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The relationship between anaerobic threshold and electromyographic fatigue threshold in college women

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Summary. The purpose of this study was to investigate the relationship between anaerobic threshold (Th_{an}) and muscle fatigue threshold (EMG_{FT}) as estimated from electromyographic (EMG) data taken from the quadriceps muscles (vastus lateralis) during exercise on a cycle ergometer. The subjects in this study were 20 female college students, including highly trained endurance athletes and untrained sedentary individuals, whose fitness levels derived from their maximal oxygen consumption ranged from 24.9 to 62.2 $ml \cdot kg^{-1} \cdot min^{-1}$. The rate of increase in integrated EMG (iEMG) activity as a function of time (iEMG slope) was calculated at each of four constant power outputs (350, 300, 250, 200 W), sufficiently high to bring about muscle fatigue. The iEMG slopes so obtained were plotted against the exercise intensities imposed, resulting in linear plots which were extrapolated to zero slope to give an intercept on the power axis which was in turn interpreted as the highest exercise intensity sustainable without electromyographic evidence of neuromuscular fatigue (EMG_{FT}). The Th_{an} was estimated from gas exchange parameters during an incremental exercise test on the same cycle ergometer. The mean results indicated that oxygen uptake ($\dot{V}O_2$) at Th_{an} was 1.39 $l \cdot min^{-1}$, SD 0.44 and $\dot{V}O_2$ at EMG_{FT} was 1.33 $l \cdot min^{-1}$, SD 0.57. There was no significant difference between these mean values ($P > 0.05$) and there was a highly significant correlation between $\dot{V}O_2$ at Th_{an} and $\dot{V}O_2$ at EMG_{FT} ($r = 0.823$, $P < 0.01$). These data supported the concept of Th_{an} on the basis that Th_{an} was associated with the highest exercise intensity that could be sustained without evidence of neuromuscular fatigue and thus suggested that EMG_{FT} may provide an attractive alternative to the measurement of Th_{an}.

Key words: Anaerobic threshold – Fatigue threshold – Physical working capacity – Integrated electromyogram – Muscle fatigue

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Introduction

The transition from aerobic to anaerobic metabolism has been a subject for special focus in human experiments during the last few years. The level of exercise just below that at which metabolic acidosis occurs has been called the anaerobic threshold (Th_{an}) (Wasserman et al. 1973). This concept has important implications in the exercise sciences and in occupational, preventive and rehabilitative medicine (Wasserman and Whipp 1975; Davis et al. 1979; Weber et al. 1982; Tanaka and Matsuura 1984; Yoshida et al. 1987; Wasserman et al. 1990). The physiological requirements for performing exercise above Th_{an} are considerably more demanding than for lower intensities. Lactic acidosis (anaerobic) threshold occurs at a metabolic rate that is specific to the individual and is usually caused by an inadequate oxygen supply (Beaver et al. 1986; Katz and Sahlin 1988; Wasserman et al. 1990). Thus, the Th_{an} can be considered to be an important assessment of the ability of the cardiovascular system to supply oxygen at a rate adequate to prevent muscle anaerobiosis during exercise (Wasserman et al. 1990).

In a series of electromyographic (EMG) studies, Moritani (1980) has demonstrated that an abrupt increase in integrated electromyogram (iEMG), representing changes in motor unit (MU) recruitment and/or MU firing frequency during incremental exercise, correlated significantly ($r = 0.97$, $n = 36$) with oxygen consumption ($\dot{V}O_2$) at Th_{an}. Two later studies (Nagata et al. 1981; Viitasalo et al. 1985) have confirmed this finding. deVries et al. (1982, 1987) have employed the iEMG method for the estimation of physical working capacity as an end point defined by the onset of muscle fatigue (PWC_{FT}). Along with the use of the critical power (CP) concept as extended to total body effort (Moritani et al. 1981), deVries et al. (1982, 1987) have demonstrated significant correlations among PWC_{FT}, Th_{an}, CP and onset of blood lactate accumulation (OBLA).

While these iEMG and CP methods have proved very useful, they unfortunately require the subject to perform until exhaustion occurs, which in turn may be limited by psychological factors. It is important to develop a method for a population with little motivation which is unaffected by psychological factors. Therefore the present study involved healthy young women of mixed training status in an effort (1) to validate the iEMG estimation of fatigue threshold (EMG_{FT}) based upon EMG fatigue curves and several constant maximal 1-min exercise periods and (2) to determine the relationship between Th_{an} and EMG_{FT}, i.e. the highest exercise intensity that can be sustained without evidence of neuromuscular fatigue.

Methods

Subjects. The subjects who volunteered for this study were 20 female college students. They were healthy normal individuals whose age ranged from 18 to 23 years with a mean age of 21 years, SD 6.1. The subjects' mean height and body mass were 158.3 cm, SD 3.5 and 50.9 kg, SD 4.3, respectively. Their fitness levels ranged from those of highly trained athletes to those of untrained sedentary individuals. Eleven subjects were recruited from a university track and field team.

EMG instrumentation and procedure. The EMG instrumentation used in this study has been fully described elsewhere (Moritani et al. 1986). Briefly, the myo-electric signal was amplified (Medelec AA6MKIII), band-pass filtered (8–800 Hz), digitized and stored on a floppy disk in a desk-top computer (Hewlett-Packard Model HP9816A). Ten consecutive 6-s iEMG signals were measured for each exercise period (see below). Myo-electric waveforms were monitored by an oscilloscope (DSS-5020A, Kikusui, Tokyo) to assure absence of artefact and clipping of the signal due to exceeding the dynamic range of the amplifier.

Surface electrodes (10 mm Ag/Ag Cl Vitrode, Nihonkoden, Kyoto) in a bipolar lead system were applied, with the active electrodes (2 cm interelectrode distance) on the lateral portion of the dominant quadriceps femoris muscle and the reference electrode over the iliac crest. Interelectrode impedance was held below 5,000 Ω in all cases by abrading the skin. As a result of finding a deep muscle temperature effect, Petrofsky (1979) has suggested that a small decrease (4%) in the root mean square value of EMG amplitude may occur when a muscle temperature increases from 34 to 39° C. However, Asmussen and Boje (1945) have shown that during exercise periods of less than 5 min the increase in muscle temperature was less than 2° C. As described previously, since maximal exercise periods of 1 min were used in this study, it was considered that the muscle temperature increase was probably 1° C or less (Asmussen and Boje 1945; Saltin and Hermansen 1966) and thus any error due to temperature would have been negligible compared to the large changes observed in iEMG.

The subcutaneous fat thickness could have been another source of error in the EMG recording. The average percentage fat of the subjects who participated in this study was, however, relatively low (14.9%, SD 2.7). Furthermore, even if this test were to be used in determining the EMG_{FT} of obese people, the slope of the line which shows the EMG voltage-time relationship should still be directly proportional to the intensity of exercise and the rate of muscle fatigue.

Protocol for EMG_{FT} determination. An initial laboratory session was used to familiarize the subjects with the equipment and experimental procedures. The cycle ergometer used in this study was electrically braked and provided an exercise intensity which was independent of pedalling frequency. A 5-min warm-up at 50 W was completed prior to the exercise tests. The power loadings used were usually 350, 300, 250 and 200 W. In some cases, the exercise intensities were changed according to the fitness levels of the subjects. The sequence for administering the power loadings was randomized. The exercise periods were a maximum of 1 min. All testing was accomplished within one visit to the laboratory, but a rest period was provided between tests for not less than 15 min for heart rate to return to within 5 beats·min^{-1} of resting values. Since the exercise periods were short, there was no reason to suspect any systematic effect of fatigue from one period to another (Astrand et al. 1960).

Apparatus and protocol for maximal oxygen consumption and Th_{an}. Our methods and procedures for determining gas exchange parameters on-line have been fully described in our previous communication (Moritani et al. 1987). When the subjects arrived for testing, electrodes were placed in the CM_5 lead position for electrocardiogram monitoring during the respiratory gas collection. The same cycle ergometer was used. At the end of a 2-min warm-up period (30 W), the respiratory gas collection was begun. During the maximal oxygen consumption ($\dot{V}O_{2\,max}$) test, the exercise intensity was increased by 30 W every minute until the limit of the subject's tolerance was reached. Throughout the tests, the subjects breathed through a low-resistance valve. The expired gas passed through a pneumotachograph (no. 2 S/H S353 Fleisch, Validyne,

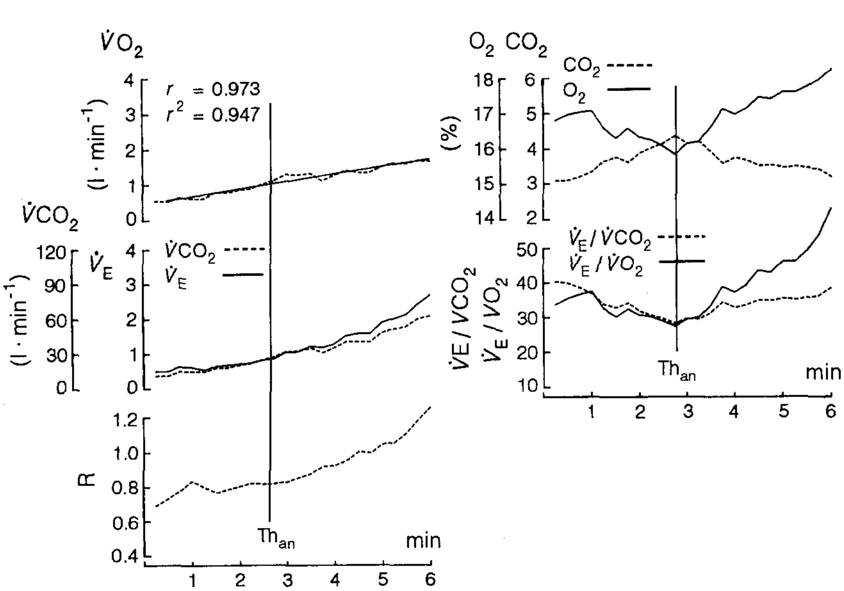

Fig. 1. A typical set of computer outputs for determination of anaerobic threshold (*Th_{an}, vertical line*) and the associated changes in the respiratory parameters, together with the equation of the regression line (*solid line*) in the upper left panel giving oxygen consumption as a function of time ($\dot{V}O_{2(t)}$) on exercise intensity; $\dot{V}_E$, ventilation volume; $\dot{V}CO_2$, CO_2 production; *R*, respiratory exchange ratio; *BTPS*, body temperature and pressure (saturated with water vapour).
$\dot{V}O_{2\,max} = 1.7\,l \cdot min^{-1} = 38.6\,ml \cdot kg^{-1} \cdot min^{-1}$; $\dot{V}E_{max}(BTPS) = 80.4\,l \cdot min^{-1}$; $\dot{V}O_{2(t)} = 0.2121 \cdot time(min) + 0.4664$; $\dot{V}O_2$ at $Th_{an} = 1.05\,l \cdot min^{-1} = 61.89\%\ \dot{V}O_{2\,max}$

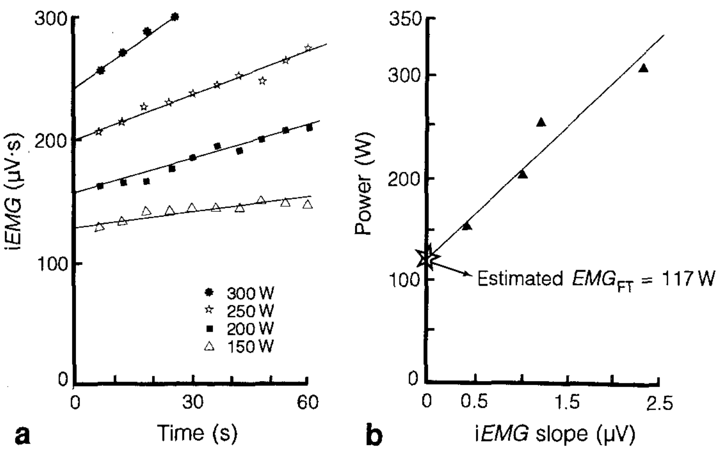

Fig. 2a, b. Method for estimating fatigue threshold (EMG_{FT}) from iEMG data. The iEMG data for each subject integrated over 6-s periods are plotted as a function of time for different exercise intensities on an ergometer (**a**). In **b** the iEMG slopes from **a** are plotted for each of the four exercise intensities and the zero slope (EMG_{FT}) is estimated by extrapolation to the *y* intercept

Table 1. Gas exchange and electromyogram-related parameters obtained during the incremental exercise test and during the fatigue threshold test

Subject	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Th_{an} $\dot{V}O_2$ ($l \cdot min^{-1}$)	EMG_{FT} (W)	$\dot{V}O_2$ at EMG_{FT} ($l \cdot min^{-1}$)
MK	41.1	1.27	147	1.04
KT	36.9	0.99	138	1.11
MH	50.3	2.08	214	1.96
YT	42.0	1.31	193	1.49
JS	41.2	1.55	179	1.13
MS	51.6	1.51	152	1.14
RO	45.9	1.26	216	1.64
SM	42.8	1.10	132	1.09
TM	25.4	0.91	124	0.79
NH	27.0	1.00	62	0.39
HT	24.9	0.96	120	0.44
KY	33.4	1.03	121	0.80
TY	41.7	1.72	181	1.83
HS	44.4	1.55	163	1.05
YM	56.1	1.01	165	1.54
JW	49.3	1.32	164	1.80
FK	58.5	1.67	210	1.73
HW	61.4	2.31	256	2.38
YM	62.2	2.30	231	2.36
TM	38.6	1.05	117	0.83
Mean	43.7	1.39	164	1.33
SD	11.1	0.44	47	0.57

For definitions see Figs. 1 and 2

Calif.) that was connected to a respiratory flow transducer. The gas sample was analysed for O_2 and CO_2 content (expired gas monitor 1H2B Sanei, Tokyo). The electrical outputs of the gas analysers and flow transducer were connected, via analog to a digital converter, to the computer which was programmed to calculate $\dot{V}O_2$, CO_2 production ($\dot{V}CO_2$), minute volume ($\dot{V}_E$), respiratory exchange ratio (*R*), ventilatory equivalent for O_2 ($\dot{V}_E/\dot{V}O_2$) and CO_2 ($\dot{V}_E/\dot{V}CO_2$) over 15-s periods. Data were stored on a disk for subsequent display and analysis.

The determination of Th_{an} was made during the $\dot{V}O_{2max}$ test using respiratory exchange parameters, i.e. the non-linear increase in $\dot{V}_E$ and $\dot{V}CO_2$, abrupt increase in the fraction of O_2 in expired air and *R* and systematic increase in $\dot{V}_E/\dot{V}O_2$ without any increase in $\dot{V}_E/\dot{V}CO_2$ (Wasserman et al. 1973; Davis et al. 1979). Figure 1 represents a typical set of computer outputs showing the changes in the respiratory exchange parameters during the incremental exercise test.

Results

Fatigue threshold

Results from a typical subject are shown in Fig. 2, which illustrates the iEMG method applied in this series of experiments to define the EMG_{FT}. This shows iEMG data for 6-s integration periods plotted as a function of time at four different powers (300, 250, 200 and 175 W) on an ergometer to determine the rate of increase in iEMG (iEMG slope). The iEMG slopes so obtained were then plotted against the exercise intensities imposed, resulting in linear plots which were extrapolated to zero slope to give an intercept on the power axis (Fig. 2b) which was interpreted as the highest exercise intensity sustainable without evidence of neuromuscular fatigue, in this case 117 W. The EMG_{FT} for 20 subjects so obtained had a mean value of 164 W, SD 47 and ranged from 62 to 256 W.

$\dot{V}O_{2max}$ and Th_{an} data

Table 1 summarizes the physiological variables measured during the progressive exercise tests. For our subjects $\dot{V}O_{2max}$ ranged from 1.21 to 3.50 $l \cdot min^{-1}$ with a mean of 2.24 $l \cdot min^{-1}$, SD 0.67 and Th_{an} expressed in terms of $\dot{V}O_2$ ranged from 0.91 to 2.31 $l \cdot min^{-1}$ with a mean of 1.39 $l \cdot min^{-1}$, SD 0.44.

Relationship between Th_{an} and EMG_{FT}

Each individual's EMG_{FT} was expressed in terms of $\dot{V}O_2$ equivalent based on the individual's Δ efficiency calculated during the maximal exercise test on the same cycle ergometer (Gaesser and Brooks 1975).

Results presented in Fig. 3 show that there was a highly significant correlation between $\dot{V}O_2$ at Th_{an} and $\dot{V}O_2$ at EMG_{FT} ($r = 0.823$, $P < 0.01$). A paired *t*-test indicated that there was no statistically significant difference between $\dot{V}O_2$ at Th_{an} (1.39 $l \cdot min^{-1}$, SD 0.44) and $\dot{V}O_2$ at EMG_{FT} (1.33 $l \cdot min^{-1}$, SD 0.57) ($t = 0.93$, $P > 0.05$). From Fig. 3, it is evident that for sedentary

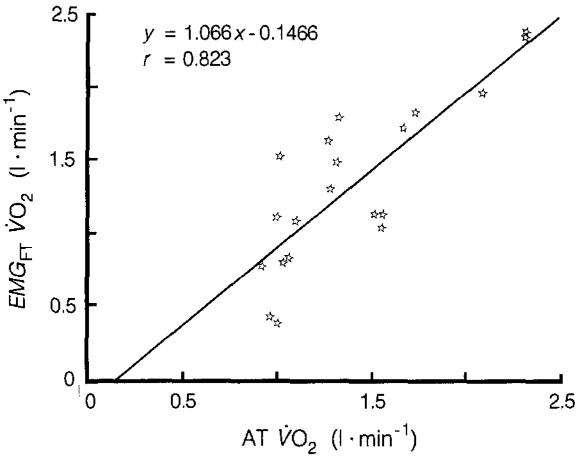

Fig. 3. Correlation between oxygen consumption at anaerobic threshold (*Th_{an} $\dot{V}O_2$*) and fatigue threshold expressed as a $\dot{V}O_2$ equivalent (*EMG_{FT} $\dot{V}O_2$*)

subjects with a $\dot{V}O_2$ at Th_{an} less than approximately $1.0\ l \cdot min^{-1}$, it was not necessarily coincident with $\dot{V}O_2$ at EMG_{FT}. This may indicate the possibility that the state of muscle fitness of the sedentary subjects, e.g. muscle mass, biochemical as well as histochemical characteristics might not have allowed a sufficiently full loading of the cardiovascular-respiratory system during such a short period of exercise for peripheral muscle fatigue to take place.

Discussion

Studies of Th_{an} in selected patients with cardiac disease (Wasserman et al. 1973; Wasserman and Whipp 1975; Weber et al. 1982) have shed some light on the physiological mechanisms of lactic acidosis among those who demonstrated anaerobiosis and lactate acidaemia at relatively low exercise intensities (0–60 W). It was suggested that partial occlusion of conducting arteries supplying active muscles due to atherosclerotic lesions might have caused an inadequate blood supply to the exercising muscles. Wasserman and Whipp (1975) have also shown that patients with anaemia may demonstrate anaerobic glycolysis and metabolic acidosis at a relatively low exercise intensity because of the inadequate blood O_2-carrying capacity to the exercising muscles. In line with these findings, we have recently shown that among other parameters tested, the maximal calf muscle blood flow showed the highest correlation ($r = 0.89$) with $\dot{V}O_2$ at Th_{an} measured during a progressive exercise test on a treadmill. These data give strong support to the suggestion that Th_{an} is the assessment of the ability of the cardiovascular system to supply oxygen at a rate which is adequate to prevent muscle anaerobiosis during exercise (Wasserman et al. 1990).

In addition to having high absolute values of $\dot{V}O_{2max}$, well-trained endurance athletes, on the other hand, are characterized by an ability to utilize a large fraction of this capacity without lactic acidosis and subsequent early muscle fatigue. Jenkins and Quigley (1990) have shown that highly trained endurance cyclists can tolerate high blood lactate levels ($8.9\ mmol \cdot l^{-1}$, SD 1.6) during 30 min exercise at their CP. This may be due to the fact that muscle respiratory capacity is of primary importance in determining the exercise intensity at which blood lactate begins to increase rapidly (Ivy et al. 1980). It is of interest to note that some previous studies (Moritani 1980; Nagata et al. 1981; deVries et al. 1982; Viitasalo et al. 1985) have shown the possibility that Th_{an} can be estimated by use of conventional EMG techniques. Muscle contraction at certain submaximal tensions causes physiological changes in the neuromuscular system which are manifested by an increased neural input to the muscle. The quantity of this neural drive is often measured by iEMG (Edwards and Lippold 1956; Viitasalo and Komi 1977; Petrofsky 1979; Moritani et al. 1982).-deVries (1968) has shown that under certain experimental conditions the EMG voltage-time relationship is linear for most subjects and that the slope of the line so determined has a close inverse relationship to the endurance time at a given load and is directly related to the percentage of maximal voluntary contraction which that load represents. It has been speculated that a progressive recruitment of additional MU might take place to compensate for the deficit in fatigued MU. In good agreement with this, there has been evidence that the decrease in pH as a result of lactate accumulation may interfere with the excitation-contraction coupling by affecting Ca^{2+} binding to troponin and the affinity of sarcoplasmic reticulum for Ca^{2+} with a subsequent deficit in the developed force (Fuchs et al. 1970; Nakamaru and Schwartz 1972; Fitts and Holloszy 1976). Therefore, the approach using iEMG would appear to be reasonable for estimating muscle fatigue threshold with the advantage of being unaffected by subjective factors such as motivation.

deVries et al. (1982) used the rate of increase in iEMG (iEMG slope) at each of four constant power outputs to identify PWC_{FT}. This study has shown PWC_{FT} to be reproducible in young men and valid when compared with criteria such as Th_{an} and CP. In a series of studies, deVries et al. (1989) have also suggested the feasibility of its use in an elderly population if the PWC_{FT} test were based upon submaximal exercise intensities. In the present study involving healthy young women with variable training status, the objective sign of muscle fatigue (the rate of iEMG increase) was obtained during a maximal 1-min exercise period. The results showed that there was a highly significant correlation between Th_{an} and EMG_{FT}. The magnitude of the correlation found among these variables suggested that approximately 67.7% of Th_{an} variance could be accounted for by the EMG_{FT}. Therefore, it seems that iEMG estimation of EMG_{FT} from neuromuscular fatigue may provide an attractive alternative to the measurement of the highest exercise intensity that can be sustained without fatigue. In addition, the use of such short periods of exercise would also allow testing, over a greater number of different exercise intensities, to improve the prediction of the EMG_{FT}.

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