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DETERMINATION OF ANAEROBIC THRESHOLD BASED ON THE DYNAMICS OF THE HEART AND STROKE RATES ESTIMATED IN THE UPPER BODY PROGRESSIVE TEST

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Abstract. In an incremental exercise the heart (HR) and stroke (SR) rates can be periodically synchronized suggesting that changes in the course of a relationship between power output (PO) and HR, recorded in the Conconi test as the deflection point (DP), may be related to changes in SR. In view of this, the aim of the present study was to analyse the course of the PO/HR, PO/SR, and SR/HR relationships in the progressive incremental exercise as well as to evaluate the accuracy of determination of anaerobic threshold (AT) based on the above three relationships. In the investigation, 12 kayakers performed the following tests on a special ergometer: the Conconi test (CT), the 30-min test (PET) with power output at DP (PO_{DP}), the critical power test (CP), and the graded exercise test until exhaustion (GT), in which power output at the anaerobic threshold (PO_{AT4}, PO_{Dmax}) was determined based on the blood lactate level (LA). The lack of DP in the PO/HR and the PO/SR relationships was detected in two and one athlete, respectively. In contrast, in the SR/HR relationship DP was recorded in all the tested subjects. The times of occurrence of DP did not significantly differ. Although, as judged by the LA dynamics in PET, the intensity of exercising exceeded that at the maximal lactate steady state (MLSS), all the athletes managed to complete the test. No significant differences were detected between PO_{DP} and PO_{AT4}, PO_{Dmax} or CP, and the agreement of the results obtained in CT with those collected in CP and GT was similar to that determined within each of the tests. The obtained results suggest that the changes in the course of the PO/HR relationship may be associated with spontaneous changes of SR. The lack of diversity among the times of occurrence of DP in the three relationships tested allows for an easy and non-invasive determination of AT even in case of a linear PO/HR relationship. The power output estimated with use of the presented method is higher than that at MLSS, but it is sustainable for at least 30 min. The accuracy of determination of anaerobic threshold based on the analysis of the three DPs appears to be comparable with that obtained with use of AT4, Dmax, and CP.

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Introduction

The ability to perform prolonged exercises can be estimated with various methods such as the anaerobic threshold or the critical power tests. However, the procedures involved require collection of blood samples, use of a sophisticated equipment or at least performing a number of exhausting exercises, all of which hamper practical utilization of these methods in sports. Anaerobic threshold can also be determined based solely on the analysis of the heart rate (HR) changes in an incremental progressive exercise [9,16]. Although this method, known as the Conconi test (CT) [11,12], has become very popular, it has also been criticised by many authors. In fact, not only the validity and reproducibility [6,21,22,24,25,34,35,37] of CT but also its scientific basis [20] have been questioned. Apparently, one of the reasons for inadequacies of the test is selection of the fixed cadence [12]. As demonstrated by other authors, increase in power output (PO) is associated with the rise in stroke rate (SR) [39]. In addition, temporary synchronisation between the locomotor rhythm and HR has been detected during exercising on both a mechanical treadmill and a cycle ergometer [23,28]. It is possible therefore that changes in the relation between intensity of the exercise and HR, defined in the Conconi test as the so called deflection point (DP), are, at least partially, associated with changes in the locomotor rhythm. In view of this, the aim of the present study was to analyse the course of the PO/HR, PO/SR, and SR/HR relationships during the progressive incremental exercise as well as to evaluate the accuracy of estimation of anaerobic threshold based on these three relationships.

Material and Methods

Prior to the investigation, approval from the Local Research Ethics Committee had been granted. After being fully informed of the aim and associated potential risks of the study, twelve male kayakers who volunteered to participate gave their written consent. The athletes represented either the national or international level in their sport; their mean (±SD) age, height, body mass, and duration of training were 20.6±2.9 years, 182.6±5.3 cm, 84.6±8.5 kg, and 7.8±2.4 years, respectively.

Within five to eight days the subjects participated in four (A-D) test sessions during which each of them randomly exercised on the wind-braked kayak

ergometer (K1 ERGO, Garran, Australia). All of the athletes had been previously familiarized with the kayak ergometer.

Session A: the graded exercise test until exhaustion (GT) consisting of the 3-min stages separated by the 30-s breaks. During the breaks, samples of the capillary blood were collected to estimate the lactate level (LA, enzymatic method, the Roche Diagnostics kit). In the first stage, the applied power equalled to 0.5 $W \cdot kg^{-1}$ and was gradually increased by 0.25 $W \cdot kg^{-1}$ in each subsequent stage. The fixed anaerobic threshold of 4 $mmol \cdot l^{-1}$ lactate (AT4) and Dmax anaerobic threshold (modified method [4]) were estimated.

Session B: the Conconi test (CT), preceded by the 15-min warm up during which HR was maintained at 110-130 $1 \cdot min^{-1}$. The test began at the 0.5 $W \cdot kg^{-1}$ workload which was increased every minute by 0.125 $W \cdot kg^{-1}$. The deflection point (DP) was established in the course of the following relationships: power output/heart rate (PO/HR), power output/stroke rate (PO/SR), and stroke rate/heart rate (SR/HR) (Fig. 1 A-C). Two and a half hours after completion of CT the subjects performed the 2-min all-out exercise preceded by the 10-min individual warm-up.

Session C: The 30-min exercise test (PET) performed with the intensity corresponding to the power output at DP. In case of the linear PO/HR relationship, the power for PET was determined from the PO/SR and SR/HR relationships. The test was preceded by the 5-min warm up at 50% of the determined power. For estimation of LA, capillary blood was collected before the exercise and during the 30-s breaks right after the 10^{th}, 20^{th} and 30^{th} minutes of the exercising. Increase in the LA level within the last ten minutes of the test lower than 0.5 $mmol \cdot l^{-1}$ was regarded as the maximal lactate steady state (MLSS) [6]. Two and a half hours after completion of PET the subjects performed the 10-min all-out exercise preceded by the 5-min warm-up.

Session D: The 20-min all-out exercise preceded by the 5-min warm-up.

Based on the results of the 2-, 10-, and 20-min all-out exercises performed in the B, C, and D sessions the critical power (CP) was estimated [10].

In all the tests, PO and SR were recorded with use of the standard ergometer software, whereas HR was measured using the Vantage NV monitor (Polar Electro, Finland). SR was individually and spontaneously selected by the athletes who were unaware of a significance of this variable in the experiment.

The tests always began at the same time in the morning, but no sooner than two hours after a light breakfast. The temperature and humidity of the air in the laboratory were maintained within the possibly steady ranges of 19-23ºC and 35-

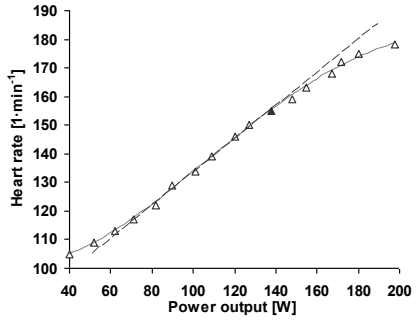

Fig. 1A

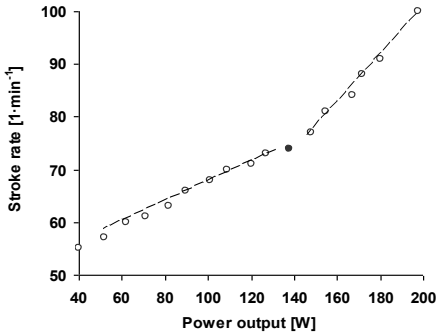

Fig. 1B

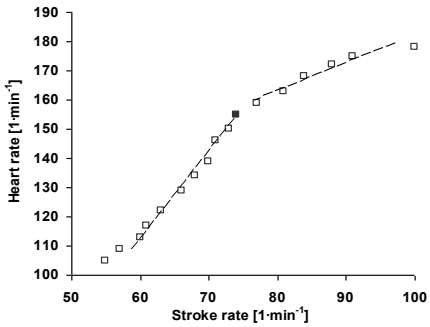

Fig. 1C

Fig. 1

Relationships between power output and hart rate (A), power output and stroke rate (B), and stroke rate and heart rate (C) in the progressive incremental exercise on the kayak ergometer. Points show mean values obtained in the consecutive stages of the test. The values marked with the closed symbols were regarded as deflection points. Presented are data obtained in athlete no. 8

40%, respectively. During the breaks between the tests the subjects were provided with the appropriate amounts of liquids.

The differences between mean values were tested by one-way analysis of variance (ANOVA with repeated measures). Level of statistical significance was set at the $P<0.05$. Moreover, the Bland-Altman analysis was employed for evaluation of the agreement between methods.

Results

PO, HR, and SR at DP and the stages (times) of occurrence of DP in the PO/HR (Fig. 1A), PO/SR (Fig. 1B), and SR/HR (Fig. 1C) relationships are shown in Table 1.

Table 1
Power output (PO [W]), hart rate (HR [$1 \cdot min^{-1}$]), and stroke rate (SR [$1 \cdot min^{-1}$]) at deflection points (DP) and test stages (time) of the occurrence of DP in the course of the PO/HR, PO/SR and SR/HR relationships

Subjects	PO/HR	Stage (min)	PO/SR	Stage (min)	SR/HR	Stage (min)
1	160/151	13	169/87	14	87/154	14
2	-	-	109/64	12	64/181	12
3	153/180	12	147/73	11	73/175	11
4	196/153	17	196/81	17	79/150	16
5	119/171	10	132/65	11	63/171	10
6	-	-	120/73	12	73/157	12
7	149/174	13	149/87	13	87/174	13
8	138/155	11	138/74	11	74/155	11
9	116/140	9	-	-	81/140	10
10	98/152	9	111/74	10	74/158	10
11	133/180	11	142/73	12	73/183	12
12	131/181	13	131/79	13	79/181	13
(mean±SD)		12.1±2.3		12.4±2.1		12.2±2.0
(a) n=9		ANOVA with rep. meas. P>0.05				
(mean±SD)		11.8±2.2		12.1±2.0		12.0±1.8
(b) n=12		ANOVA with rep. meas. P>0.05				

(a) – only complete data
(b) – missing data replaced with the intra-individual means

Establishment of the deflection point for the PO/HR relationship appeared to be impossible in two subjects (no. 2 and 6), whereas in the third athlete (no. 9) DP was impossible to estimate for the PO/SR relationship. In contrast, in case of the SR/HR relationship DP was demonstrated in all the subjects. In athlete no. 7, inverse deflection points in the three analysed relationships were noticed. The times of the occurrence of DP in all the relationships did not differ significantly. This was the case both when the analysis included only the results of athletes exhibiting DP in all the three relationships and when the missing data were replaced by the intra-individual means calculated as the average time of the occurrence of DP in two other relationships.

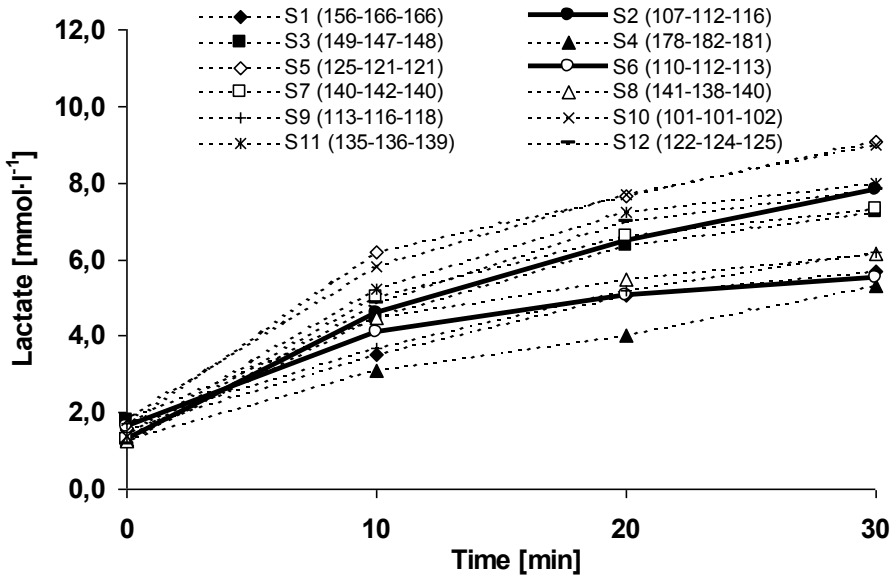

Fig. 2
Changes in the blood lactate level in kayakers subjected to a 30-min exercise (PET) at the power determined in the Conconi test (CT). Solid lines represent results obtained in the athletes exercising at the intensity determined from the power output/stroke rate and the stroke rate/heart rate relationships. Mean power outputs developed in the consecutive stages of PET are shown in brackets

Fig. 2 shows changes in the LA level as well as the mean values of PO in the consecutive stages of PET. There was no significant variation of PO which also did not differ from the applied value (PO_{DP} in Table 2). In contrast, the differences between the mean LA levels were statistically significant ($P<0.001$). In athletes no. 2 and 6 the intensity of PET determined from the PO/SR and SR/HR relationships exceeded that at MLSS in similar degree to other kayakers.

The critical power and the power output at Dmax, AT4, and DP are presented in Table 2. The differences between the means were statistically insignificant.

Table 2
Critical power (CP [W]) and power output at anaerobic threshold (PO [W]) estimated on the kayak ergometer with use of different methods (Dmax, AT4, DP)

Subjects	CP	PO_{Dmax}	PO_{AT4}	PO_{DP}
1	150	147	171	160
2	116	109	98	109
3	138	145	150	153
4	199	198	199	196
5	125	113	110	119
6	108	123	126	120
7	139	136	145	149
8	126	135	148	138
9	119	128	117	116
10	119	123	107	98
11	139	139	150	133
12	116	135	136	131
mean	133	136	138	135
±SD	24	23	29	27
	ANOVA with rep. meas. $P>0.05$			

Mean differences between the examined methods and the limits of agreement are shown in the Bland-Altman plot (Fig. 3). Although the mean differences were relatively small (range from 0.8 to 5.4 W), in individual cases they exceeded 20 W. Nevertheless, agreement of the DP-based analysis with other methods, i.e. CP, Dmax, and AT4 (left panel) was similar to those detected among the latter three methods (right panel).

Discussion

The most important finding of the present study is that during the progressive incremental exercise on the kayak ergometer performed at the spontaneous chosen SR notable deflections occur not only in the course of the PO/HR relationship but also, concurrently, during the PO/SR and SR/HR relationships. In case of the SR/HR relationship, detection of DP in all the tested subjects seems to corroborate the hypothesis that changes in the course of the relationship between intensity of the exercise and HR, defined in the Conconi test as DP, are at least partially associated with changes of the rhythm of exercising.

Numerous authors have demonstrated that in some individuals the course of the PO/HR relationship can be entirely linear [24,31]. In fact, Hoffman *et al.* [18] demonstrated this type of the course in 6.2% of the 227 young, physically active men subjected to the lower extremities test. Difficulties in the establishment of DP were also reported in subjects exercising with the upper extremities [17,32]. In one of these studies, DP was undetectable in 16% of the subjects tested on the electrically-braked arm-cranking ergometer [32]. Similar percentage of athletes exhibiting the linear PO/HR relationship was found in our present investigation.

In the present study, increase in the intensity of the exercise was associated with the rise in SR. Based on the competition efforts on various distances, a similar relationship was previously detected in swimmers [30]. However, our investigations carried out on the wind-braked kayak ergometer demonstrated that above the certain power output levels steeper courses of this relationship are detectable in most of the athletes. The higher than expected increase in SR detected in the consecutive stages of the test may result from the fatigue and decreased ability to develop the force of a single stroke (SF). Maintenance of the applied power through the increase of SR (and decrease of SF) minimizes recruitment of the fatigable fast twitch (type II) muscle fibres [2] and increases blood flow through the muscles [14], protecting thereby the organism from exhaustion. On the other hand, this may be associated with higher increase of potassium concentration in the blood [41], the effect presumably responsible for the occurrence of the deflection in the course of the PO/HR relationship [19,26].

The different response of the cardiovascular system detected in the present study in kayaker no. 7 was previously described by other authors [18]. Notably however, even though other relationships (i.e., PO/SR and SR/HR) also exhibited the reversed course, all three DPs appeared at the same stage of the test.

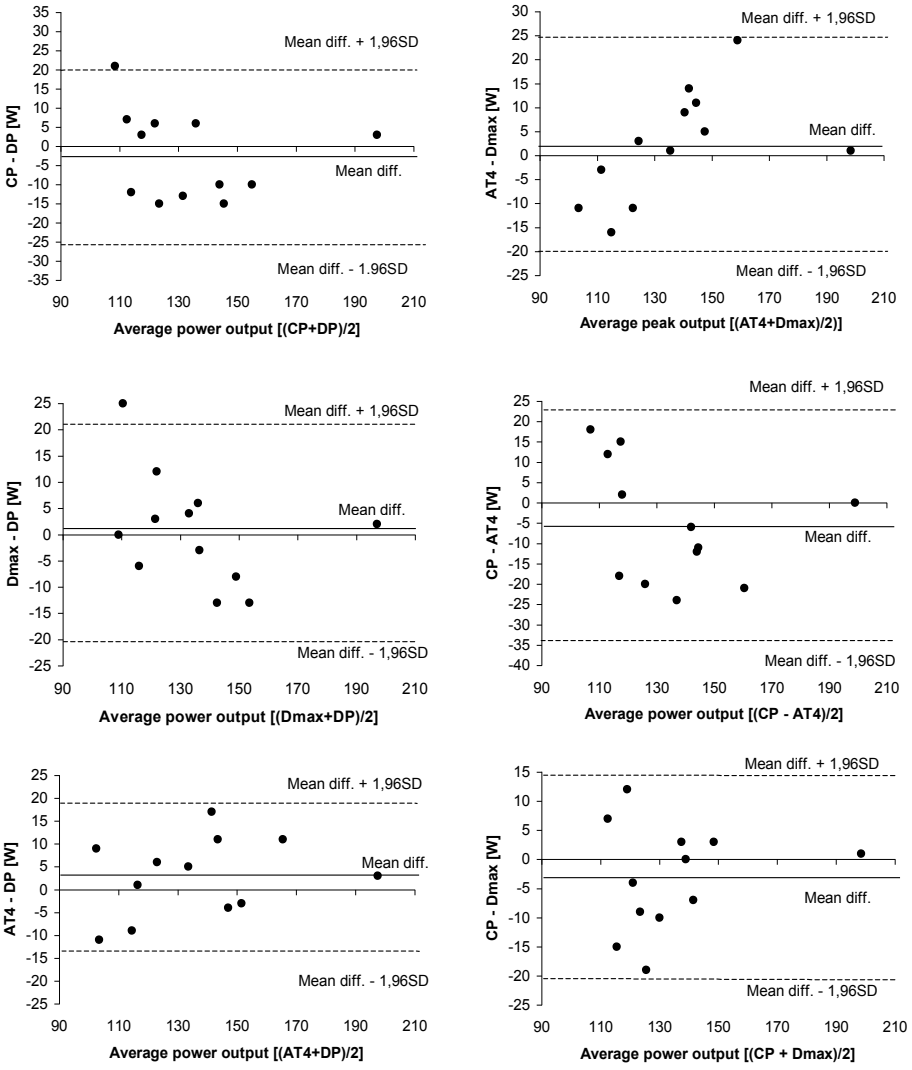

Fig. 3
Agreement between methods of determination of anaerobic threshold (DP, Dmax, AT4) and critical power (CP) - the Bland-Altman plot. The x axis shows mean of the results of the o methods ([A+B/2]), the y axis - absolute differences ([B-A]) between the two methods; solid lines represent mean differences between the methods, and dashed lines – the limits of agreement, i.e. the limits of the acceptable differences

This could additionally confirm our presumptions concerning the effect of SR on HR in the incremental efforts. However, in view of the reports by other authors [32] who registered DP also in tests based on exercising with a steady crank frequency, physiological basis of this phenomenon has to be further investigated.

Although the intensity of PET exceeded the intensity at MLSS, all the kayakers were able to complete the exercise. In contrast, in the study of Bourgois and Vrajens [6], who carried out a similar investigation in rowers, only four out of ten athletes managed to perform the whole 30-min test and one of them exhibited a steady LA level. Schmid *et al.* [32] verified anaerobic threshold estimated in eight elite paraplegic (PP) athletes and eight physically active normal health students (NH) subjected to the Conconi test on the electrically-braked arm ergometer. In their study, the 24-min exercise consisted of three eight-minute phases during which power outputs were by 10 W lower, equal to, and by 10 W higher than the power at DP. Six PP and five NH subjects had to abort the test before its completion. In the remaining athletes, the LA dynamics indicated that MLSS had been exceeded: the post-exercise concentrations of this metabolite ranged from about 6.5 to 10 $mmol \cdot l^{-1}$ and were even higher than those recorded in our own studies in kayakers who completed the whole PET (5.3 - 9.1 $mmol \cdot l^{-1}$). However, during evaluation of these results it should be borne in mind that exercising with upper extremities is to a greater extent based on glycogenolysis associated with a higher production of LA than exercising at the same relative intensity with lower extremities [1,40]. Moreover, as indicated by the results of other authors [15,33], in the former case MLSS may be detectable at the significantly higher lactate concentrations (even as high as 6-7 $mmol \cdot l^{-1}$) than during exercising with lower limbs. In view of the fact that in the present study in kayakers increase in the LA level within the last ten minutes of PET equalled to 0.9 ± 0.3 $mmol \cdot l^{-1}$ it can be assumed that PO_{DP} was only moderate higher than the power at MLSS.

Although PO_{DP} resulted in exceeding MLSS, it was not significantly different from PO_{AT4}, PO_{Dmax}, and CP (Table 2). Different results were obtained by Kuipers *et al.* [24] on a mixed group of the well-trained or sedentary subjects tested on a cycle ergometer. Above mentioned authors demonstrated that PO_{DP} was significantly higher than PO_{AT4} (286 ± 32 W and 250 ± 51 W respectively, $P<0.05$). Likewise, in the study of Schmid *et al.* [32] performed in the physically active students and the paraplegic athletes subjected to exercises on a arm ergometer, PO_{DP} was significantly (139.9 ± 22.1 vs. 107.7 ± 12.9) and insignificantly (118.7 ± 15.2 vs. 108.9 ± 20.2) higher, respectively, than PO_{AT4}. Differences between PO_{DP} and PO_{AT4} or PO_{IAT} were also found in oarsmen [7] examined on the rowing ergometer (PO_{DP} 251 ± 21 vs. PO_{AT4} 234 ± 31 W, $P>0.05$; PO_{DP} vs. PO_{IAT} 195 ± 31 W,

P<0.01). In order to correctly interpret the above differences one has to remember that analytical methods may significantly affect the values related to the fixed anaerobic threshold of 4 $mmol \cdot l^{-1}$ lactate [8].

The lack of significant differences between PO_{DP} and CP, PO_{Dmax} or PO_{AT4} might suggest that estimation of the capacity for the long-lasting physical work is independent of the method applied in the present study. On the other hand, the Bland-Altman plot indicates that although mean differences between the methods are relatively small, the limits of agreement between them can reach 20 W. Consequently, as the assessment of adaptation to the effort may diverge in individual cases, these methods should not be used interchangeably (Fig. 3, left panel).

A separate question is whether such widely accepted methods yield comparable results. The relationships between MLSS, AT4, CP, and Dmax were described by various authors. In the experiments of Burgois and Vrijens [7] carried out in ten rowers exercising at the power output at AT4 the lactate steady state was attained by five athletes; four of the subjects, however, owing to the fatigue, had to abort the test before its completion. Other investigators also demonstrated that MLSS was exceeded during exercises performed with the power output at AT4 [3,29,36] and at CP [13,27]. In addition, CP was found to be significantly higher than PO_{AT4} [10]. On the other hand, MLSS was registered during swimming at the critical velocity [38], and the results obtained by Bishop [5] suggested that MLSS can be attained in efforts performed at PO_{Dmax}.

The described relationships between the discussed methods are presented in the Bland-Altman analysis (Fig. 3, right panel). Although mean differences between the values were small, the limits of agreement reached, on average, 20 W. However, these differences were comparable to those found during the comparison of PO_{DP} with PO_{AT4}, PO_{Dmax} and CP (Fig. 3, left panel).

The obtained results confirm the hypothesis that alterations in the course of a relationship between intensity of the effort and HR, reflected in the Conconi test as the deflection point, are related to spontaneous changes in the rhythm of work. The lack of diversity among the times of occurrence of DP in the PO/HR, PO/SR, and SR/HR relationships allows for the easy and non-invasive estimation of AT even when the classic PO/HR relationship is entirely linear. Power output estimated with the presented method is higher than the power at MLSS but it can be sustained by at least 30 min. The accuracy of estimation of anaerobic threshold based on the analysis of three DPs in an incremental exercise seems to be comparable with that obtained using AT4, Dmax, and CP.

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