Spectral analysis of erector spinae muscle surface electromyography as an index of exercise performance in maximal treadmill running

Akihiro Nagamachi, Takaaki Ikata, Shinsuke Katoh, and Tetsuki Morita

Department of Orthopedic Surgery, The University of Tokushima School of Medicine, Tokushima, Japan

Abstract : Thirteen male athletes (mean 20.7 years) participated in the present study which investigated the relationship between mean power frequency (MPF) and exercise intensity determined from gas analysis during maximal treadmill running. All subjects performed two consecutive ramp exercise tests on the treadmill. Myoelectric signals from surface electrodes on the erector spinae muscles were digitized and MPF was calculated every ten seconds. Gas exchange data was collected using an automated breath-by-breath system, from which the anaerobic threshold (AT), respiratory gas exchange ratio (R= $\dot{V}CO_2/\dot{V}O_2$) and % $\dot{V}O_2 = \dot{V}O_2/\dot{V}O_{2max}$ were obtained.

During loading, MPF showed a steady decrease, followed by a sudden fall to a base level in both tests. After loading, MPF recovered within 30 seconds in all subjects. The test-retest reliability coefficient of MPF and R at the point of sudden fall in MPF were 0.757 (p=0.0018), and 0.808 (p=0.0004).

These findings suggest that a sudden fall and a base level of MPF indicate local muscle fatigue, and the spectral analysis of trunk muscle surface EMG provides a reliable index of exercise performance in maximal treadmill running. J. Med. Invest. 47 : 29-35, 2000

Key words : *electromyography, muscle fatigue, paravertebral muscle, spectrum analysis, treadmill running*

INTRODUCTION

Since Wasserman *et al*. proposed the anaerobic threshold (24), the metabolic thresholds, e.g. the onset of blood lactate (OBLA) (13), which were determined from the changes of blood and/or gas parameters, have been used to assess physical capacity of individuals and to determine the level of exercise intensity. Although endurance is affected by the central nervous system condition, cardiopulmonary function and other factors, local muscle fatigue is one of the most important factors for endurance. Assessment of guidelines for exercise therefore should not be based on metabolic state alone but also muscle activity.

Received for publication November 29, 1999 ; accepted January 12, 2000.

Address correspondence and reprint requests to Akihiro Nagamachi, M.D., Department of Orthopedic Surgery, Mitoyo General Hospital, 708 Himehama, Toyohama-cho, Mitoyo-gun, Kagawa 769-1695, Japan and Fax : +81-875-52-4936.

Although depletion of energy supply and/or metabolic end-products (i.e. lactate, H^+, P_i, ADP) accumulation are regarded to be the limiting factors of performance, the mechanism of muscle fatigue near exhaustion has not been well elucidated because of the difficulty of continuous sampling of muscle tissue or blood during exercise. Surface EMG (sEMG) can non-invasively demonstrate continuous muscle activity during exercise. The shift of its power spectrum towards lower frequencies as muscle fatigue progresses in sustained static contraction (5, 16, 20, 21) and these spectral changes reflect the metabolic state of the involved muscle (1). Therefore, sEMG spectral analysis may detect muscle fatigue near exhaustion.

There are some reports on myoelectric changes during dynamic exercise (3, 10), however, only a few studies demonstrated the changes in the power spectrum during maximal exercise (23). If a turning point or the lowest limit of mean power frequency (MPF) in maximal exercise can be detected, it will be an index of appropriate intensity of exercise.

Quadriceps femoris, biceps brachii or adductor pollicis muscles are often used to analyze muscle fatigue (8, 18, 23), however, these muscles move vigorously in dynamic exercise and the mechanical noise of myoelectric signals are not negligible. The erector spinae muscle do not move vigorously during treadmill running, and MPF of the erector spinae muscle was reported to decrease in static contraction similar to other muscles (2, 7, 14). Since the erector spinae muscle contains relative high percentages of slow twitch fibers (12), it may be more resistible to fatigue than other muscles (17), and so fatigue of the erector spinae muscle may represent fatigue of other muscles. Therefore, the erector spinae muscle was selected in this study.

This study investigated the relationship between spectral changes of sEMG and exercise intensity determined from respiratory gas analysis during maximal treadmill running, and identified the role of spectral analysis of the elector spinae muscle sEMG as an index of exercise performance in treadmill running.

Table 1. Exercise protocol on treadmill

Stage NO.	Speed (km/h)	Grade (%)	Time (sec)
1	8.0	2.0	120
2	9.0	2.0	120
3	10.0	2.0	60
4	12.0	2.0	60
5	13.8	2.0	60
6	14.4	4.0	60
7	15.0	4.0	60
8	15.6	4.0	60
9	16.2	4.0	60
10	16.8	4.0	60
11	17.4	4.0	60
12	18.0	4.0	60
13	18.6	4.0	60
14	19.2	4.0	60
15	19.8	4.0	60
16	20.4	4.0	60

MATERIALS AND METHODS

Subjects

Thirteen male athletes aged between 19 and 24 years (mean 20.7) participated in this study. Mean body height was 170.2±4.3 cm and mean body weight was 67.5±8.2 kg. All subjects were physically active and trained regularly. Written informed consent was obtained from all subjects prior to participation in this testing session. Subjects were instructed not to consume any food or beverage for at least 2 hours before each testing session.

Exercise protocols

All subjects repeated two consecutive ramp exercise tests on the treadmill over several days. After three minutes rest, the ramp test was started. The protocol of ramp exercise is shown in Table 1. The exercise intensity increments were continued until the subject could no longer maintain running on the treadmill.

sEMG data analysis

Since MPF is a robust parameter and has a greater noise immunity (4), spectral changes were assessed by MPF. Myoelectric signals were recorded with two Ag-AgCl surface electrodes placed over the belly of the erector spinae muscle 2 cm apart and a reference electrode was placed over the spinous process of the first lumbar vertebra. All electrodes were placed after abrasion of the skin surface to reduce the source impedance to less than 3 kΩ. The myoelectric signals were amplified through a low-pass filtered with a 0.5 kHz cutoff frequency, and sampled in 0.5 seconds sequences at a rate of 1 kHz into a computer, then a 1,024-point first Fourier transformation was performed and MPF was calculated every ten seconds (SIGNAL PROCESSOR 1000, NEC Co., Tokyo, Japan).

Gas exchange analysis

Gas exchange measurements were collected continuously using an automated breath-by-breath system (OXYCON-SIGMA, Mijhardt Co., Netherlands) (19). The subject breathed through a face mask into a turbine transducer for the determination of ten seconds ventilation. After conversion of the analog voltage outputs from the ventilation module and the gas analyzers into digital signals, ventilation, O_2 uptake ($\dot{V}O_2$) and CO_2 production ($\dot{V}CO_2$) were calculated and printed on-line every ten seconds using appropriate software on a microcomputer, from which % $\dot{V}O_2$= $\dot{V}O_2$/ $\dot{V}O_{2max}$, anaerobic threshold (AT) and respiratory gas exchange ratio (R= $\dot{V}CO_2$/ $\dot{V}O_2$) were obtained. The gas analyzers were calibrated before each test with room air and a precision-analyzed gas cylinder with 5% CO_2 and 95% N_2 composition, while the turbine transducer was calibrated with a known volume.

Data analyses

The test-retest reliability and reproducibility of MPF, R and % $\dot{V}O_2$ determined from the two incremental exercise tests was assessed using a Pearson-product moment correlation and Wilcoxon signed-rank, respectively. For all statistical analyses, the $P<0.05$ level of significance was used.

RESULTS

All subjects completed two ramp exercises and reached exhaustion. Before loading, MPF and R were 74.2±7.2 Hz, 0.81±0.07 in the first test and 74.7±8.3 Hz, 0.80±0.06 in the second test, respectively. During loading, MPF showed a steady decrease which was followed by a sudden fall to a base level in both tests. Within 30 seconds of quitting loading, MPF recovered to the level before loading in all subjects (Fig.1). At the point of the sudden fall, MPF, R and % $\dot{V}O_2$ were 59.4±12.4 Hz, 0.99±0.06, 74.3±7.4% in the first test and 55.0±11.2 Hz, 0.96±0.06, 74.6±7.3% in the second test, respectively. This sudden fall in MPF was observed after AT at which MPF, R and % $\dot{V}O_2$ were 57.3±12.9 Hz, 0.89±0.10, 65.8±9.2% in the first test and 59.2±11.0 Hz, 0.86±0.06, 61.2±9.9% in the second test. At the beginning of the base level, MPF, R and % $\dot{V}O_2$ were 41.4±9.8 Hz, 1.00±0.04, 78.0±7.7% in the first test and 43.7±6.9 Hz, 1.00±0.10, 78.7±6.7% in the second test, respectively (Table 2 & Fig. 2).

The test-retest reliability coefficient of MPF, R and % $\dot{V}O_2$ at the point of sudden fall were 0.757 ($p=0.0018$), 0.808 ($p=0.0004$) and 0.602 ($p=0.606$), respectively (Fig.3). There was no difference between the mean values of MPF, R and % $\dot{V}O_2$ at the

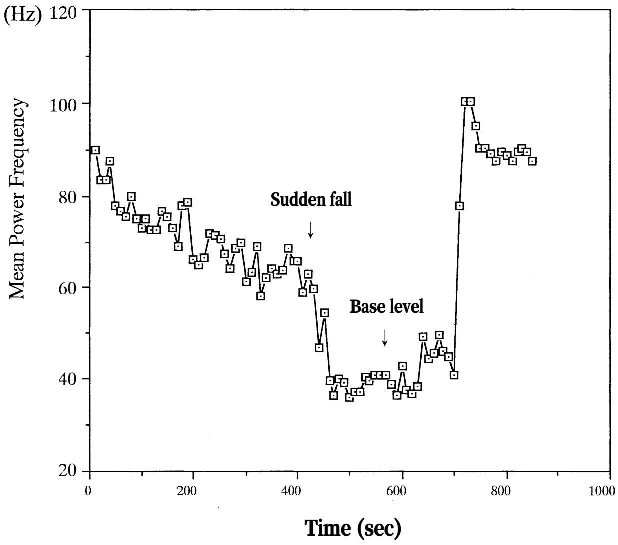

Fig. 1. A typical data set showing the changes in MPF versus exercise duration During loading, MPF showed a steady decrease which was followed by a sudden fall to a base level. The sudden fall was observed at the point of MPF=64.1 Hz, R=0.96 and % $\dot{V}O_2$=81.7%.

Table 2. MPF, R and % $\dot{V}O_2$ at each point

		Before loading	Anaerobic threshold	Sudden fall	Base level	End of loading	Recovery
MPF	First test	74.2±7.2	57.3±12.8	59.4±12.4	41.4±9.8	44.0±11.2	73.4±7.0
(Hz)	Second test	74.7±8.3	59.2±10.9	55.0±11.2	43.7±6.9	44.3±9.7	71.7±6.8
R	First test	0.80±0.07	0.89±0.10	0.99±0.06	1.00±0.04	1.21±0.07	1.22±0.07
	Second test	0.80±0.06	0.86±0.06	0.96±0.06	1.00±0.10	1.21±0.06	1.21±0.08
% $\dot{V}O_2$	First test		65.8±9.2	74.3±7.3	78.0±7.7	95.2±6.9	74.6±15.7
(%)	Second test		61.2±9.9	74.6±7.3	78.7±6.7	93.6±5.7	75.9±15.3

(mean±SD)
MPF : mean power frequency
R : gas exchange ratio (R= $\dot{V}CO_2$/ $\dot{V}O_2$)
% $\dot{V}O_2$: $\dot{V}O_2$/ $\dot{V}O_{2max}$
Recovery : 30 seconds after end of the loading

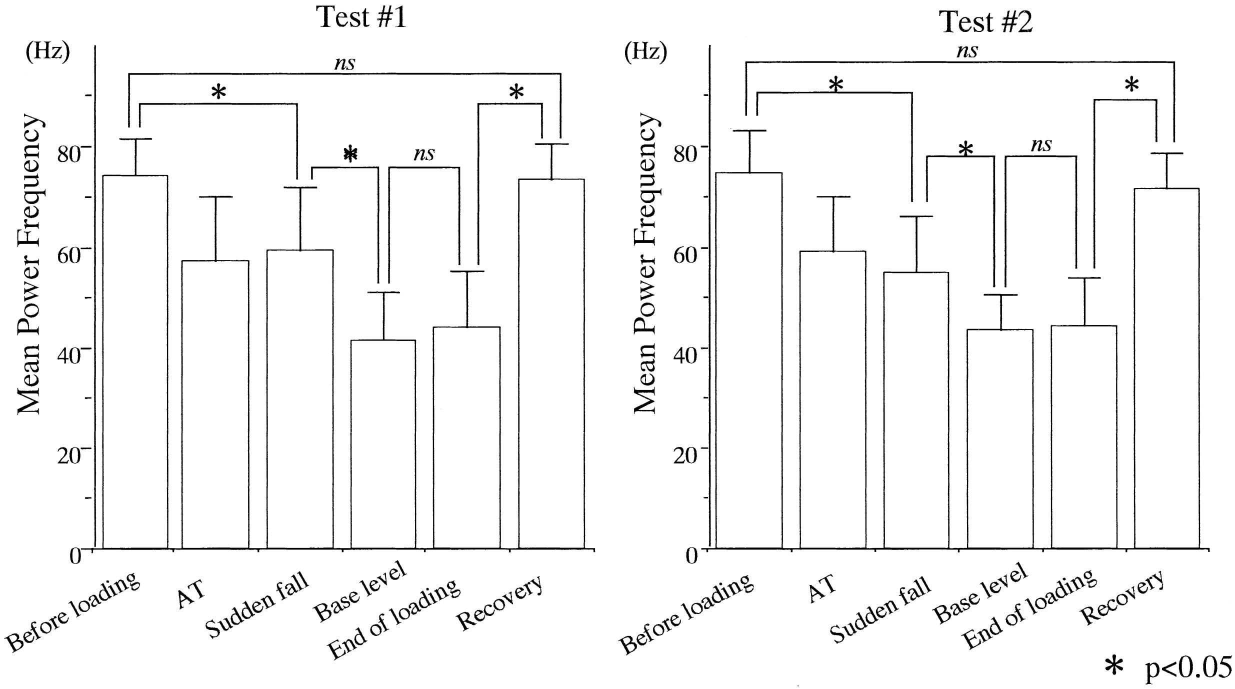

Fig. 2. Mean power frequency at each point

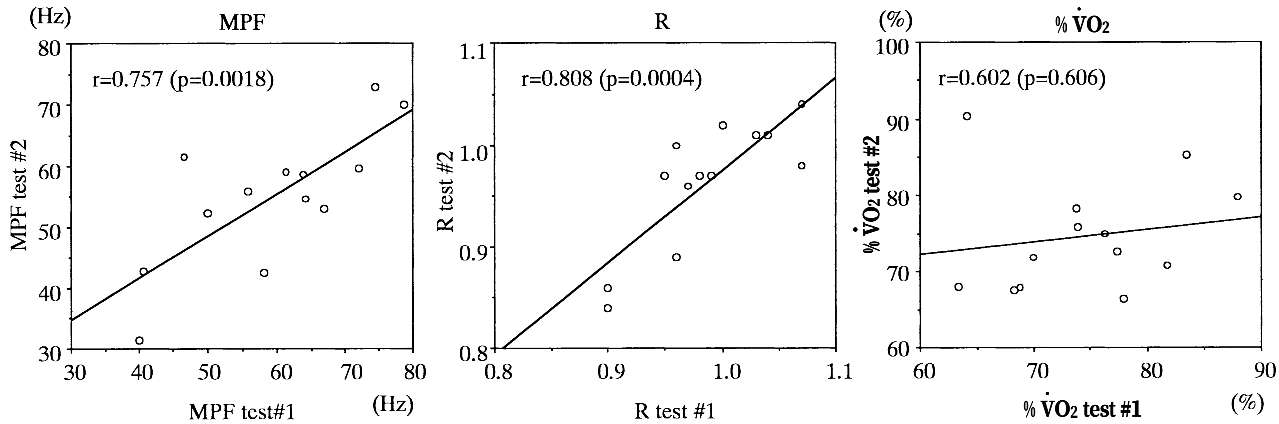

Fig. 3. The test-retest reliability coefficient of MPF, R and % V̇O2 at the point of sudden fall in MPF

point of sudden fall in MPF determined from the two tests.

DISCUSSION

In the present study, MPF of the erector spinae during treadmill running showed a steady decrease beyond AT. After AT, a sudden fall and a base level of MPF were observed. These kinds of steady changes in muscle activity have been commonly reported in previous studies (2, 5, 7, 10, 14), however, abrupt changes of MPF have not previously been reported. In the present study, we confirmed its occurrence twice in all subjects. Few previous studies, to our knowledge, examined the changes in muscle activities during exercises which reached exhaustion. All subjects in the study by Takaishi *et al.* (23) and some subjects in Helal *et al.* (11) showed non-linear changes of EMG of the vastus lateralis during ergometric exercise. Patterns of EMG changes in the previous two studies were different from the present study's findings, although they showed a non-linear pattern. Takaishi *et al*. demonstrated a non-linear increase of integrated EMG and Helal *et al*. demonstrated increased MPF during exercise before fall. The property of the muscles examined may influence those differences.

As generally reported, MPF decreases as muscle fatigue progresses. Although central and peripheral factors are responsible, the main factor contributing to the MPF shift towards lower values may be peripheral, i.e, a slowing of the muscle action potential conduction velocity (4, 15, 16). These changes in myoelectric properties during muscle contraction might be related to the intramuscular pH of involved muscle, however, the mechanisms of such changes during contraction remain a matter of debate. In the state of steady decrease, energy supply for muscle contraction is mainly dependent on aerobic processes, however, muscle and blood lactate accumulation have already occurred because the activity of the glycogenolytic pathway is elevated in the first twitch fibers (13). Thus, before AT, a steady decrease of MPF could be explained by the decrease in intramuscular pH.

After AT, a sudden fall and a base level of MPF were observed and MPF recovered rapidly after quitting loading. The mechanism of these abrupt changes cannot be fully explained by the decrease of intramuscular pH, because it is unlikely that an abrupt increase in intramuscular proton accumulation, which is attributed to the sudden fall of MPF, occurred. Moreover, MPF recovered rapidly to the preloading level despite intramuscular pH possibly remaining at a lower value. Taking these observations into account, intramuscular pH is suggested not to be the major determinant of myoelectric alterations in fatigued muscle.

Similar MPF changes were observed in quadriceps femoris in one of the seven subjects in the preliminary study (fig.4). In the treadmill running, the quadriceps femoris move vigorously and the mechanical noise of myoelectric signals and problems associated with the surface electrodes affect the MPF. Similar phenomena may occur in other muscles.

Muscle fatigue is not defined as the decrease in MPF, but a failure to maintain the required or expected force leading to a reduced performance of a given task (9). As previously described, MPF showed a non-linear change in the present study. In the state of steady decrease of MPF, force output was sufficient, and the decrease may not indicate muscle fatigue but a progressive state of muscle fatigue. The subjects ran and force output might be insufficient after the sudden fall and base level is attained. It was thought that the sudden fall and the base level of MPF indicated local muscle fatigue.

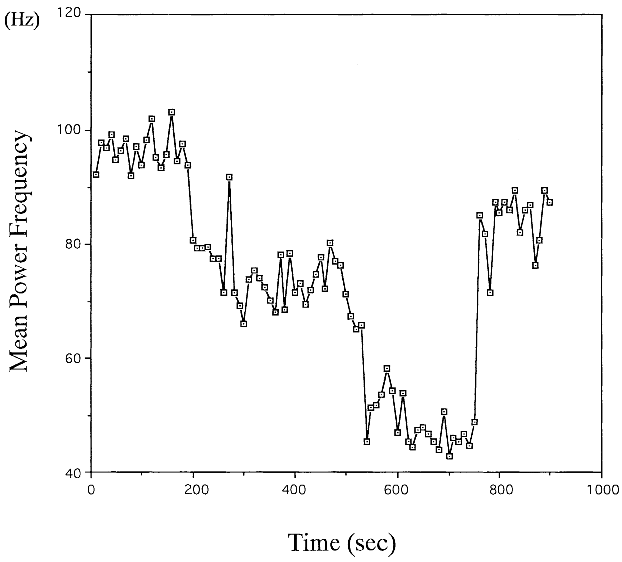

Fig.4. Similar MPF changes were observed in the quadriceps femoris in one of seven subjects.

It was also suggested that local muscle fatigue occurred after AT and before exhaustion.

A sudden fall in MPF was observed at the point near R=0.97 and $\%\dot{V}O_2$=75% after AT. At approximately R=1.00 and $\%\dot{V}O_2$=80%, the base level was observed and continued until the exhaustion. When the base level was observed, the formation of lactate would exceed its removal and lactate and H^+ would continuously accumulate and the high-energy phosphate compound phosphocreatinine would decrease until a level was reached where anaerobic energy production is insufficient to meet the demand and muscle contraction ceases (22). Therefore, the sudden fall and base level in MPF indicate submaximal and peak exercise performance in the treadmill running. These parameters compare favorably with conventional gas exchange detection. Furthermore, sEMG can continuously demonstrate non-invasive real-time muscle activity during exercise. These parameters, therfore, are available to elucidate running protocols.

In the present study, the significant test-retest reliability coefficient of MPF and R at the sudden fall were obtained, however, that of $\%\dot{V}O_2$ was not significant. Gas exchange methods for estimation of $\dot{V}O_2$ greatly depend on ventilatory response. A disadvantage of this method is the possibility that the hyperventilation phase may be partially included in calculation (6) of ten seconds ventilation. After AT, subjects begin to feel dyspnea and hyperventilation to improve discomfort is common. Although the absolute volume of $\dot{V}O_2$ increases by hyperventilation, the relative value of $\dot{V}O_2$ and $\dot{V}CO_2$ may not change. The reasons for the poor reliability of %$\dot{V}O_2$ at the point of a sudden fall may be wide $\dot{V}O_2$ variation which is attributed to this hyperventilation.

CONCLUSION

In conclusion, a sudden fall and a base level of MPF indicate local muscle fatigue. They also suggest that local muscle fatigue occurs after AT and before exhaustion. The spectral analysis of erector spinae muscle sEMG provides a reliable index of exercise performance in maximal treadmill running.

REFERENCES

1. Béliveau L, Helal J-N, Gallard E, Hoecke JV, Atlan G, Bouissou P : EMG spectral shift and ^{31}P-NMR determined intracellular pH in fatigued human biceps brachii muscle. Neurology 41 : 1998-2001, 1991
2. Biedermann H J, Shanks GL, Inglis J : Median frequency estimates of paraspinal muscles : reliability analysis. Electromyogr Clin Neurophysiol 30 : 83-88, 1990
3. Bouissou P, Estrade P Y, Goubel F, Guezennec C Y, Serrurier B : Surface EMG power spectrum and intramuscular pH in vastus lateralis muscle during dynamic exercise. J Appl Physiol 67 : 1245-1249, 1989
4. Castaldo R, Quatro E, Clemente F : A real-time FFT analyser for monitoring muscle fatigue. J Biomed Eng 13 : 465-468, 1991
5. Cooper R G, Stokes M J : Load-induced inflexion of the surface electromyographic signal during isometric fatiguing activity of normal human paraspinal muscle. Electromyogr Clin Neurophysiol 34 : 177-184, 1994
6. Dickstein K, Aarsland T, Svanes H, Barvik S : A respiratory exchange ratio equal to 1 provides a reproducible index of submaximal cardiopulmonary exercise performance. Am J Cardiol 71 : 1367-1369, 1993
7. Dieën JH, Toussaint HM, Thissen C, Van de Ven A : Spectral analysis of erector spinae EMG during intermittent isometric fatiguing exercise. Ergonomics 36 : 407-414, 1993
8. Duchateau J, Hainaut K : Effects of immobilization on electromyogram power spectrum changes during fatigue. Eur J Appl Physiol 63 : 458-462, 1991
9. Edwards RHT : Human muscle function and fatigue. In : Porter R, Whelan J, eds. Human muscle fatigue physiological mechanisms. Pitman, London, pp. 1-8, 1981
10. Hagberg M : Muscular endurance and surface electromyogram in isometric and dynamic exercise. J Appl Physiol 51 : 1-7, 1981
11. Helal JN, Guezennec CY, Goubel F : The aerobic-anaerobic transition : re-examination of the threshold concept including an electromyographic approach. Eur J Appl Physiol 56 : 643-649, 1987
12. Johnson MA, Polgar J, Weightman D, Appleton D : Data on the distribution of fibre types in thirty-six human muscles. An autopsy study. J Neur Sci 18 : 111-129, 1973
13. Karlsson J, Holmgren A, Linnarson D, Åström H : OBLA exercise stress testing in health and disease. In : Lollgen H, Mellorwicz H, eds. Progression Ergometry. Springer-Verlag Co, Berlin, pp. 67-91, 1984
14. Kondraske GV, Deivanayagam S, Carmichael T, Mayer T G, Mooney V : Myoelectric spectral analysis and strategies for quantifying trunk muscular fatigue. Arch Phys Med Rehabil 68 : 103-110, 1987
15. Kranz H, Williams AM, Cassell J, Caddy DJ, Silberstein RB : Factors determining the frequency content of the electromyogram. J Appl Physiol 55 : 392-399, 1983
16. Lindström L, Magnusson R, Petersen I : Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. Electromyography : 341-356, 1970
17. Linssen WHJP, Stegeman DF, Joosten EMG, Merks HJH, Ter Laak HJ, Binkhorst RA, Notermans SLH : Force and fatigue in human type I muscle fibres. A surface EMG study in patients with congenital myopathy and type I fibre predominance. Brain 114 : 2123-2132, 1991
18. Linssen WHJP, Stegeman DF, Joosten EMG : Variability and interrelationships of surface EMG parameters during local muscle fatigue. Muscle Nerve 16 : 849-856, 1993
19. Merilainen PT : Sensors for oxygen analysis : Paramagnetic, electrochemical, polarographic, and zirconium oxide technologies. Biomed Instr Tech : 462-466, 1989
20. Moritani T, Muro M, Nagata A : Intramascular and surface electromyogram changes during

muscle fatigue. J Appl Physiol 60 : 1179-1185, 1986
21. Roy SH, Luca CJ, Snyder-mackler L, Emley MS, Crenshaw RL, Lyons JP : Fatigue, recovery, and low back pain in varsity rowers. Med Sci Sport Exer 22 : 463-469, 1990
22. Sahlin K : Metabolic Factors in Fatigue. Sports Med 13 : 99-107, 1992
23. Takaishi T, Ono T, Yasuda Y : Relationship between muscle fatigue and oxygen uptake during cycle ergometer exercise with different ramp slope increments. Eur J Appl Physiol 65 : 335-339, 1992
24. Wasserman K, Whipp BJ, Koyal SN, Beaver WL : Anaerobic threshold and respiratory gas exchange during exercise. J Appl Physiol 35 : 236-243, 1973