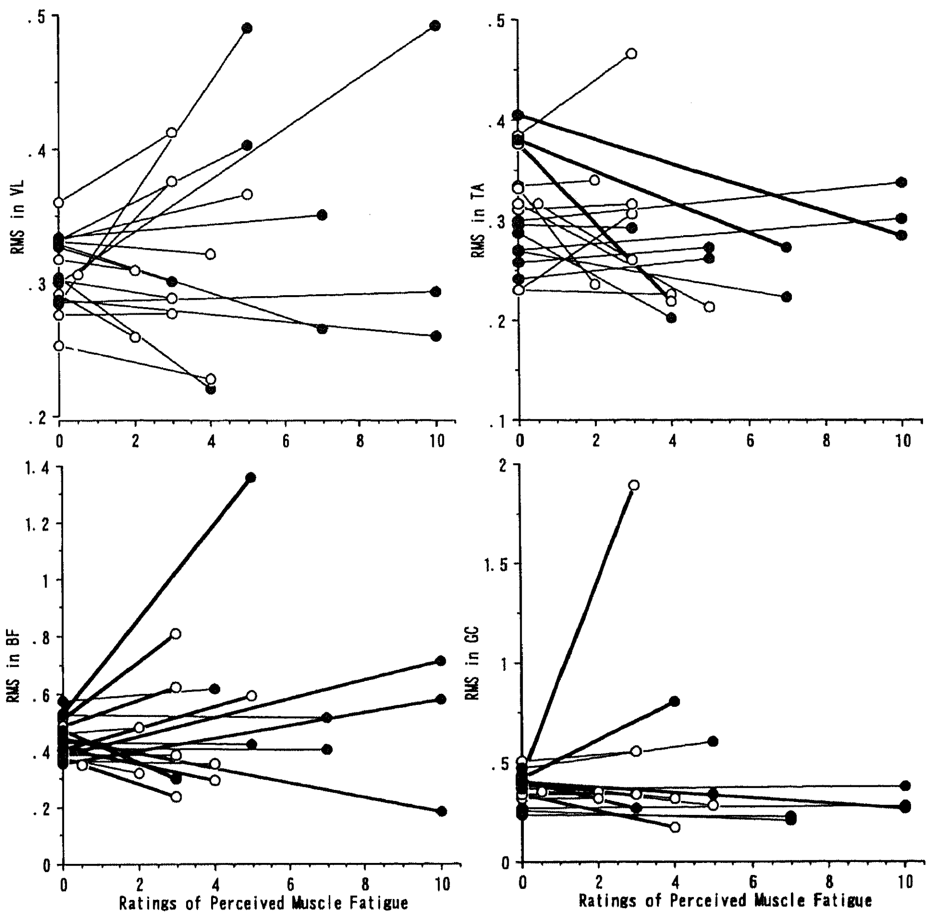

Figure. 2 Correlation between perceived muscular fatigue and normalized RMS values during bicycle ergometry. There was no significant correlation in the four muscles for initial and final data of exercise with two workloads per nine subjects (n=36). Individual changes are shown by lines between the initial and final values, where open circles (70-watt workload) and filled circles (100-watt workload) represent each mean value of the 36 time data points of the normalized RMS. The thick line represents significant change within subjects by ANOVA for 36 time data points. $P < 0.05$. VL : vastus lateralis, BF : biceps femoris, TA : tibialis anterior, GC : gastrocnemius.

time data point were then averaged.

statistics

RMS values for each muscle were normalized by the largest RMS value during the initial averaged five cycles of exercise for quantitative analysis of activity. The initial and the final values for the normalized RMS and the MDF were each statistically compared using analysis of variance (ANOVA). As a post hoc test, the Bonferroni-Dunn method was used at each data point between the initial and the final values. Correlation between perceived muscular fatigue and EMG values was examined by the scale for ratings and the mean value of the 36 time data points in the normalized RMS or the MDF. A difference of $P < 0.05$ was considered significant.

RESULTS

There was no significant correlation between ratings of perceived muscular fatigue and normalized RMS in all four muscles employing the initial and the final data of the exercise with two workloads per nine subjects (Fig 2). Individual changes are shown by lines between the initial and the final values, where the thick line represents significant change in the normalized RMS by ANOVA for 36 time data points. In the vastus lateralis, no significant difference was observed between the initial and the final normalized RMS

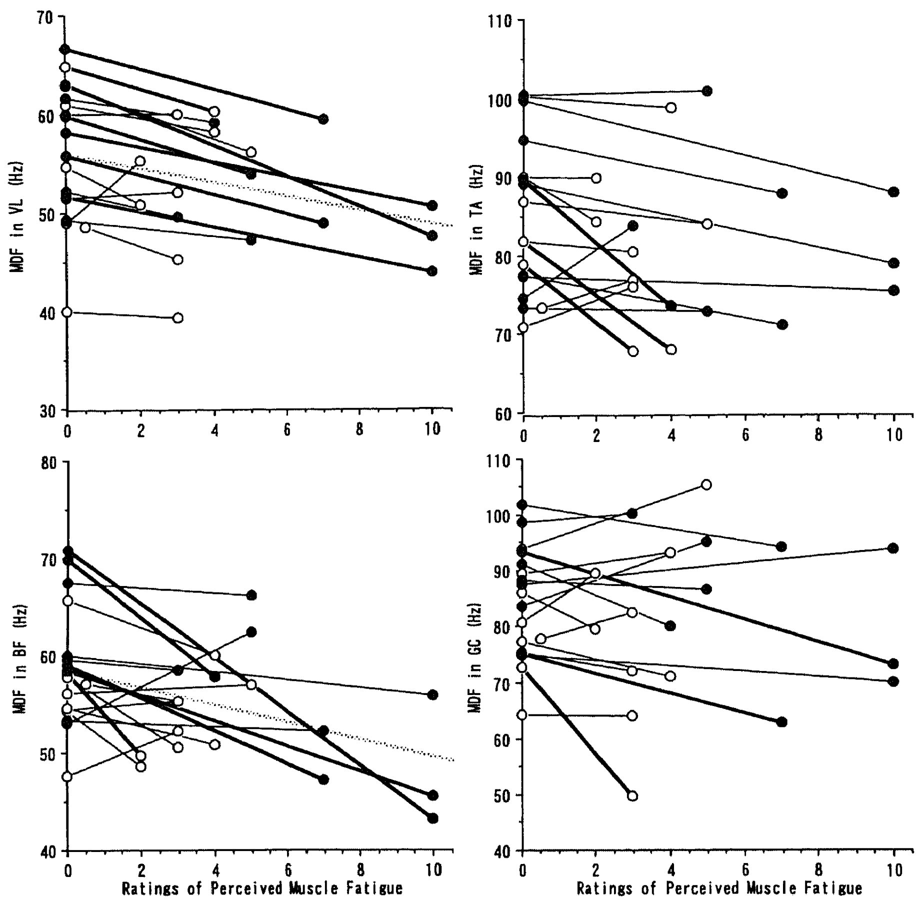

Figure. 3 Correlation between perceived muscular fatigue and MDF values during bicycle ergometry in two trials by nine subjects (n=36). Significant negative correlation was observed in the vastus lateralis and the biceps femoris. The regression line (the pale line) in the vastus lateralis is $y = 55.9-0.7x$, $r = -0.33$ and in the biceps femoris is $y = 58.5-0.9x$, $r = -0.43$. Individual changes are shown by lines between the initial and final values, where open circles (70-watt workload) and filled circles (100-watt workload) represent each mean value of the 36 time data points of MDF. The thick line represents significant decrease within subjects by ANOVA for 36 time data points. $P < 0.05$. VL : vastus lateralis, BF : biceps femoris, TA : tibialis anterior, GC : gastrocnemius.

values among individuals. In the biceps femoris, 6 of 18 trials (two workloads by nine subjects) showed significant increase and 4 trials showed significant decrease in the final RMS compared with the initial value. In the tibialis anterior, the final RMS significantly decreased in 3 trials and, in the gastrocnemius, the final RMS significantly increased in 2 trials and decreased in 3 trials.

As shown in Figure 3, there was a significant negative correlation between ratings of perceived muscular fatigue and the mean value of MDF in the vastus lateralis and the biceps femoris, but not in the tibialis anterior and the gastrocnemius. The ratings of perceived muscular fatigue of all subjects at the beginning of exercises were 0 (perceived as nothing at all) except for in one trial with 70-watt ergometry rated 0.5 (just noticeable). At the end of the exercise, the ratings ranged from 2 to 5 (light to heavy) in 70-watt trials and from 3 to 10 (moderate to almost maximal) in 100-watt trials. In addition, in the vastus lateralis, when the ratings of perceived muscular fatigue were above 5 (greater than heavy), all of the final MDF values significantly lower than the initial values. However, in the other muscles, the rating scale 10 (almost maximal) did not always show a significant decrease in the final MDF compared with the

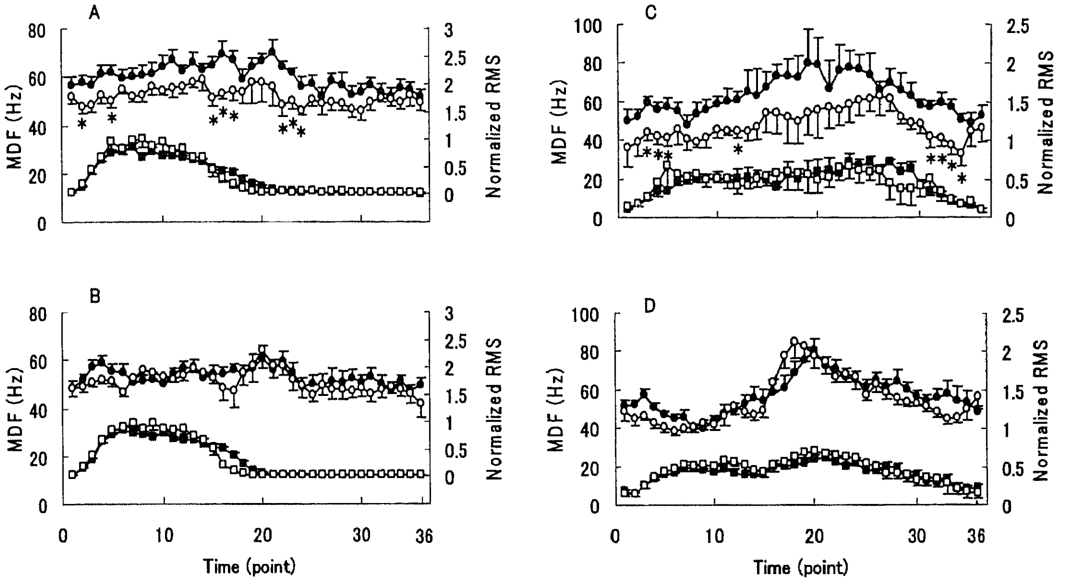

Figure. 4 Time course of initial MDF (●), final MDF (○), initial normalized RMS (■), and final normalized RMS (□) obtained from the vastus lateralis (A and B) and from the biceps femoris (C and D) during the cycle of exercise, divided into two groups by significant decrease in MDF between initial and final values by ANOVA : MDF-decreased group (A, n=7 and C, n=5) and group showing no decrease in MDF (B, n=9 and D, n=12). The interval of time points is 0.032 sec and the time for one cycle motion is almost equivalent to the 36 time point length. Values are mean ± SE. For values without error bars, the size of SE is smaller than symbol. * Significant difference between initial and final values by Bonferroni-Dunn method after ANOVA ($P < 0.05$).

initial value.

Figure 4 shows the normalized RMS and MDF according to the time points of the cycle in the vastus lateralis and the biceps femoris, muscles in which significant correlations were observed between the ratings of perceived muscular fatigue and MDF. Eighteen trials were divided into two groups according to change in MDF between the initial and the final values : a group showing significant decrease and a group showing no decrease by ANOVA. There were 7 trials that showed significant decrease in MDF in the vastus lateralis and 5 trials that showed significant decrease in MDF in the biceps femoris (Fig 3). In MDF-decreased groups, the final MDF data tended to be lower than the initial data at any time point in both muscles ; however, this decrease was mostly significant in those periods when the normalized RMS was increasing or decreasing. In the tibialis anterior and the gastrocnemius, as only 3 trials in each muscle showed significant decrease in the final MDF compared with the initial values, these MDF data were not included in the analyses for dividing the groups.

The vastus lateralis showed a peak in RMS and the biceps femoris showed two peaks during one cycle motion (Fig 4). The peak in RMS in the vastus lateralis represented muscular contraction for knee extension when pushing down on the pedal. The first peak in RMS in the biceps femoris represented eccentric muscular contraction when pushing down on the pedal and the second peak was the concentric contraction to pull up the pedal. Although the final values of peaks in RMS in these two muscles tended to be higher than the initial values, there was no significant difference by ANOVA between the initial and the final values in either the group where MDF decreased or the group showing no decrease.

DISCUSSION

During static muscular contraction, decrease in MDF and MNF can be shown by means of a fast Fourier transform (FFT) calculation[3, 9, 12]. Petrofsky[13] examined changes in RMS and MDF by FFT in the quadriceps muscle during cycle ergometer exercise, finding that with fatigue, heavy workload increased

RMS and decreased MDF. In contrast, Kiryu and colleagues[14] reported that MNF in the vastus lateralis varied individually with fatigue during cycle ergometer exercise, while EMG activities increased. Thus, a strategy for evaluating muscular fatigue using frequency of EMG signals during cycle ergometry has not been established.

Cycle ergometry is a dynamic exercise engaging many muscles in the lower extremity[15]. The contribution of each muscle to the bicycle exercise has been assessed by EMG activity[16,17], and the vastus medialis and lateralis were determined to be the two most activated muscles in the lower extremity. Moreover, findings of a magnetic resonance imaging study suggested a relative high engagement of the vastus lateralis during cycle exercise in the upper thigh[15]. Given these observations, we hypothesized that EMG values in the vastus lateralis might be more affected by muscular fatigue than the other muscles.

The results of the present study showed that a heavier workload (100 watts) decreased the final MDF in the vastus lateralis compared with the initial value for 6 of 9 subjects who perceived muscular fatigue as heavy or greater. Moreover, a significant correlation was shown between the MDF and perceived muscular fatigue in the vastus lateralis. It is suggested that perception of severe muscular fatigue is possibly associated with fatigue of the vastus lateralis accompanied by reduced MDF during cycle ergometer exercise. However, despite the significant correlation between the MDF in the biceps femoris and perceived muscular fatigue, an individual significant decrease in the final MDF did not always appear when the subject's perception was heavy or greater. The differences in changes of MDF in the vastus lateralis and the biceps femoris may be due to the low activity of the biceps femoris during the exercise[16]. The contributions of the tibialis anterior and the gastrocnemius to the cycle exercise appear to be less important and to involve less physiological fatigue, because there was no correlation between the MDF in the tibialis anterior or the gastrocnemius and perceived fatigue. A possible explanation for this is that the activities of the two lower leg muscles, represented by % of maximum EMG activity, are lower than that of the vastus lateralis, and the relatively active soleus muscle (the slow muscle) seems to effectively support the gastrocnemius as a co-contraction muscle[16]. Moreover, the timing of contraction of the tibialis anterior in one cycle motion is markedly different than that of the other leg muscles on an individual basis[17]. In the present study, the discrete changes in MDF among subjects in the two lower leg muscles suggest variability of the degree of engagement of the muscles during bicycle exercise based on the contribution rate between agonist and the contraction timing. Indeed, as subjects in this study were asked to report perceived muscular fatigue on the whole lower extremity, the specific portion of the leg where the subjects felt fatigue was not distinguishable. Moreover, it was difficult for subjects to pinpoint the fatigued muscle, instead they mentioned vaguely "somewhere in the leg" as the fatigued part. Thus, although the rating of perceived muscular fatigue is thought to be useful in determining major muscle fatigue during this exercise, it seems that it is not suitable for determining the fatigued muscle itself.

The final MDF was significantly decreased compared with the initial value during the periods when the RMS value was increasing or decreasing in MDF-decreased groups. Morphological studies have shown that the MNF during the state of fatigue negatively correlates with the area and proportion of type 1 fibers[10,18,19]. This result indicates that, in the fatigued condition, a large proportion of contracting type 1 fibers reduces the MNF compared with the nonfatigued condition. In addition, our result suggests that this recruitment of type 1 fibers occurs mainly in pre- and post-peak muscular contraction even in the eccentric or concentric phase. This hypothesis is supported by Potvin's[20] report of no significant differences between the MNF reductions with fatigue during the eccentric and concentric contractions.

It has been observed that RMS or EMG activity increases with fatigue during dynamic muscle contraction when workload is constant[13,14,21], and shows a more rapid increase in heavy exercise during incremental cycle exercise EMG activity[5,22]. In contrast, the present study did not show a significant correlation between RMS and perceived muscular fatigue, and various changes in RMS were observed within individual subjects ; however, the peak values of the final RMS tended to be higher. Gerdle and colleagues[7] reported that, at the individual level, MNF showed higher correlation coefficients than the RMS for peak torque during fatigable isokinetic exercise. Nussbaum[21] also observed the better reliability of MNF and MDF than RMS for measuring changes during dynamic tasks. It could be considered that our results on the difference of RMS between the initial and the final values depended on individual variation.

It can be concluded that, in the vastus lateralis, MDF during bicycle ergometry shows good correlation with perceived muscular fatigue at the individual level. In addition, when the subjects report a perception of the load as greater than heavy, MDF in the vastus lateralis significantly decreases compared with the initial value. These findings could be utilized for individuals who train using ergometry exercise.

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エルゴメータ使用時の自覚的筋疲労と筋電図評価値との関係

染矢富士子，三秋　泰一

要　旨

本研究では，自転車エルゴメータ使用時における，下肢筋の自覚的疲労と表面筋電図から得られる中央周波数（MDF）および交流実効値（RMS）との関係について検討した。対象は９名の健康な女子大生で，５分間の定常負荷運動を体力的な個人差を考えて70および100-watt の２種類の負荷量について施行してもらった。筋電図の測定筋は外側広筋，大腿二頭筋，前脛骨筋，腓腹筋とした。自覚的筋疲労をボルグの10段階スケールで評価したところ，MDF と負の相関があったのは外側広筋と大腿二頭筋であり，前脛骨筋と腓腹筋の MDF とは関連性が認められなかった。また，自覚的に「きつい」かそれ以上に筋疲労を訴えると，外側広筋の MDF は有意に減少した。一方，RMS はどの筋においても，自覚的筋疲労との関連性を示さなかった。自転車を漕ぐ動作で MDF が減少するタイミングを検討したところ，RMS がピーク値を示す前後において，外側広筋と大腿二頭筋の MDF が５分間の運動により有意に減少した。以上より，今回評価した下肢筋のうち，外側広筋の MDF の減少は自転車エルゴメータでの自覚的筋疲労をよく反映しており，特にその現象は筋活動量がピークとなる前後でよく観察された。