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Parallel changes in the onset of blood lactate accumulation (OBLA) and threshold of psychomotor performance deterioration during incremental exercise after training in athletes

Jan Chmura [a], Krystyna Nazar [b,*]

[a] University School of Physical Education in Wroclaw, Poland

[b] Department of Applied Physiology, Mossakowski Medical Research Centre, Polish Academy of Sciences, Warsaw, Poland

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ABSTRACT

During aerobic exercise with increasing intensities choice reaction time (CRT) progressively shortens up to 60–80% of maximal workload, and then it rapidly increases. The aim of this study was to determine whether workload associated with the shortest CRT operationally called "the psychomotor fatigue threshold" is related to the metabolic response to exercise. Thirteen male soccer players (aged 23.3 ± 1.0 yrs) participated in this study. Before and after 6 weeks of training in the pre-competition period they underwent treadmill test at 0 grade with running speed increasing every 3 min by 2 km/h starting from 6 km/h until exhaustion. At each stage of exercise CRT, heart rate, respiratory gas exchange and blood lactate [LA] were measured and the workload corresponding to [LA] of 4 mmol/l (OBLA) was recorded. After training, CRT was significantly shortened at rest (from m ± SEM = 345 ± 12 to 317 ± 12 ms) and during exercise (from 304 ± 10 to 285 ± 11 ms at the psychomotor fatigue threshold and from 359 ± 13 to 331 ± 13 ms, $p<0.001$at the last stage). Both OBLA and the psychomotor fatigue threshold were shifted towards greater running velocities (by 0.92 ± 0.26 and 0.85 ± 0.22 km/h, respectively). The psychomotor fatigue threshold exceeded OBLA both before and after training. Significant correlations were ascertained between OBLA and psychomotor fatigue threshold ($r = 0.97$) and between the changes in OBLA occurring during training and those in psychomotor fatigue threshold ($r = 0.88$). It is concluded that endurance training not only increases exercise tolerance due to its influence on metabolism but also facilitates psychomotor performance during heavy exercise.

1. Introduction

According to the conventional understanding of fatigue it is a psychophysiological state that develops during effort and includes metabolic changes in working muscles limiting performance (Fitts, 1994) and central fatigue originating in the nervous system (CNS). Inability to sustain the rate of motoneuron activation and sensation of fatigue are the best-known symptoms of central fatigue. During exercise with increasing intensity, blood lactate concentration usually starts to rapidly increase at a power output between 50 and 70% of the maximal workload. For practical purposes the exercise load during which lactate concentration attains 4 mmol l^{-1} is defined as onset of blood lactate accumulation (OBLA) (Heck et al., 1985; Weltman, 1995). This workload is usually higher than the breaking point of the blood lactate curve which is called "the anaerobic threshold", but during running it corresponds to the maximal load of steady state lactate concentration (Figueira et al., 2008). During running it coincides also with the "critical power" representing the transition from the exercise load tolerable for a long time to the "severe" intensity. When critical power is exceeded, changes in the muscle cell indicating development of peripheral fatigue, such as depletion of high energy phosphates and accumulation of H^+ and P_i, occurs (Jones et al., 2008).

The relationships between peripheral fatigue and central fatigue are not fully recognized. According to Noakes et al. (2005) central fatigue is not related to the failure of homeostasis or any organ dysfunction but it represent a mechanism that prevents occurrence of these adverse phenomena and is controlled by the "central governor in the brain". The central governor integrates afferent signals from peripheral organs including skeletal muscles, induces sensation of fatigue and using feed-forward processes controls motor unit recruitment and autonomic nervous system activity. However, the central fatigue that occurs during exhausting effort may be directly related to the factors impairing CNS mental or/and regulatory functions, such as e.g. reduction of cerebral blood flow, hyperthermia, hypoglycemia or hyperammonemia (see Nybo and Secher, 2004; Secher et al., 2008; Ogoh and Ainsle, 2009).

* Corresponding author. Department of Applied Physiology, Mossakowski Medical Research Centre, Polish Academy of Sciences, 5 Pawinskiego str., 02-106 Warsaw, Poland. Tel./fax: +48 22 6086624.
E-mail address: nazar@cmdik.pan.pl (K. Nazar).

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Our previous studies (Chmura et al., 1994; Kruk et al., 2001; Mikulski, et al., 2002; Ziemba et al., 1999) demonstrated that psychomotor performance assessed as multi-choice reaction time during graded cycling exercise showed the characteristic biphasic pattern: that is the gradual shortening until power output of approximately 60–80% of maximal workload was attained and then a rapid increase in reaction time in the final stages of exercise. We consider the latter phase to be an indication of central fatigue development and refer to the exercise load associated with the shortest reaction time as "the threshold of psychomotor fatigue." Although the ability to evaluate and react quickly to environmental stimuli in spite of developing fatigue is very important in team play and other sport activities, the relationship between indices of endurance such as anaerobic threshold or OBLA and the threshold of psychomotor performance deterioration has not been investigated. The data in the available literature concerning relationship between aerobic capacity and cognitive performance are inconclusive (see Etnier et al., 2006).

Aerobic endurance training shifts OBLA towards higher exercise loads and thus increases the tolerable exercise intensity due to the metabolic adaptation at the level of skeletal muscles (Weltman, 1995). This adaptation occurs even without meaningful changes in aerobic capacity as determined by maximal oxygen consumption. Since the sensory feedback input from exercising muscles and other organs as well as humoral factors circulating in blood and an increase in body temperature can influence CNS function (see Nybo and Secher, 2004), we hypothesized that OBLA and threshold for deterioration of psychomotor performance both change in the same direction and improve with exercise training. The aim of this study was to check this hypothesis. Therefore, blood lactate concentration and multi-choice reaction time were determined during incremental running exercise in soccer players before and after 6 weeks of conditioning in the pre-competition period.

2. Materials and methods

2.1. Subjects

Thirteen male professional soccer players with at least 3 yr competitive experience (mean age 23.3 ± 1.0 yrs, height 183 ± 1.3 cm, body mass 77.9 ± 1.4 kg, and maximal oxygen uptake 57.2 ± 1.6 ml/kg/min) participated in the study after giving an informed consent. The protocol of the study was accepted by the Ethical Committee at the University School of Physical Education in Wroclaw. The subjects were subjected to a multistage incremental exercise test performed until volitional exhaustion on two occasions: before (Test I) and after (Test II) 6 weeks of training in the pre-competition period.

2.2. Training program

This training was a part of the normal soccer team practice during the pre-competition period. The subjects participated in 60 training sessions. Fourteen sessions was designated to improve aerobic endurance and included 45–30 min of running at heart rate corresponding to OBLA. The other sessions were devoted to anaerobic endurance, strength, running speed, and game specific skills were trained. The total time of training was 96 h. All the subjects of this study completed the full training program.

2.3. Exercise test

The exercise tests were performed on a motor driven treadmill set at 0% gradient. Starting from 6 km/h (1.7 m/s) the speed of the treadmill was increased every 3 min by 2 km/h (0.6 m/s) until exhaustion. The stages were separated by 30 s rest periods during which blood was taken from the finger tip for determination of blood lactate [LA] concentration. During running heart rate (HR) was monitored using a Sports Tester (Polar Electra, Kempele, Finland) and the oxygen uptake (VO_2) and pulmonary ventilation (Ve) were determined using a Jaeger gas analyzer (Hoechberg, Germany).

The OBLA that is the running speed corresponding to the [LA] of 4 mmol/l was detected by interpolation from the [LA]-running speed relationship curve. The [LA] was determined from blood samples by an enzymatic method using Boehringer (Manheim, Germany) commercial tests.

2.4. Choice reaction time determination

Multiple-choice reaction time (CRT) was measured before exercise and during the last 2 min of each running stage. The console emitting the color light signals and a sound was mounted on the wall 1.5 m in front of the treadmill, at the eye level of the subjects. Immediately before the choice reaction tests, switch devices were placed into the right and left hands of the subject. The test included 15 positive (red light or a sound) and 15 negative (green and yellow lights) stimuli applied in a randomized order in 1 to 4 s intervals. The subjects were asked to press and then to release, as quickly as possible, the button of the switch device kept in the right hand in response to the red light, the button in the left hand in response to the sound and to not react to the negative stimuli. The total time for each choice reaction trial was 107 s. The subjects were familiarized with the procedure before starting the study by practicing the task both at rest and during running until no errors were made. The stimuli and the subjects' responses were recorded using the reaction time measuring device (MRK 432, Zabrze, Poland). The reaction time was determined to the nearest 0.01 s. The results are presented as the mean reaction time of 15 responses to the positive stimuli. The psychomotor fatigue threshold was defined as the running speed corresponding to the shortest choice reaction time.

2.5. Statistics

To compare CRT values obtained before and after training a 2-way analysis of variance for repeated measures was used where the first factor was training (pre, post) and the second time of CRT measurement during each stage of exercise tests (rest, 8,10, 12, 14, 16, and 18 km/h). For the *post hoc* comparisons a paired Student's t test were used. The normality of the data distribution was checked by Shapiro–Wilk W test. The significance of differences between measured indices at OBLA, at the psychomotor fatigue threshold or at the maximal stage of exercise before and after training was evaluated by a paired Student's t test. A Pearson correlation coefficient was used for assessment of the relationship between the selected variables. A $p<0.05$ was used as the level of significance. For calculations Statistica version 6. (Statsoft Inc., Tulsa OK., USA) was used. The data are presented as means with standard errors (SEM).

3. Results

During Test I, the maximal complete exercise stage for all subjects was at the speed of 18.0 km/h, oxygen uptake 4.39 ± 0.34 l/min, HR 193 ± 2 beats/min, pulmonary ventilation 145.7 ± 2 l/min, and blood [LA] 9.84 ± 0.6 mmol/l. None of these values was significantly changed after 6 weeks of pre-competition conditioning period. However, the running speed corresponding to OBLA was increased by 0.92 ± 026 km/h (Table 1).

The repeated-measures ANOVA revealed that training had a significant effect on CRT ($p<0.01$) although there was no significant interaction between effects of training and exercise. Comparison of CRT attained during the Test I and Test II showed significantly smaller values during Test II than in the Test I both at rest and during exercise. In both tests the pattern of changes in the reaction time during

Table 1
Running speed and accompanying physiological variables corresponding to OBLA and psychomotor fatigue threshold during test I (before the precompetition period) and test II (after the precompetition period).

Variable	OBLA		Psychomotor fatigue threshold	
	Test I	Test II	Test I	Test II
Running speed (km/h)	13.39 ± 0.16	14.31 ± 0.20**	14.48 ± 0.19††	15.81 ± 0.17††**
Heart rate (min^{-1})	165.7 ± 2.2	169.9 ± 1.8	171.2 ± 3.2	174.0 ± 1.8
Oxygen uptake (ml kg min^{-1})	43.3 ± 1.4	47.3 ± 1.3	45.7 ± 0.9	48.8 ± 1.1
Pulmonary ventilation (l min^{-1})	84.5 ± 3.5	94.9 ± 3.1**	97.5 ± 3.4††	108.0 ± 2.9††**
Blood lactate (mmol l^{-1})	4.0	4.0	4.79 ± 0.3††	5.64 ± 0.8††**

Values are means ± SE; Asterisks denote significant differences between the values obtained in test II and test I: ** $p<0.01$; crosses denote significant difference between values obtained at OBLA and psychomotor fatigue threshold: †† $p<0.01$.

exercise was similar: CRT gradually decreased until the work intensity of approximately 70–80% of the maximal aerobic workload, and then it increased until the end of the effort (Fig. 1). During the Test I, reaction time decreased by 13.4% (from 345 ± 10 to 304 ± 11 ms, $p<0.0001$), and after exceeding the psychomotor fatigue threshold it increased to 359 ± 12 ms ($p<0.001$) at the end of the test. The psychomotor fatigue threshold occurred at a workload exceeding OBLA by 8.2% which corresponded to 1.1 km/h. Accuracy of choice responses was not affected by exercise in either test until maximal running speed when some subjects made one or two errors.

After 6 weeks of training, the decrease in CRT before the psychomotor fatigue threshold was attained was 10.1% (from of the initial value of 317 ± 12 to 285 ms) and the increase in CRT at the final stage of exercise was 16% of the minimal value (from 285 ± 11 to 331 ± 13 ms).

Both OBLA and the psychomotor fatigue threshold were shifted towards greater running velocities (by 0.92 ± 0.26 and 0.85 ± 0.22 km/h, respectively). The shortest CRT occurred at the running speed of 15.8 ± 0.17 km/h that corresponded to 87.9% of the maximal speed and exceeded OBLA by 9, 2% ($p<0.001$). At the psychomotor fatigue threshold CRT values were also significantly shorter after the pre-competition conditioning than before the conditioning ($p<0.01$). The psychomotor fatigue threshold, OBLA and the accompanying physiological variables are presented in Table 1.

The correlation coefficient between the running speed corresponding to OBLA and that associated with the shortest CRT calculated for both tests ($n = 13$) was 0.972 with 95% confidence interval from 0.906 to 0.990 ($p<0.001$). Moreover, a highly significant correlation was ascertained between the changes in OBLA occurring during the pre-competition training period and those in psychomotor fatigue threshold ($r = 0.879$, $n = 13$, 95% confidence interval from 0.635 to 0.963 ($p<0.001$)). This relationship is presented in Fig. 2.

4. Discussion

The present data obtained during treadmill tests confirmed the previous findings from progressive cycling showing that exercise affects speed of the response during choice reaction task but it did not considerably influence the accuracy of the response (Chmura et al., 1994; McMorris and Graydon, 2000). Similarly as in the previous study two phases in the changes of CRT were found during incremental exercise with the greatest reaction speed at the exercise load exceeding the blood lactate threshold (Chmura et al., 1994).

The new finding of the present study is that there is a high positive correlation between OBLA and the psychomotor fatigue threshold as well as between changes in OBLA found after conditioning period and those of exercise load associated with the best psychomotor performance. In most of the subjects both OBLA and psychomotor fatigue threshold were shifted toward the higher workloads after the conditioning period. It should be noted that in two subjects there was no elevation of either OBLA or the psychomotor fatigue threshold. The reason for the lack of training-induced improvement is unknown but this result strengthens our assumption that the changes in physical endurance and psychomotor skill during exercise are interrelated.

The time course of the changes in the choice reaction time during exercise may depend on changes in the central nervous system activation. There is a body of evidence from psychophysiological studies that the relationship between the level of arousal and psychomotor skill can be described as the inverted letter U (Duffy, 1957, 1962, 1972; Arent and Landers, 2003) indicating that the speed of psychomotor reaction and its accuracy increases with the level of central nervous system arousal until an optimal level of arousal is attained and then decreases. However, some other authors suggest that catastrophe theory better describes the arousal–psychomotor performance relationship (Fazey and Hardy, 1988; Hardy and Parfitt, 1991).

The nature of the effect of exercise on arousal and facilitation of CRT remains unclear. The investigation of Audriffren et al. (2008) indicated that arousal affects activation and results in the increase in speed of the response by energizing motor outputs as assessed by EMG. The recent study of Chang et al. (2009) confirmed this conclusion. However, some effect of arousal during the pre-motor

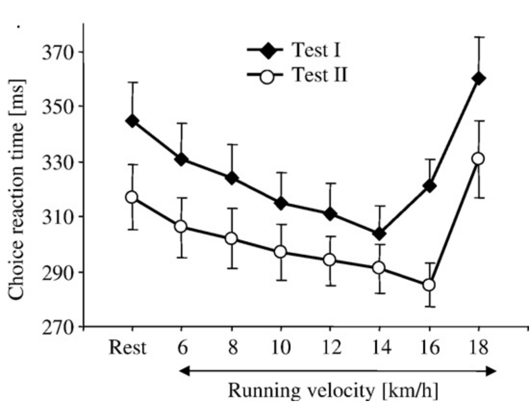

Fig. 1. Time course of changes of choice reaction time during running with increasing velocity before (I test,) and after (II test) 6 week conditioning in pre-competition period. Values are means ± SE.

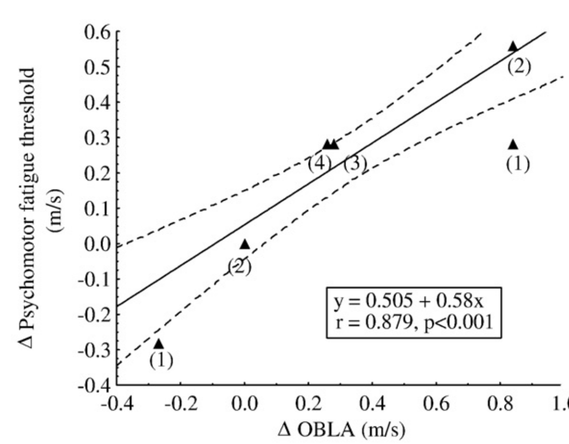

Fig. 2. Relationship between changes in the exercise load corresponding to onset of blood lactate accumulation during 6 weeks of the pre-competition period and those of the psychomotor fatigue threshold. Number of the data pairs making each point is presented in parentheses.

period representing all stages of information processing before muscle activation cannot be excluded.

The plausible explanation for the psychomotor fatigue threshold may be insufficient cerebral blood flow to maintain a high level of activation during strenuous exercise (see Ogoh and Ainsle, 2009; Secher et al., 2008). It was demonstrated that global cerebral blood flow increases during exercise, but this increase is reduced during strenuous exercise towards baseline level in spite of enhanced brain metabolism (Moraine et al., 1993; Hellström et al., 1996). The reduction of the cerebral blood flow is secondary to a decrease in the arterial CO_2 tension caused by hyperventilation. During incremental exercise, pulmonary ventilation rises exponentially with exercise intensity in response to the release of lactic acid from exercising muscles. Moreover, the ventilatory threshold is shifted towards higher exercise intensities by training similarly as the blood lactate threshold (Weltman, 1995). This may explain the relationship between OBLA and the psychomotor fatigue threshold, and the effect of training on both indices.

On the basis of the present findings it may be also speculated that information from muscle chemoreceptors plays some role in the development of central fatigue. The muscle chemoreceptors also called as metaboreceptors are the afferent nerve endings, which are stimulated by chemical changes in the muscle extracellular milieu such as an increase in the concentration of hydrogen ions. It is known that the reflexes evoked by these receptors play a role in the stimulation of the sympathetic nervous system and in the control of circulatory responses to exercise (Rowell and O'Leary, 1990).

The limitation of this study is lack of a control group consisting of athletes not engaged in training. However, since all the subjects participating in this study were well familiarized with treadmill exercise tests as well as with the CRT measurement, the difference in lactate and psychomotor performance between Test I and Test II seems to be caused by training rather than by learning or familiarization with the testing procedure. Another limitation is the relatively small number of subjects.

From the practical point of view it is important that athletes are able to maintain high psychomotor skill during exercise levels exceeding OBLA that is at the domain of severe exercise intensity. Furthermore, it is means that physical training improves endurance performance along with shifting the psychomotor fatigue threshold towards higher levels of work intensities.

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