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The effect of the lowest heat stress limit conditions on psychomotor parameters in soccer players

Marek Konefał[1], Krzysztof Błażejczyk[2], Jan Chmura[1], Piotr Żmijewski[3], Paweł Różański[4], Błażej Szmigiel[1], Paweł Chmura[5]

[1] Department of Human Motor Skills, Wrocław University of Health and Sport Sciences, Wrocław, Poland; [2] Institute of Geography and Spatial Organization, Polish Academy of Sciences, Warsaw, Poland; [3] Department of Biomedical Sciences, Józef Piłsudski University of Physical Education, Warsaw, Poland; [4] Department of Combat Sports, Józef Piłsudski University of Physical Education, Faculty of Physical Education and Health in Biała Podlaska, Biała Podlaska, Poland; [5] Department of Team Games, Wrocław University of Health and Sport Sciences, Wrocław, Poland

Abstract

Study aim: This study aimed (i) to describe psychomotor parameters for different temperature and humidity conditions, and (ii) to verify whether conditions at the borderline between some and great thermal discomfort on the humidex scale affect psychomotor parameters in soccer players.
Material and methods: Twenty-four male soccer players aged 21.02 ± 3.22 years from a Polish 4th league club performed a graded treadmill running exercise test. Directly before the test and during the break after each load, blood was collected to determine lactate concentration ([LA]) and serotonin concentration (SER). The heart rate (HR), pulmonary ventilation (Ve) and oxygen uptake (VO_2) were recorded and the psychomotor test was performed. Measurements were carried out: (1) at rest, (2) at the lactate threshold ($T_{[LA]}$), (3) at the threshold of psychomotor fatigue (T_{PF}), and (4) at maximum intensity. Percentage differences between maximum intensity (100%) and the values of the tested parameters recorded at the $T_{[LA]}$ and T_{PF} were also calculated. The tests were conducted in a climatic chamber at an ambient temperature of 28.5°C, with a relative air humidity of 58.7%.
Results: It was confirmed that the T_{PF}, which reflects the highest efficiency of the central nervous system, occurs at a higher running speed than the $T_{[LA]}$. For practical application, it was found that at the HSL, the T_{PF} occurs at: 84% of maximum running speed, 52% of maximum [LA] concentration, 93% SER_{max}, 91% HR_{max}, 73% VE_{max}, 84% VO_{2max}.
Conclusion: Understanding the psychomotor and physiological responses of soccer players at the borderline between some and great thermal discomfort (on the humidex scale) can support coaches in optimizing training sessions to prepare players for playing in more challenging climatic conditions.

Keywords: Anaerobic threshold – Reaction time – Serotonin – Soccer – Heat stress

Introduction

Heat stress is a serious problem for athletes because it significantly impairs the performance of specific motor tasks and the accuracy of decision-making [39]. In particular, psychomotor skills diminish, the speed and precision of movements decrease, and concentration disorders appear [29, 33]. Peripheral fatigue resulting from heat stress may have a negative impact on the total distance players can cover during a match, as well as on the distance covered at high intensity, the number of accelerations, sprints and jumps [28, 33]. According to Grantham et al. [16], soccer players at air temperatures below 22°C are not exposed to heat stress and its negative effects, while the risk of heat stress and its negative consequences, is low between 22 and 28°C, but high above 28°C. An additional burden for the soccer player's body exposed to high ambient temperatures is high air humidity. When playing in warm and humid conditions, players' heat production from intense physical activity often exceeds their ability to dissipate excessive heat, which may increase the risk of exertional heat illness [36, 37]. Hensen [18] noted that at temperatures close to or near the comfort zone (20–22°C), relative humidity fluctuations in the range of 20–60% did not affect the thermal comfort of physically active people. Based on the above publications, it is worth noting that conditions close to air temperatures of 28°C and close to

Author's address Marek Konefał, Department of Human Motor Skills, Wrocław University of Health and Sport Sciences, I.J. Paderewskiego 35, Wrocław 51-612, Poland marek.konefal@awf.wroc.pl

60% relative humidity are close to great discomfort, i.e. they can be defined as the “lowest heat stress limit” [15]. These conditions correspond to the calculated average of the maximum values occurring in the last ten years in Qatar on the day of the year on which the World Cup in 2022 began, i.e. ambient temperature 28.5 ± 1.92°C and relative air humidity 58.7 ± 8.64% [11].

Climatic conditions are significant modifiers of the physiological and psychomotor reactions of soccer players during the match [24, 31]. Heat stress has many consequences for the body. It causes an increase in the internal body temperature above 38.5°C, an accelerated heart rate (due to the redirection of blood flow to the surface of the skin) and the transition from aerobic to anaerobic energy metabolism, which leads to faster depletion of muscle glycogen [46]. It impairs the function of the cardiovascular system, reducing the oxygen supply to working muscles, and thus causing peripheral fatigue [33].

However, the psychophysiological process that causes fatigue is complex and involves central fatigue in addition to peripheral fatigue. Signals from all bodily systems are integrated into the brain as a safety mechanism to prevent physiological adjustments in any of the systems involved in the exercise from being exceeded [46]. Central nervous system (CNS) fatigue symptoms are less well understood. Research suggests that the central source of fatigue is related to the activity of several neurotransmitters, including serotonin (5-HT), dopamine (DA) and norepinephrine (NA) [17, 26, 48]. Serotonin is one of the main neurotransmitters causing central fatigue, the concentration of which in the brain depends on the availability of the amino acid tryptophan. The symptoms of central fatigue include: decreased ability to exercise (similar to peripheral fatigue), decreased coordination, decreased speed and precision of movements, increased muscle tremor, decreased concentration, perception, anticipation, speed and correctness of reaction, and psychomotor efficiency [29, 34].

As scientific research shows, hard physical work can reduce cognitive performance [5], but moderate-intensity physical exercise can improve psychomotor performance [45]. Upon closer analysis, Chmura et al. [8] found that a specific level of peripheral fatigue does not reduce, and even improves the psychomotor performance of players. This is related to the upper limit of exercise load and fatigue tolerance occurring above the lactate threshold, which is accompanied by the shortest reaction time, the highest level of differentiation of audiovisual stimuli and the most optimal performance, i.e. with the threshold of psychomotor fatigue (T_{PF}). Exceeding the T_{PF} leads to a rapid deterioration of these variables [6].

So far, the psychomotor fatigue threshold in the context of climatic conditions at the 2022 FIFA World Cup in Qatar and additionally thermoneutral climatic conditions have been demonstrated only in one study [23]. In the above studies, based on a limited number of parameters, taking into account only the reaction time, preliminary relationships between psychomotor fatigue and lactate thresholds were found.

However, the threshold of psychomotor fatigue in relation to many other physiological parameters and essential human heat balance measures has not been studied so far in the context of climatic conditions which are at the borderline between some and great thermal discomfort on the heat stress scale. From a practical point of view, any information on climatic conditions, and in particular the conditions at the borderline between some and great thermal discomfort analyzed in the context of psychomotor and physiological parameters, may be useful for training staff in order to optimally and safely physically prepare soccer players for playing in various, variable and often unfavourable climatic conditions. Therefore, this study aimed (i) to describe psychomotor parameters for different temperature and humidity conditions, and (ii) to verify whether conditions at the borderline between some and great thermal discomfort on the humidex scale affect psychomotor parameters in soccer players.

Material and methods

Subjects

In the present research we have applied a part experimental study described in detail by Konefał et al. [23]. In the experiment twenty-four soccer players aged 21.02 ± 3.22 years from a Polish 4th league club volunteered for this investigation. All athletes were instructed to maintain a normal diet 24 h prior to testing. Their body height was 180.22 ± 4.38 cm, body weight 74.20 ± 7.43 kg, training experience 9.0 ± 1.3 years. The players trained five times a week. The inclusion criteria were complete test results of all players without cognitive alterations, recent surgeries or injuries. Furthermore, only outfield players were considered. To record credible and reliable results of the experiment, all players were instructed not to consume alcohol or take any drugs for at least 24 hours before the tests, to maintain normal diets and not to perform heavy training loads the day before the test. The study was carried out in October and November 2018. The test took place from 9 am to 2 pm from Monday to Friday. The study was conducted in compliance with the Declaration of Helsinki and was approved by the local ethics committee and they were funded from National Science Centre grant no. 379162.

Procedures

Ambient micrometeorological conditions

The tests were carried out in a certified testing laboratory, in a Weiss Technik WK-26 climatic chamber, at an ambient temperature of 28.5°C and relative air humidity of 58.7% [11]. These are the conditions corresponding to the average of the maximum values of ambient temperatures and relative air humidity recorded in the last 10 years on November 21 in Doha, Qatar (date and place of the World Cup in 2022. Moreover this is at a temperature corresponding to the lower limit of heat stress adopted based on Grantham et al. [16] research and the upper limit of the standard related to air humidity [18]. In the climatic chamber air ventilation with an average speed of 2 m · s^{-1} was applied to reduce heat strain in subjects examined in the experiment. When preparing the measuring protocol we verified the risk using Belding-Hatch's [2] Heat Stress Index (HSI, in %). In conditions of no air movement the HSI was about 100% (indicating the maximal level of heat stress tolerated by young, acclimated persons). Application of air movement has reduced the HSI to approximately 40%, i.e. below intensive heat stress which represents a health hazard for non-acclimated persons [3, 4].

Table 1. Acronyms and definitions used in the text

Acronym/ Symbol	Definition	Unit
CRT	Choice reaction time	ms
EWL	Evaporative water loss	ml · h^{-1}
HR	Heart rate	beats · min^{-1}
HSI	Heat Stress Index	%
HSL	Heat stress limit	not applicable (n.a.)
[LA]	Lactate concentration in capillary blood	mmol · l^{-1}
M	Metabolic heat production	W · m^{-2}
Max intensity	At maximum intensity conditions	n.a.
PST	Physiological subjective temperature	°C
Rest	At rest conditions	n.a.
S	Net heat storage	W · m^{-2}
SER	Serotonin concentration	ng · ml^{-1}
$T_{[LA]}$	At the lactate threshold conditions	n.a.
T_{PF}	At the threshold of psychomotor fatigue conditions	n.a.
Tskin	Mean skin temperature	°C
V	Speed	km · h^{-1}
Ve	Pulmonary ventilation	l · min^{-1}
VO_2	oxygen uptake	ml · kg^{-1} · min^{-1}

Testing protocol

An exercise test with increasing load was performed on a Cybex 790T treadmill. After entering the climatic chamber, the player adapted himself in a sitting position to the conditions in the chamber for 10 minutes (Rest). Every exercise test started with a speed (V) of 8 km · h^{-1} and V was increased every 3 minutes by another 2 km · h^{-1} until exhaustion, with 1 minute passive break.

Directly before the test and during the break after each load, blood samples were taken from the fingertip to determine serotonin concentration (SER) (ng · ml^{-1}) (commercial ELISA test – DRG MedTec) and lactate concentration in capillary blood ([LA], mmol · l^{-1}) (Roche Diagnostics Cobas b 123 Analyser, Germany). During the whole test, the heart rate (HR, bpm) was recorded (sport-tester POLAR RS-400). In addition, pulmonary ventilation (Ve) (l · min^{-1}) and oxygen uptake VO_2 (ml · kg^{-1} · min^{-1}) – were determined using the CORTEX MetaMax 3b mobile ergospirometer.

Incremental exercise test and tested parameters

The psychomotor test was performed before the incremental exercise test and in the last 30 seconds of each three-minute load. Choice reaction time (CRT) was recorded using an APR device (UNI-PAR, Poland). According to the procedures described by Chmura et al. [7] and applied in research by Konefał et al [23] the measurement programme consisted of 25 visual stimuli: red, green and yellow.

Essential characteristics of the heat balance of examined subjects were also defined, namely: metabolic heat production (M, W · m^{-2}), mean skin temperature (Tskin, °C), net heat storage (S, W · m^{-2}), physiological subjective temperature (PST, °C) and evaporative water loss (EWL, ml·h^{-1}). The Man-ENvironment heat EXchange model (MENEX) of Błażejczyk [3] was applied for this purpose. A detailed equation of the above measures are done in Błażejczyk and Matzarakis [4], Szymczak and Błażejczyk [44]. The calculations were made using the BioKlima 2.6 software package.

To achieve the aim of the study, the levels of the tested parameters and heat balance measures were determined at four measurement points: (1) at rest – Rest, (2) at the lactate threshold – $T_{[LA]}$, (3) at the threshold of psychomotor fatigue – T_{PF}, (4) at maximum intensity – Max intensity. Percentage differences between Max intensity (100%) and the values of the tested parameters recorded in $T_{[LA]}$ and T_{PF} were also calculated.

The lactate threshold ($T_{[LA]}$) was determined using the Dmax method, which allows to determine the individual threshold value [13]. The psychomotor fatigue threshold (T_{PF}) was defined as the running speed corresponding to the shortest choice reaction time [6].

Statistical analyses

The Shapiro–Wilk test was applied to check the normality of the data distribution and the Mauchly's sphericity test. The data are presented as means ± standard deviations (SD). A repeated measures ANOVA for the compared values of tested parameters obtained for Rest, $T_{[LA]}$, T_{PF} and after the incremental exercise test (Max intensity) was used. The Fisher's least significant difference (LSD) test was applied to check differences between pairs of means. A $p < 0.05$ was used as the level of significance. All statistical analyses were performed using the STATISTICA ver. 13.3 software package (StatSoft. Inc., USA).

Results

Statistical analysis of physiological and kinematic parameters in relation to successive measurement times in the incremental exercise test (Rest, $T_{[LA]}$, T_{PF}, Max intensity) showed that the level of all parameters increased with subsequent measurements, as shown in Table 2. This relationship was also noted in the percentage values of the tested parameters. The exception was CRT, the time of which was shortened in T_{PF} by 3% compared to the value obtained with $T_{[LA]}$. See Table 2.

Discussion

This study aimed (i) to describe psychomotor parameters for different temperature and humidity conditions, and (ii) to verify whether conditions at the borderline between some and great thermal discomfort on the humidex scale affect psychomotor parameters in soccer players.Heat stress is becoming more and more common at

Table 2. Differences in values and percent of maximal values of parameters tested at the lowest heat stress limit and subsequent measurement times in incremental exercise test (mean ± SD)

Parameters	Climate conditions	**Rest** (1)	$\mathbf{T_{[LA]}}$ (2)	$\mathbf{T_{PF}}$ (3)	**Max intensity** (4)	F (<0.001)	SSD (<0.05)
[LA] [mmol · l^{-1}]	HSL	1.56 ± 0.33	3.98 ± 0.71	5.10 ± 1.91	9.67 ± 2.55	178.59	1<2<3<4
	%max	–	43 ± 8	52 ± 12	100		
V [km · h^{-1}]	HSL	–	13.43 ± 0.97	14.25 ± 1.36	17.08 ± 1.02	125.21	2<3<4
	%max	–	79 ± 3	84 ± 7	100		
CRT [ms]	HSL	309.0 ± 30.36	273.85 ± 26.49	263.21 ± 20.44	281.58 ± 26.72	50.49	1>2>3<4
	%max	–	97 ± 5	94 ± 4	100		
HR [beats · min^{-1}]	HSL	69.89 ± 6.55	171.93 ± 8.23	177.51 ± 12.41	195.04 ± 2.77	1702.23	1<2<3<4
	%max	–	88 ± 4	91 ± 6	100		
Ve [l · min^{-1}]	HSL	–	87.78 ± 17.90	96.79 ± 20.68	132.16 ± 18.77	85.52	2<3<4
	%max	–	67 ± 11	73 ± 10	100		
VO_2 [ml · kg^{-1} · min^{-1}]	HSL	–	45.34 ± 6.84	47.42 ± 4.72	56.61 ± 5.55	64.12	2.3<4
	%max	–	80 ± 7	84 ± 7	100		
SER [ng · ml^{-1}]	HSL	71.19 ± 22.62	90.96 ± 23.07	94.50 ± 26.27	101.79 ± 23.82	33.57	1<2.3<4
	%max	–	90 ± 12	93 ± 13	100		
M [W · m^{-2}]	HSL	–	727.4 ± 127.5	760.1 ± 100.5	907.2 ± 114.5	64.23	2.3<4
	%max	–	80 ± 7	84 ± 7	100		
Tskin [°C]	HSL	–	32.5 ± 0.2	32.6 ± 0.1	32.8 ± 0.2	64.00	2.3<4
	%max	–	99 ± 0.2	99 ± 0.3	100		
S [W · m^{-2}]	HSL	–	310.3 ± 60.2	325.8 ± 47.4	394.9 ± 53.7	64.02	2.3<4
	%max	–	78 ± 8	83 ± 8	100		
PST [°C]	HSL	–	48.5 ± 2.1	49.1 ± 1.6	51.3 ± 1.7	61.68	2<3<4
	%max	–	95 ± 2	96 ± 2	100		
EWL [ml · h^{-1}]	HSL	–	976.6 ± 153.8	1015.8 ± 121.7	1194.9 ± 139.6	64.54	2.3<4
	%max	–	81 ± 6	85 ± 7	100		

CRT: choice reaction time; EWL: evaporative water loss; HR: heart rate; HSL: heat stress limit; [LA]: lactate concentration in capillary blood; M: metabolic heat production; Max intensity: at maximum intensity conditions; PST: physiological subjective temperature; Rest: at rest conditions; S: net heat storage; SER: serotonin concentration; $T_{[LA]}$: at the lactate threshold conditions; T_{PF}: at the threshold of psychomotor fatigue conditions; Tskin: mean skin temperature; V: speed; Ve: pulmonary ventilation; VO2: oxygen uptake.

major sporting events. Recently, the World Cup in Brazil in 2014 and the Olympic Games in Tokyo in 2021 were held in extreme thermal and hygroscopic conditions [10, 21]. Currently, such conditions apply to players playing in the World Cup in Qatar, where players performed at the borderline of some and great thermal discomfort [41]. The consequence of this is a decrease in endurance and speed abilities [10, 28, 35]. However, in hot and humid environments, top-level players modulate their activity patterns, lowering physical activity while maintaining technical-tactical efficiency [31]. This is possible by maintaining the level of psychomotor fitness. Why is this happening? Perhaps because, as claimed by Chmura and Nazar [6], the highest efficiency of the central nervous system occurs with higher fatigue tolerance.

Once again, it turned out that the psychomotor fatigue threshold (T_{PF}) occurs at a higher running speed than the lactate threshold ($T_{[LA]}$), even in difficult thermal conditions such as the lowest heat stress limit. In our research, T_{PF} occurs at a running speed of 14.25 km·h^{-1}, which is significantly higher than the $T_{[LA]}$ speed (13.43 km · h^{-1}). In such conditions, the physical efforts generated a great amount of heat which in short intervals reached 760 W · m^{-2}. At the same time intensive processes of heat loss by convection and evaporation were noted. These were intensified by air movement. Despite this, during short $T_{[LA]}$ and T_{PF} phases the net heat storage reached 310–326 W · m^{-2} and at maximal physical effort almost 400 W · m^{-2}. In those phases, the physiological subjective temperature registered by thermal sensors at the skin reached 48-51°C, which was felt as very hot. In elevated air temperature (28.5°C) and air movement (2 m · s^{-1}) in the chamber a significant amount of sweat was generated and evaporated from the skin. In consecutive phases of the experiment, evaporative water loss reached 976–1195 ml per hour. One should remember that each phase of the experiment lasted only 2–3 minutes and therefore such great values of M, S and EWL did not present a risk of overheating and dehydration of the body (compare [21]). Intensification of sweating is an effective way to reduce the risk of overheating, both in sports and working environments [14, 32, 42].

Comparing the research of Chmura and Nazar [6] and Konefał et al. [23] performed in thermoneutral conditions, the results of our research showed that in heat stress conditions the T_{PF} occurs at lower running speeds: by 0.23 km/h and 0.75 km/h, respectively. This proves a lower tolerance of the CNS to increasing fatigue under heat stress conditions. It follows that incriminating ambient conditions are conducive to a significant acceleration of the occurrence of the T_{PF}. At the lowest heat stress limit, runners achieve optimal psychomotor performance at lower running intensity. This is beneficial from the point of view of the technical and tactical activity of soccer players [31]. On the other hand, the $T_{[LA]}$, regardless of climatic conditions, was at a relatively constant level in all the mentioned studies. It should be emphasized that a temperature of 28.5°C with humidity below 60% is the lower limit at which the high risk of heat stress begins [16]. Presumably, a higher value of ambient temperature or relative air humidity would cause a deeper physiological response, e.g. changes in the lactate threshold [46].

When analysing the T_{PF} at the lower heat stress limit in the context of practical use, it is interesting what percentage of the maximum values of physiological parameters accompanies the shortest reaction time, the highest level of differentiation of audiovisual stimuli and making optimal decisions. According to our research, under these conditions, the T_{PF} occurs at 84% of maximum running speed and 52% of maximum [LA] concentration. In addition, the T_{PF} occurs at 91% HR_{max}, 73% VE_{max}, and 84% VO_{2max}. There are studies showing that even with a higher percentage of the maximum lactate concentration – up to 57% – and rapidly increasing fatigue, the efficiency of the central nervous system may still be optimal [6].

In the modern game of soccer, large reserves are seen in the optimal performance of players, and in this aspect a new quality is sought [30]. In order to implement information about T_{PF} in soccer training, percentage values are needed to determine when it occurs. One of the most commonly used physiological parameters by which we can assess the moment of occurrence and then monitor the load on the T_{PF} is %HRmax [9]. In addition, %VO_2max can also be used in practice [47]. In our research, in heat stress CRT shortened with increasing exercise intensity of young soccer players, to approx. 84% of VO_{2max} (HR – 177 bpm), and then rapidly increased, and in research of Chmura et al. [11] at 75% of VO_{2ma}x (HR – 164 bpm). The values recorded by Chmura et al. [8] were lower probably due to the tests being performed in a more comfortable environment [17].

Monitoring loads at the threshold of psychomotor fatigue allows one to push the limit of the highest efficiency of the CNS towards ever higher intensity of effort and ever greater tolerance of increasing fatigue in the brain. The cause of exercise fatigue is complex [25]. One of the neurotransmitters associated with central fatigue is serotonin. It is well-documented that prolonged exercise increases serotonin levels [1, 43]. In our study, the level of serotonin concentration steadily increased with increasing load in the progressive test. At the threshold of psychomotor fatigue, it was 93% of SER_{max}. However, despite the study being conducted at the lowest heat stress limit, the level of this parameter in all subsequent measurements was within the physiological norm (ISO/DIS 7933 [19]). To better understand the efficiency of the CNS functioning at the threshold of psychomotor fatigue, further research is needed, also taking into account other neurotransmitters such as dopamine, adrenaline, noradrenaline and tryptophan, including in conditions of heat stress [22, 27, 40].

The authors are fully aware of many factors that could have influenced the results of the present analyses. One limitation was the performance of the tests in a climatic chamber and not in the real conditions of a soccer match.. Also, the effort during the tests was performed on a treadmill, which is not specific to soccer. Additionally, it would be valuable to test and compare psychomotor parameters not only in one but in several different temperature and humidity conditions. Moreover, a larger number of professional soccer players would be a more valuable research material. Therefore, these results should be treated with caution. In order to better understand CNS performance, more complex psychomotor tests that are more sensitive to hot environmental conditions should be included in future research [38]. It would be advisable to continue research on T_{PF} in different age groups and training levels, taking into account different CRT measurement methods and different exercise protocols. In addition, it would be worth analysing psychomotor parameters under the influence of higher heat stress.

Conclusion

It was confirmed that at the lowest heat stress limit, the threshold of psychomotor fatigue, which reflects the highest efficiency of the central nervous system, occurs at a higher running speed than the lactate threshold.

At the lowest heat stress limit, athletes achieve optimal psychomotor efficiency faster (at lower running intensity) than in thermoneutral conditions (based on comparison with other studies). This proves a lower tolerance of the CNS to increasing fatigue under heat stress conditions.

For practical use, it has been shown that at the lowest heat stress limit, T_{PF} occurs at 84% of maximum running speed and 52% of maximum [LA] concentration, and at 93% SERmax, 91% HRmax, 73% VEmax and 84% VO_{2max}. It should be emphasized, however, that these reactions may be very individualized.

Understanding the psychomotor and physiological responses of soccer players at the borderline between some and great thermal discomfort (on the humidex scale) can support coaches in optimizing training sessions to prepare players for playing in more challenging climatic conditions.Before the start of exercise experiments in elevated air temperature and humidity it is necessary to verify the level of thermal and hydric stress to protect against the risk of overheating, especially in the young population. In our experiment we applied for this purpose air movement, which reduced heat stress to a safe level.

Practical application

In order to use the data described in this paper and the intensity at the T_{PF} threshold in practice, it is proposed to first determine the psychomotor fatigue threshold based on the course of changes in the speed and correctness of reactions (CRT) during exercises with increasing load. After determining the T_{PF}, it is recommended to implement a system of exercises that stimulate the body to break the fatigue barrier in the brain described in Chmura et al. [9].

The implementation of such exercise will allow the T_{PF} to shift towards higher loads and greater tolerance of the brain to increasing fatigue. Intensities at thresholds can be measured most simply by measuring HR. It can only be used for well-prepared aerobic endurance athletes from the U-17 groups [9].

Conflict of interest: Authors state no conflict of interest.

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