Journal of Human Kinetics volume 11, 2004, 3-14

Relationships Between Electromyographic Characteristics, Mechanical Work Efficiency and Body Temperatures During Running Exercise Test in Men

by
Ilona Pokora[1]

The purpose of this study was to compare the changes in mechanical work efficiency, body temperatures (mean skin, local skin and mean body temperatures) and bioelectrical muscle activity of the vastus lateralis muscle in untrained male subjects (n=8) performing a dynamic exercise test on a treadmill. The relationships between EMG characteristics and blood lactate concentration were also investigated.
The subjects ran at 1% grade with progressive speed of running until volitional exhaustion. During exercise, external work (determined by Snellen's formula), energy expenditure (determined by measuring oxygen uptake and respiratory exchange ratio), mechanical work efficiency (E%), surface electromyography (EMG), aural, mean body, mean skin and local skin temperatures were determined. EMG was sampled at 1000 Hz and stored in 5/60 s intervals. Mean power frequency (MPF) and average amplitude of EMG (AEMG) were analyzed from row EMG.
The amplitude of EMG signals during running correlated negatively with E% (r=-0,548) and positively with blood LA concentration (r=0,442), while MPF correlated positively with mean skin (r=0,358) and local skin (r=0,446) temperatures. The relationships between MPF from one side and mean body temperature and E% from the other were not significant.
These findings suggest that: 1) the amplitude of EMG signals is a good indicator of muscle activity 2) the frequency of EMG power spectrum is dependent on changes in skin temperature but it does not well reflect changes in motor unit recruitment during dynamic exercise.
Key words: *electromyography, temperature, mechanical work efficiency, exercise, running.*

[1] Department of Physiology, Academy of Physical Education, Katowice, Poland

Introduction

During exercise working muscles are the largest consumers of energy. The metabolic needs of working muscle increase as a function of work and depend on exercise intensity. During isometric contraction all metabolic energy is converted into heat (W=0) whereas during dynamic exercise part of this energy is converted into mechanical work (required for movement, (W>0). Amount of energy converted to mechanical work or to heat depends on both metabolic energy production and mechanical work efficiency. Mechanical work efficiency (E%) has been defined as the ratio of external mechanical work to corresponding metabolic rate. Many factors appear to play a role in determining mechanical work efficiency. Among them are: age, gender, air resistance, body temperature, type of contractions, velocity of contractions, muscular fatigue, mobilization and availability of energy substrates, level of performance, and type of recruited fibres (Costill and Fox 1969, Rowell et al. 1969, Bransford and Howley 1977, Pokora et al. 1999, Pokora 2000, Kyrölainen et al. 2001, Pokora and Grucza 2003).

A decrease in mechanical work efficiency was observed in skeletal muscle with both increased speed and work rate, because during exercise more energetically inefficient fast-twitch fibres were selectively recruited as the speed of movement or/and intensity of work increase (Suzuki 1979). Muscle activity can be monitored by electromyography (EMG). Surface electromyography recordings provide a safe, easy and non-invasive method allowing objective qualification of the activity and fatigue of working muscles (Komi and Tesch 1979, Moritani et al. 1982) whereas estimation of mechanical work efficiency (from whole-body VO_2) approximates very well the efficiency of working limb muscles (Poole 1992). It has been shown that muscle activity changes during fatiguing exercise (Häge 1992) and after heating or cooling of muscles (Petrofsky 1979). However, little is known about to the relationships between frequency and amplitude of electromyographic signals, mechanical work efficiency and body temperature variables during exercise with progressive speed of running. Changes in the pattern of recruited muscle fibres according to the increase in speed of running may be associated with same changes in EMG. Because the EMG power spectrum and amplitude of the EMG signals has been shown to be sensitive to fibre type content, as well as activity and temperature of working muscles (Petrofsky and Lind 1980) it was suspected that analysis presumed of muscles EMG would exhibit differences in spectrum statistics during exercise.

The main aim of this experiment was to investigate the relationships between mechanical work efficiency, body, and skin temperatures and amplitude as well as frequency of EMG signals of exercising vastus lateralis muscle during treadmill running. An attempt was made to find out - whether the analysis of amplitude and frequency of EMG signals during running could be used as a good indicator of changes in the type of recruited muscle fibres and whether changes in these signals depend on changes in mechanical work efficiency or body and local temperature.

Since the relationship between EMG and the above mentioned varaibles during graded exercise is not fully understood, three questions were posed:

1. Are changes in speed of running accomplished with the same changes in mechanical work efficiency ?
2. What changes in amplitude and frequency of EMG occur, do to changes in mechanical work efficiency during running ?
3. Are there any relationships among muscular activity, mechanical work efficiency and considered physiological and biochemical variables ?

Material and method

Subjects:

Eight healthy male subjects participated in this study (subject characteristics are presented in Table 1). None of the subjects were professional athletes. The experimental protocol was approved by the Bioethical Committee of the Academy of Physical Education in Katowice.

Table 1. General characteristics of tested subjects.

Characteristic (n=8)	Values are given as means ± SD
Age (years)	21,43±1,38
Height (cm)	177,9±5,64
Body mass (kg)	75,7±4,96
VO_2max (ml · kg^{-1} · min^{-1})	51,7±2,3
W_{max} (W)	311±18,04
HR_{max} (beats · min^{-1})	199±5,11

Exercise test

The subjects were asked to retrain from any strenuous physical activity for 48h before starting the incremental running test on a motorized treadmill (Jaeger, Germany) at 1% grade. The test began with a warm up at 4 km · h^{-1} (for 6 min) then the running speed was increased by 1.5 km · h^{-1} every 3 min until volitional exhaustion. The subjects ran for 3 min at a constant speed with 1min rest between each velocity, while blood samples were taken for analysis.

Measurements

During exercise, oxygen uptake (VO_2), minute ventilation (V_E), respiratory exchange ratio (RER) (gas analyzer OXYCON Jaeger, Germany), aural temperature (Tau), mean (Tsk) and local skin (TskL) temperatures as well as blood lactate concentration and bioelectrical muscle activity (EMG) were continuously measured. Based on VO_2 and RER values the energy cost of running was calculated calorimetrically for each speed of running. Additionally total external work (W_{tot}) was calculated according to Snellen's formula (1960) for each 3 min period of running. The aural temperature (T_{au}) was recorded with an Ellab (type TE3, Denmark) thermometer. Skin temperatures on the chest, arm and thigh were measured using a digital thermometer (Radiometer, type Cannon TB77B, Denmark). Mean skin temperature T_{sk} and mean body temperature (T_b) were calculated according to Burton's formula (1935) and the Stolwijk and Hardy's equation (1966), respectively. Changes in local skin temperature (T_{skUD}) above vastus lateralis muscles were continuously measured using skin thermistors (a digital thermometer TTK311R, Temed, Poland) placed on the skin above VL, medially to the (EMG) electrodes. The accuracy of all temperature measurements was 0.1 ^{o}C. All experiments were conducted under thermoneutral conditions (air temperature 23 ^{o}C, with relative humidity at 48%).

For each 3 min period of work the efficiency of mechanical work (E%) was calculated as the ratio of external work accomplished to energy expended. Each exercise intensity was separated by a rest period of 1min. During each rest interval, blood samples were taken to determine changes in blood lactate (LA) concentration (Boehringer Mannheim, Germany).

EMG recording and analysis

During the exercise test the surface electromyogram (sEMG) was recorded continuously (using 5s/60s measurement mode) from vastus lateralis muscle (biagricular knee extensor) of left and right leg. Before placement of the electrode, the skin over the appropriate muscles was shaved and cleaned with acetone and alcohol. Then, bipolar silver/silver chloride surface electrodes were positioned over the muscles. Effective stabilization of the electrodes was achieved by adhesive sport tape.

The sEMG signal was sampled at 1000 Hz, and stored in 5s/60s intervals. For measuring EMG muscle activity the Mega ME3000P (Kuopio Finland) system was used comprising preamplifier cables, two channel ME 3000P data acquisition units and a microprocessor. The measurements were made simultaneously from the right and left vasti lateralis (VL) muscle. After the test mean power frequency (MPF) and average amplitude of EMG (AEMG) signals at each load (speed of running) were calculated. Fatigue indices, MPF and AEMG were analysed form row EMG data analysis, using the Mega ME3000P Fast Fourrier transform spectrum analysis program (from each level 520 samples $\cdot$ s^{-1} were analyzed).

Statistics

Multiple regression analysis was used to examine the relationships among determined variables. Differences in mechanical work efficiency, physiological, biochemical variables as well as EMG characteristics for each speed of running were assessed using analysis of variance for repeated measures (ANOVA). For significant F-ratio the Newman-Keuls post-hoc analysis was used to reveal differences between particular variables. For all statistical analysis the 0.05 level of significance was accepted.

Results

In the present study E% decreased from 36% at the beginning of exercise until 26% at the end of the test (Δ E%~ 10%) (Fig. 1a). Figure 1a shows the changes in mechanical work efficiency in relation to changes in total external work performed during the running test. The decrease of E% was significantly faster at the beginning of exercise when compared to submaximal and maximal speed of running.

A significant negative correlation between mechanical work efficiency and amplitude of EMG signals (AEMG) was found (R=-0.548) (Fig. 2a). The highest amplitude of EMG signals was detected at maximal speed of running and lowest mechanical work efficiency. The changes in amplitude of EMG signal were positively correlated with changes in blood LA concentration (R=0.442) (Fig. 2b) and with external work performed during the exercise (R=0.354). Blood lactate concentrations increased during exercise with the rise in power output (Fig. 1b).

Mean power frequency (MPF) increased during exercise until submaximal work loads, whereas at maximal speed of running a decrease in MPF was observed when compared to submaximal work loads. The MPF was not correlated with changes in E%, however significant correlations of MPF with local (T_{skUD}) and mean skin (T_{sk}) temperatures were determined (Fig 3a and 3b).

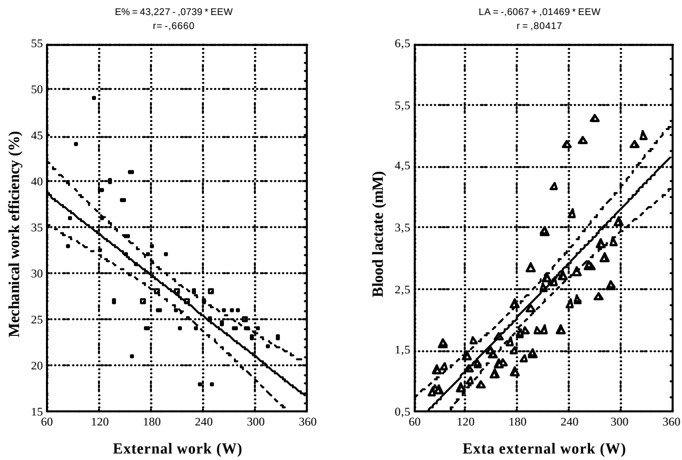

Fig. 1. Relationships between extra external work (picture left) and mechanical work efficiency (%) as well as blood lactate concentration (picture right) during exercise test at a gradually increased speed of running

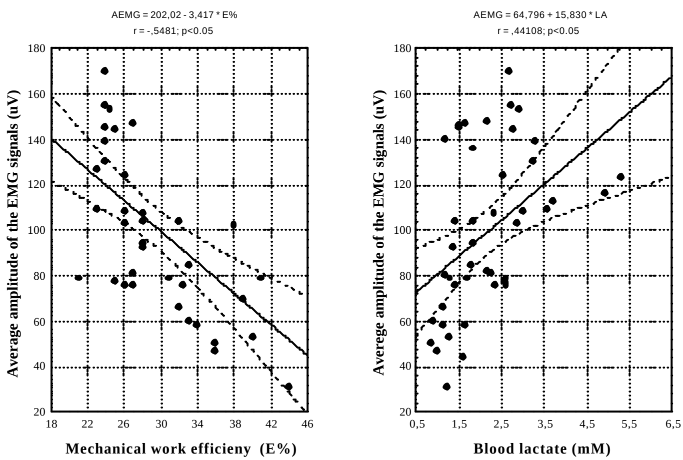

Fig. 2. Relationships between changes in amplitude of EMG signals and mechanical work efficiency and blood lactate concentration during the running exercise test.

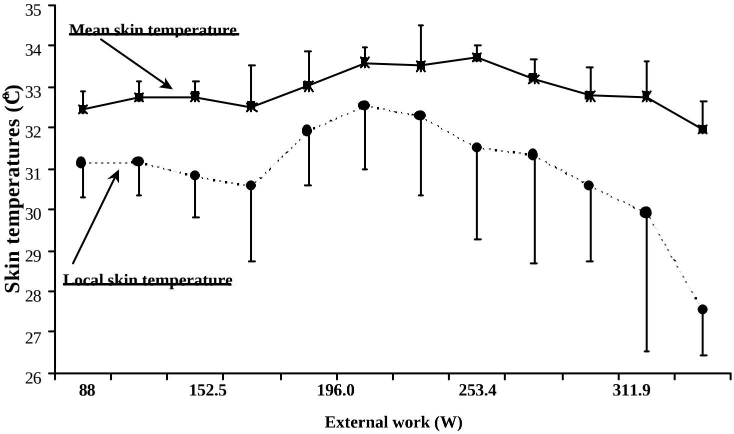

Fig. 3. Relationships between mean power frequency and EMG signals as well as body temperatures (mean and local skin temperature) during the running exercise test.

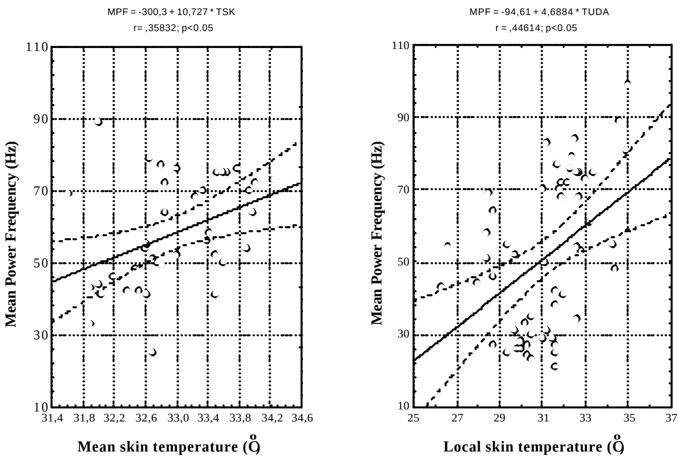

Fig. 4. Time course of mean and local skin temperatures during the exercise test performed in thermoneutral environment at a gradually increased speed of running.

Changes in local skin temperature during exercise had a biphasic character (similar to changes in MPF). At the beginning of exercise a systematic increase in T_{sk} until submaximal speed of running (12km/h) was observed, whereas a significant decrease in T_{sk} and T_{skUD} was reported at maximal speed. The highest local skin temperatures were detected at speeds of 8 and 10 km·h^{-1} (Fig. 4).

Discussion

In this study the changes of frequency and amplitude of EMG signals during the running exercise protocol in relation to changes in metabolic work efficiency and to body and skin temperatures were investigated. The obtained results showed that the pattern of amplitude of EMG signals was correlated with changes in mechanical work efficiency and blood lactate concentration, whereas frequency of EMG signals was not correlated with E% but correlated significantly with skin temperatures. The changes in amplitude and frequency of EMG were similar in right and left VL muscles, (the differences in EMG activity between R and L VL muscles were < 20%).

The efficiency of muscular contraction reflects the product of phoshorylation efficiency with which chemical energy from metabolic substrates is converted to ATP, and the contraction-coupling efficiency with which the energy released during ATP hydrolysis is converted to mechanical energy through muscle shortening (Whipp and Wasserman 1969). In this study mechanical work efficiency showed a substantial decrease during running from 36% at the beginning of the exercise until 26% at maximal speed of running. These results are in agreement with an earlier study of Duffield and MacDonald (1923) who demonstrated that at constant load, efficiency of muscular work decreases as the speed of movement increases but are in conflict with data reported by Cavagna et al. (1977), who observed an increase of mechanical efficiency during incremental running. Those inconsistencies may be a result of differences in experimental methodologies employed, including the selection of appropriate baseline corrections to the efficiency calculation, use of postexercise VO_2 in estimation of caloric cost of exercise, and the time at which VO_2 was measured. In this study a decrease in E% increased the caloric equivalent of VO_2 with an increment of work, a result of contractile properties of muscle, and recruitment of less economical muscle fibres. Slow-twitch muscles (recruited at the beginning of exercise) demonstrated greater efficiency than fast-twitch muscles, selectively engaged at submaximal and maximal speed of contraction (Gaesser and Brooks 1975). It is known that slow fibres, which are less powerful, have a higher efficiency than the faster ones of the same animal (Coyle et al. 1992, Horwitz et al. 1994). The empirical Hill relation may show another explanation of these results, which predict that increase in power (produced by a straighter force velocity curve) would be accompanied by decreases in efficiency. During fatigue motor units originally chosen for the task become unable to sustain the original mechanical power output. If motor units used first, were those which were capable of performing the task with greatest efficiency, compared to other units, used at the end of exercise, better suited for higher power tasks but with lower efficiency. The decrease in E% was faster within the range of low speeds of running and slower at the end of exercise. If the velocity of contraction is low, the rate of ATP hydrolysis is greater than that required for muscle action and therefore most of this energy is released as heat. This was reflected by a faster decrease in mechanical efficiency within the range of slow speed of running.

A decrease of mechanical work efficiency was asocciated with an increase of amplitude (AEMG) of EMG signals and was not correlated with frequency of EMG characteristics (MPF). The frequency component of EMG shifted to higher values. It is known that frequency of EMG depends on the duration of motor units action potentials, the number of active motor units and frequency of motor unit discharge (Lindsröm et al. 1970). Systematic increase in MPF observed in this study may be the result of recruitment of additional muscle fibres according to the increase in speed of running as well as an increase in the conduction velocity (associated with changes in muscle temperature). Both these variables are known to increase mean power frequency of EMG signals, whereas development of muscular fatigue decreases MPF. Petrofsky (1979), who collected EMG from VL muscle during a dynamic exercise test observed that EMG frequency signal increases with a rise in muscle temperature. In the present study a significant relationship was observed between MPF and mean and local skin temperatures, but no correlation with external work was found. Changes in median power frequency during the running exercise test had a biphasic character, similar to changes in skin temperature. It is presumed that at lower workloads the effect of the increase in skin temperature might increase MPF faster than fatigue could decrease it. The net effect was an increase in MPF. At maximal speeds of running, MPF and skin temperatures decreased. The decreased MPF was presumably due to fatigue, because fatigue might decrease MPF faster than muscle temperature could increase it. The net effect was a decrease in MPF. This may limit the advisability of using MPF for detection of muscle fatigue during dynamic activity and it may also explain a lack of correlation between MPF and changes in mechanical work efficiency observed in this experiment. In this study the majority of EMG power occurred at frequency range of 120-144 Hz and at skin temperature of 34^{o}C. Shifting MPF to lower frequencies (as the effect of fatigue) was detected only for maximal speed of running.

Amplitude of EMG signals increased during exercise with a decrease in mechanical work efficiency and increase in running velocity. This result was probably caused by the change in motor unit recruitment pattern during exercise. Mero et al. (1986) suggested that during incremental exercise a relative increase in amplitude of EMG signal occurred with an increase in running velocity because more fast twitch, fatigable motor units are selectively recruited. In the present study increased muscle recruitment was present because the initial EMG activity was significantly lower at the beginning of exercise and increased during exercise, according to an increase in speed of running and decrease of work efficiency. Because fast- twitch motor units are generally larger than slow twitch fibres and, therefore their contribution to the total activity of muscle was proportionally higher at faster speeds of running. Fast twitch motor units have been shown as having significantly higher spectrum amplitude than slow twitch motor units. The recruitment of FT motor units was associated with extensive lactate production and its accumulation in the blood. In this study the newly recruited motor units increased production of ATP through anaerobic pathway and it was associated with an increase in blood lactate concentration, EMG amplitude and development of muscular fatigue.

Conclusions

The results of the present study showed that:

1. The sEMG frequency spectrum presented a complex waveform, being influenced not only by fatigue, but even to a larger extent, by skin temperature.
2. Amplitude of sEMG increased during exercise due to the development of fatigue and acidity of working muscles and decrease in mechanical work efficiency.

References

Bransford D., Howley E. (1977) Oxygen cost of running in trained and untrained men and women. Med.Sci.Sports Exerc. 9: 41-44

Burton A. (1935) Human calorimetry, the average temperature of the tissue of the body. J.Nutr.8: 261-280

Cavagna GA., Kaneko M. (1977) Mechanical work and efficiency in level walking and running. J.Physiol (Lond) 268: 467-481

Costill D., Fox E. (1969) Energetics of marathon running. Med.Sci.Sports Exerc. 1: 81-86.

Coyle E., Sidossis L, Horowitz J., Beltz J. (1992) Cycling efficiency is related to the percentage of type I muscle fibres. Med.Sci.Sports Exerc. 24; 782-788

Duffield F., MacDonald J. (1923) Relationship between speed and efficiency. J.Physiol., London 58, Proc. xiii.

Ferguson RA., Ball D., Sargent AJ. (2002) Effect of muscle temperature on rate of oxygen uptake during exercise in humans at different contractions frequencies. J.Exp.Biol. 205: 981-987.

Gaesser Brooks (1975) Muscular efficiency during steady-rate exercise: effects of speed and work rate. J.Appl.Physiol 38(6): 1132-1139.

Hägg GM. (1992) Interpretation of EMG spectral alterations and alt eration indexes at sustained contraction. J.Appl.Physiol. 73: 1211-1217.

Helal JN., Guezennec C., Gaubel F. (1987) The aerobic-anaerobic transmission re-examination of the threshold concept including an electromyographic approach. Eur.J.Appl.Physiol. 56: 643-649.

Komi PV. Tesch P. (1979) EMG frequency spectrum, muscle structure and fatigue during dynamic contractions in men. Eur. J. Appl. Physiol. 42: 45-50.

Kyrolainen H., Komi PV. Belli A. (1995) Mechanical efficiency in athletes during running. Scand.J.Med.Sci.Sports. 5: 200-208

Lindström L., Kadefors R., Peterson I. (1977) An electromyography index of localized muscle fatigue. J. Appl.Physiol.43: 750-754.

Moritani T., Nagata A., Muo M. (1982) Electromyographic manifestations of muscular fatigue. Med.Sci Sports Exerc. 14: 198-202.

Mero A., Komi P. (1986) Force, EMG, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speed in sprinters. Eur.J.Appl.Physiol. 55: 553-561.

Petrofsky JS (1979) Frequency and amplitude analysis of the EMG during exercise on the bicycle ergometer. Eur. J.Appl. Physiol. 41: 1-15.

Petrofsky JS., Lind AP. (1980) The influence of temperature on the amplitude and frequency components of the EMG during brief and sustained isometric contractions. Eur. J.Appl.Physiol 44: 189-200.

Pokora I., Grucza R., Kaciuba-Uscilko H. (1999) Influence of a low-carbohydrate diet on thermoregulatory responses to prolonged exercise in men. J.Therm.Biol. 24: 471-475

Pokora I. (2000) Changes in mechanical work efficiency during graded exercise tests performed on a bicycle ergometer and a treadmill in relation to development of fatigue. Med.Sportiva Polonica vol 4/1: 97-102

Pokora I., Grucza R. (2003) Influence of a low-carbohydrate diet in thermoregulatory responses to exercise in women during follicular and luteal phase of the menstrual cycle. Biology of Sport 20/4; 343-362.

Poole D., Gaesser GA., Hogan M., Knight D., Wanger P. (1992) Pulmonary and leg VO_2 during submaximal exercise implications for muscular efficiency. J.Appl.Physiol. 72: 805-810.

Rowell L., Brengelman G., Murnayja K., Kroning K., Kusumi F. (1969) Human metabolic response to hyperthermia during mild to maximal exercise. J.Appl.Physiol. 26: 395-402.

Snellen JW. (1960) External work in level and grade walking on a motor-driven treadmill. J.Appl.Physiol. 15 (5): 759-763.

Stolwijk J., Houdas J. (1966) Calorimetric studies of responses of man to thermal transients. J.Appl.Physiol. 21: 967-977

Suzuki Y. (1979) Mechanical efficiency of fast and slow-twitch muscle fibres in man during cycling. J. Appl.Physiol. 47: 263-267.

Whipp BJ., Wasserman K. (1969) Efficiency of muscular work. J.Appl.Physiol.26: 644-648.