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POWER OUTPUT AND MECHANICAL EFFICIENCY OF HUMAN MUSCLE IN MAXIMAL CYCLE ERGOMETER EFFORTS AT DIFFERENT PEDALLING RATES

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Abstract. The aim of this work was to verify the hypothesis that the lowering of the pedalling rate (elicited by the increase of the exterior load) during maximal efforts performed with identical work amount causes the growth of the generated power (until the maximal values are reached) and next its fall and does not influence the gross and net mechanical efficiency changes. The above experiment was conducted with 13 untrained students who performed 5 maximal efforts with the same work amount. The first was the 30 s maximal effort (Wingate test) with the load equal 7.5% of the body weight (BW). The amount of work performed in this test was accepted as the model value for following tests to achieve. Every 3 days, each examined had next trials consisting of maximal efforts on the cycle ergometer with loads of: 2.5, 5, 10, 12.5% BW and lasting until the value of power reached in the 30 s Wingate test occurred. Changing of the external load elicited various pedalling velocity. The force-velocity (*F*-*v*) and power-velocity (*P*-*v*) dependence was calculated for every examined subject basing on the results of performed maximal efforts. The maximal power (P_{max}) and optimal velocity (v_o) were calculated basing on the *P*-*v* relationship depicted with the second order polynomial equation. The gas analyser (SensorMedics) equipped with the 2900/2900c Metabolic Measurements Cart/System software was used as for the oxygen output measuring during maximal efforts performance and in the resting phase. The ventilation and gas variable changes were monitored breath-by-breath in the open ventilation system. The POLAR-SportTester was used for the heart retraction (HR) measurement during both: efforts and resting. The capillary blood was taken from the fingertip before the test and: immediately after it, every 2 min for the first 10 min of the rest and in the 20^{th} min of resting. The blood was used for the acid-base balance determination with the use of the blood gas analyser – Ciba-Corning 248. The average pedalling rate decreased during effort from 151.5 rpm to 80 rpm and the power grew from 293.5 W to 761 W along with the increase of the load from 2.5% to 12.5% BW. Powers varied among specific trials with the

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exception of values obtained with load equal 10 and 12.5% BW. The increase of the gross and net mechanical efficiency from 5.9 to 8.1% and from 12.2 to 19.0% respectively was also observed. The gross mechanical efficiency values reached by the load of 2.5% BW differed significantly in relation to values obtained in efforts with loads of 7.5, 10 and 12.5% BW. In the case of HR_d (difference between HR_{max} and HR measured in relaxation), crucial disagreements were noticed between efforts with load of 2.5% and 12.5% BW. HR_{max} values did not differentiate performed trials. The mechanical efficiency and HR_d did not vary significantly in trials with 5, 7.5, 10, 12.5% BW loads. Maximal efforts conducted with loads of 5% and 7.5% BW elicited similar changes of the acid-base balance in all measurements. ***(Biol.Sport 22:35-51, 2005)***

Key words: Mechanical efficiency - Force-velocity relationship - Power output - Fatigue index - Cycle ergometer

Introduction

The ability of human to develop highest power values in short time plays an important role in many sport disciplines and every day activity. Power depends on force and velocity. In maximal efforts power is measured on the non-isokinetic cycle ergometer e.g.: Monark 824 [8,27,49] and isokinetic [5,35,39]. The most frequently used agents for the maximal power determination are the force-velocity (*F-v*) and power-velocity (*P-v*) relationship [16,28,35,39,49,52]. References present that the muscles power and the *F-v* and *P-v* characteristics were studied while the performance of maximal efforts with the same duration but different values of: done work, pedalling rate or the load.

The mechanical efficiency is usually used for the human's motorial efficiency description. The higher efficiency (economy) is being connected with better results achieved in various sport disciplines [14,23,33]. The mechanical efficiency in chosen motorial actions amounted from 2% to 80% dependently on: working limb [50], amount and time of work [51], performed exercises (eccentric, concentric, mixed) [2,3], practiced sport discipline [38], type of muscles fibres [4] or calculation methods (e.g.: running velocity counted on the basis of film [29] or as a treadmill velocity used by examined [36]). Many studies analyse the gross mechanical efficiency (GE) for it is easy to measure and does not require the correction considering the restful oxygen intake [19]. However, some of authors suggest, that the net mechanical efficiency gives more information about muscles efficiency [13,26]. Some papers results show that the gross efficiency obtained in the sub-maximal efforts grows along with the load [10,19,42] and it changes according to the pedalling rate [18]. In works of Böning *et al*. [6], Chavarren and Calbet [9], Gaesser and Brooks [19], Hagberg *et al*. [22], Seabury *et al*. [42] was stated that the gross mechanical efficiency (GE) was decreasing, reversely to the pedalling rate which was increasing. Other authors noticed that GE was relatively balanced in efforts with power of 280-290 W, independently on the pedalling velocity [18,43]. On the other hand, in the study of Buśko and Kłossowski [7] is showen that the net mechanical efficiency is not depended on the sub-maximal effort power and pedalling velocity but on the performed work value. There are only few works in references describing mechanical efficiency in maximal efforts [21,35,51]. Maximal efforts presented there were differentiated with its time, amount of load or pedalling rate and mechanical efficiency values amounted from 1% to 24.6%. Researches depicting changes of the mechanical efficiency in maximal efforts with identical work amount and different pedalling velocity performed on the non-isokinetic cycle ergometer were not found.

The aim of this work was to verify the hypothesis that the lowering of the pedalling rate (elicited by the increase of the exterior load) during maximal efforts performed with identical work amount causes the growth of the generated power (until the maximal values are reached) and next its fall and does not influence the gross and net mechanical efficiency changes.

Material and Methods

The study encompassed 13 untrained, physical education students. Examined group characteristic: age – 21.9±1.1 years, body height – 182.9±5.6 cm, body weight – 81.3±7.3 kg.

The Scientific Research Board of Ethics accepted the above research. All participants were informed about the study aim and methodology as well as about the possibility of immediate resignation at any time of the experiment. Subjects agreed on the above conditions in written.

Experiment: Before the study all participants acquainted the research procedure. Next, they performed 30 s maximal effort (Wingate test) with the load equal 7.5% body weight (BW). The amount of work obtained in this test was accepted as the value for following exercises to achieve. Every 3 days, each examined performed next trials consisting of maximal efforts on the cycle ergometer with loads equalling: 2.5%; 5.0% 10% and 12.5% BW until the value of work reached in the 30 s Wingate test. The change of the exterior load elicited various pedalling rates during the maximal efforts with the same work quantity. All maximal efforts were performed on the Monark 824 E cycle ergometer (Sweden) connected with the IBM PC Pentium equipped in the “MCE v. 4.0” software (“JBA” Z. Staniak, Poland). Gauges were fastened at the fly-wheel, which made a 6 m distance during one pedals rotation. Examined fixed the handle-bar and chair and next, performed tests in sitting position without standing on pedals. They started motionless. Feet were fastened to pedals with straps. Subjects were eagerly spurred to obtain the maximal velocity in the shortest time and keeping it till the end of the test. Using the “MCE v. 4.0” software following calculations and measurements were done: mean power (P_m), mean velocity (v_m), the highest power in respective trial (P_n) counted in 3 s intervals, velocity allowing the development of P_n (v_n), mechanical work amount (W_m) and fatigue index (FI) calculated as the difference between P_n and the smallest power value gained in the exercise finish and divided by $P_{n.}$

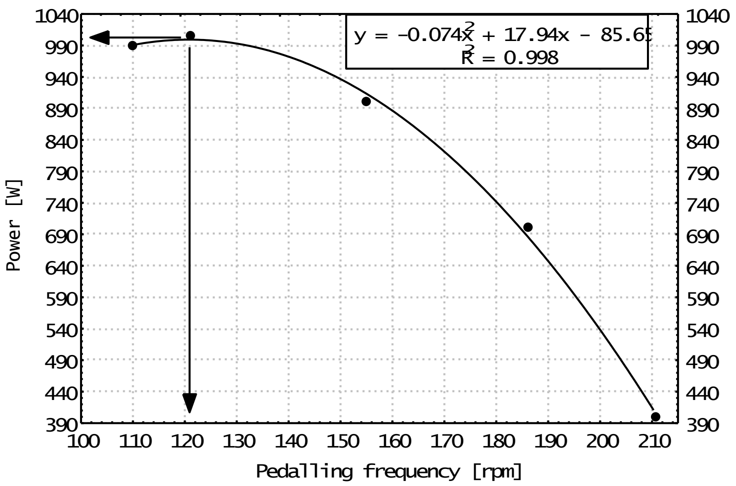

Fig. 1
Power-pedalling velocity (P_n-v_n) relationship obtained by one subject in maximal efforts on the cycle ergometer. Arrows point the maximal power (P_{max}) and the corresponding optimal frequency of pedalling (v_o).

Attained results enabled determination of force-velocity (*F*-*v*) and power-velocity (*P*-*v*) relationship which were used for the individual maximal power (P_{max}) and optimal velocity (v_o – pedalling rate allowing production of maximal power [49]) estimation. The maximal power and optimal rate of pedalling were calculated basing on the individual equations of the second order polynomial regression describing the *P*-*v* relationship [25,31]. The highest point at the curve (the highest value of function) was defined as the maximal power (P_{max}) and responding to it pedalling rate as the optimal velocity (Fig. 1) [32].

As for the oxygen intake specification during the maximal efforts performance and in the resting phase (till V_E reaches the restful value) the SensorMedics (USA) gas analyser with 2900/2900c Metabolic Measurements Cart/System software was used. Ventilation and change of the gas variables were monitored breath-by-breath in the open ventilation system. The gas analyser was calibrated before each examination with the O_2 and CO_2 gases (AGA Gas BV, Holland).

The gross mechanical efficiency (GE) was calculated as the mechanical work and total energy (E_c) ratio, and the net mechanical efficiency (NE) as the mechanical work and net total energy (E_{cnet} – total energy value diminished by restful energy value) ratio.

Heart retraction measuring was done during every effort and after it using the POLAR-SportTester of OY company (Finland).

The capillary blood was taken from the fingertip before the test and: immediately after it, every 2 min for the first 10 min of the rest and in the 20th min of resting. The blood was taken to the heparinized capillaries and the acid-base balance was marked. Using the blood gas analyser Ciba-Corning 248 (G.B.) following acid-base balance indices were analysed: BE, HCO_{3act}, pH.

All measurements were taken in the morning.

The MANOVA analysis of variance was used for the results verification. The significance of differences between averages was compared post hoc using the Tukey's test. The ANOVA procedure with reiterated recordings (5x8) was used for the acid-base balance results analysis. The significance of differences between averages was confronted post hoc using the LSD test. The order of dependence among measured values was estimated on the basis of Pearson's correlation coefficients. All calculations were conducted with the STATISTICA^{TM} software (v.5.5, StatSoft, USA).

Results

The studies results are presented in Table 1. The average velocity (v_m) decreased during maximal efforts on the cycle ergometer from 151.5 rpm to 78.0 rpm; P_n and P_m increased from 383.3 W and 293.5 W to 958.0 W and 761.0 respectively along with the enlargement of the load from 2.5% to 12.5 BW. Power values differed between the respective trials with the exception of the load equal 10 and 12.5% BW. Average gross mechanical efficiency (GE) values obtained by the load of 2.5% BW differed significantly in relation to qualities gained in efforts with

Table 1
Average (±SD) measured variables: v_m – mean velocity; v_n – speed by which the highest power occurred; W_m – mechanical work; P_n - the biggest power in respective trial; P_m – mean power; FI – fatigue index; E_c – gross total energy; E_{cnet} – net total energy; GE – gross mechanical efficiency; NE – net mechanical efficiency; t – effort time; HR_{max} – maximal heart rate; HR_d – difference between HR_{max} and restful HR in examined group (n=13)

Variables	Load				
	2.5% BW	5.0% BW	7.5% BW	10.0% BW	12.5% BW
v_m [rpm]	151.5± 8.9	142.0± 7.2[a]	113.8± 5.5[ab]	98.2± 7.9[abc]	78.0± 9.2[abcd]
v_n [rpm]	192.5±11.2	171.1±9.2[a]	141.9±5.7[ab]	119.0± 9.9[abc]	97.2± 10.3[abcd]
W_m [kJ]	20.0± 1.7	20.2± 1.6	20.1± 1.7	20.2± 1.7	20.1± 1.7
P_n [W]	383.3±34.7	681.9±67.1[a]	844.0±77.2[ab]	948.4±109.1[abc]	958.0±142.8[abc]
P_n/BM [W/kg]	4.72± 0.28	8.39± 0.45[a]	10.39± 0.43[ab]	11.67± 0.97[abc]	11.93± 1.26[abc]
P_m [W]	293.5±28.5	547.9±46.7[a]	670.9±56.8[ab]	761.0± 87.5[abc]	753.8± 96.3[abc]
E_c [kJ]	344.9±58.3	288.0±51.0	273.1±66.1[a]	260.0± 47.2[a]	254.2± 45.3[a]
E_{cnet} [kJ]	168.4±32.7	129.7±29.5[a]	115.2±26.8[a]	112.6± 27.8[a]	106.7± 14.2[a]
GE [%]	5.9±1.0	7.2±1.2	7.8±2.1[a]	8.0± 1.4[a]	8.1± 1.1[a]
NE [%]	12.1± 2.6	16.0± 2.8[a]	16.3± 3.2[a]	16.9± 3.2[a]	17.6± 1.6[a]
FI [%]	24.7± 3.3	21.1± 4.1	21.1± 4.4	19.2± 5.8[a]	18.2± 2.8[a]
t [s]	68.5±4.1	36.9± 2.0[a]	30.0± 0.0[ab]	26.6± 1.9[abc]	27.0± 3.4[abc]
HR_d [beat/min]	106.5± 7.2	105.0±11.4	97.8± 9.9	100.5± 9.3	94.2± 8.9[ab]
HR_{max} [beat/min]	177.0± 9.0	174.2± 8.1	168.8±12.6	169.2± 10.9	166.5± 9.7

Statistically significant differences at $p<0.05$: [a] - 2.5% BW vs. 5.0. 7.5. 10.0, 12.5% BW, [b] - 5.0% BW vs. 7.5. 10.0, 12.5% BW, [c] - 7.5% BW vs. 10.0, 12.5% BW, [d] - 10.0% BW vs. 12.5% BW.

load equal 7.5, 10 and 12.5% BW. The net mechanical efficiency (NE) attained in during the 2.5% BW loaded effort varied crucially in comparison to efforts with 5.0, 7.5, 10.0 and 12.5% BW. In the case of HR_d (difference between HR_{max} and HR measured while resting) some important differences were observed among efforts with 2.5% and 12.5% BW loads. The HR_{max} values were not significantly different. The HR_{max} and v_m relation was linear (Fig. 2). The mechanical efficiency and HR_d did not vary crucially in exercise with the load of 5, 7.5, 10 and 12.5%

BW. The maximal power (P_{max}) counted from the individual *P-v* characteristics amounted to 1050.6±164.1 W (relative value – 12.98±2.13 W/kg) and occurred by the optimal pedalling rate (v_o=107.6±11.2 rpm). The "optimal, mean pedalling

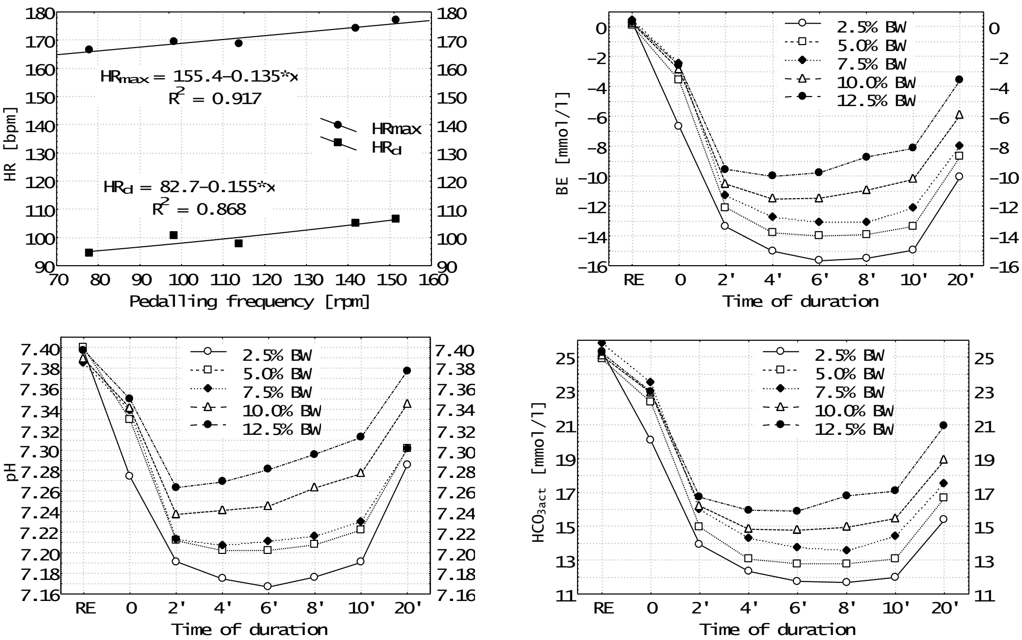

Fig. 2
Interdependence of maximal heart retraction (HR_{max}), heart retraction frequency difference between HR_{max} and restful HR (HR_d) and the average pedalling rate as well as the change of the acid-base balance mean values effected by maximal efforts with identical work amount and load: 2.5; 5; 7.5; 10; 12.5% BW. RE – restful value; 0 – measurement done immediately after the effort; 2', 4', 6', 8', 10' and 20' – recordings made in 2, 4, 6, 8, 10 and 20 min of the rest

velocity" (90±5.8 rpm) was calculated from the individual mean power-mean velocity and gross total energy-mean velocity relationship (Fig. 3) described by the second order polynomial equation. The optimal, mean pedalling rate allowed determination of the mean power (P_m=768.3±83.6 W) and "economic pedalling velocity” = 87.9±16.1 rpm where the lowest use of the gross total energy occurred (E_c=228.5±55.4 kJ). Both calculated pedalling velocitys did not differ significantly.

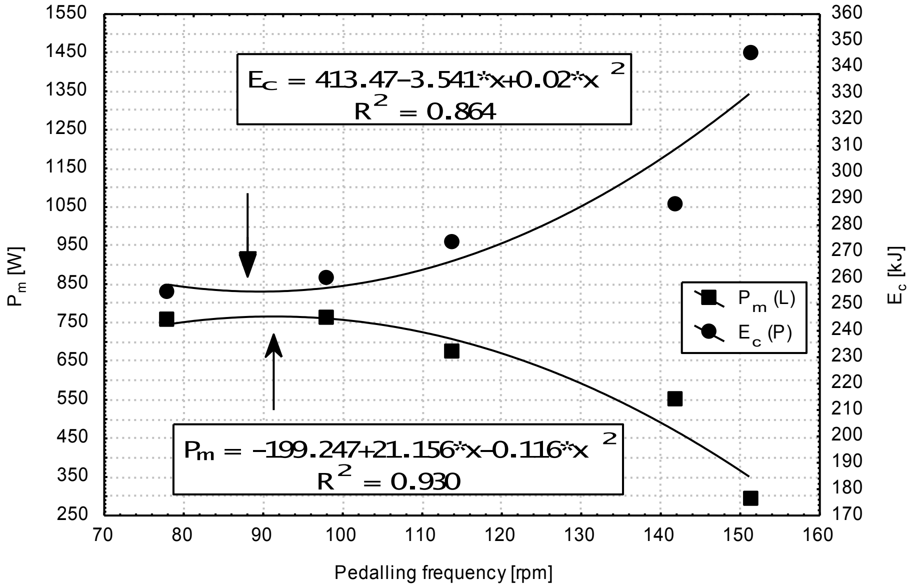

Fig. 3
Relationship of mean power-mean velocity ($P_m – v_m$) and gross total energy-mean velocity ($E_c – v_m$) acquired for average values of examined group. Arrows show the optimal and economical pedalling rate

Changes of the average acid-base balance values (±SD) are presented in tables 2-4. Generally, in all measurements of the acid-base balance any significant differences between efforts with loads of 5.0 and 7.5% BW were stated. All remaining cases varied statistically between efforts with the exception of the restful values.

Table 2
Changes of BE (averages ±SD) under the influence of maximal efforts performed with the same work amount on the cycle ergometer with loads equalling: 2.5; 5.0; 7.5; 10.0 and 12.5% BW. RE – restful value; 0 – measurement done immediately after the effort; 2', 4', 6', 8', 10' and 20' – recordings made in 2, 4, 6, 8,10 and 20 min of the rest in examined group (n=10)

	Load				
	2.5% BW	5.0% BW	7.5% BW	10.0% BW	12.5% BW
RE	0.33±0.93	0.09±1.81	0.44±0.91	0.24±1.31	0.30±1.14
0'	-6.64±1.93	-3.56±1.69[a]	-2.45±1.38[a]	-2.86±1.81[a]	-2.58±2.0a
2'	-13.39±1.41	-12.10±1.35	-11.27±1.73[a]	-10.53±1.32[ab]	-9.54±1.34[abc]
4'	-15.03±1.69	-13.80±1.49	-12.73±1.83[a]	-11.54±1.17[ab]	-10.02±1.44[abcd]
6'	-15.67±1.82	-14.01±1.62[a]	-13.08±2.01[a]	-11.48±1.27[abc]	-9.77±1.69[abcd]
8'	-15.51±1.92	-13.92±1.96	-13.11±2.09[a]	-10.95±1.50[abc]	-8.72±1.63[abcd]
10'	-14.96±2.27	-13.37±2.12	-12.11±2.43[a]	-10.22±1.63[abc]	-8.14±1.44[abcd]
20'	-10.06±2.68	-8.70±2.69	-8.01±3.04	-5.92±2.35[ab]	-3.57±1.34[abcd]

Statistically significant differences at $p<0.05$: [a] - 2.5% BW vs. 5.0. 7.5. 10.0, 12.5% BW, [b] - 5.0% BW vs. 7.5. 10.0, 12.5% BW, [c] - 7.5% BW vs. 10.0, 12.5% BW, [d] - 10.0% BW vs. 12.5% BW.

Table 3
Changes of HCO_{3act} (averages ±SD) effected by maximal efforts performed with identical work amount on the cycle ergometer with loads of: 2.5; 5.0; 7.5; 10.0 and 12.5% BW. RE – restful value; 0 – measurement done immediately after the effort; 2', 4', 6', 8', 10' and 20' – recordings made in 2, 4, 6, 8, 10 and 20 min of the rest in examined group (n=10)

	Load				
	2.5% BW	5.0% BW	7.5% BW	10.0% BW	12.5% BW
RE	25.35±1.11	24.89±2.30	25.80±0.88	25.08±1.92	25.25±1.39
0'	20.07±1.64	22.34±2.47[a]	23.52±1.46[a]	22.89±1.85[a]	22.96±2.21[a]
2'	13.92±1.54	14.95±1.43	16.01±1.70[a]	16.21±1.50[a]	16.72±1.25[ab]
4'	12.34±1.42	13.06±1.41	14.29±1.53[ab]	14.83±1.18[ab]	15.95±1.24[abc]
6'	11.75±1.51	12.79±1.44	13.75±1.61[a]	14.77±1.13[ab]	15.90±1.47[abc]
8'	11.68±1.48	12.79±1.70	13.57±1.84[a]	14.94±1.35[ab]	16.80±1.37[abcd]
10'	11.98±1.68	13.07±1.77	14.43±1.98[a]	15.46±1.41[ab]	17.08±1.22[abcd]
20'	15.38±2.22	16.67±2.36	17.55±2.59[a]	18.90±2.02[ab]	20.95±1.23[abcd]

Statistically significant differences at $p<0.05$: [a] - 2.5% BW vs. 5.0. 7.5. 10.0, 12.5% BW, [b] - 5.0% BW vs. 7.5. 10.0, 12.5% BW, [c] - 7.5% BW vs. 10.0, 12.5% BW, - 10.0% BW vs. 12.5% BW.

Table 4
Changes of pH (averages ±SD) under the influence of maximal efforts performed with the same work amount on the cycle ergometer with loads amounting to: 2.5; 5.0; 7.5; 10.0 and 12.5% BW. RE – restful value; 0 – measurement done immediately after the effort; 2', 4', 6', 8', 10' and 20' – recordings made in 2, 4, 6, 8, 10 and 20 min of the rest in examined group (n=10)

	Load				
	2.5% BW	5.0% BW	7.5% BW	10.0% BW	12.5% BW
RE	7.397±0.017	7.400±0.010	7.385±0.018[b]	7.389±0.016	7.397±0.019
0'	7.274±0.035	7.330±0.028[a]	7.339±0.032[a]	7.341±0.026[a]	7.350±0.014[a]
2'	7.192±0.026	7.212±0.026	7.213±0.033	7.237±0.019[abc]	7.264±0.026[abcd]
4'	7.205±0.091	7.202±0.032	7.208±0.038	7.241±0.021	7.269±0.027[abc]
6'	7.167±0.038	7.202±0.032[a]	7.212±0.042	7.245±0.024[abc]	7.281±0.030[abcd]
8'	7.177±0.040	7.208±0.034[a]	7.216±0.042[a]	7.263±0.026[abc]	7.296±0.029[abcd]
10'	7.191±0.044	7.222±0.037	7.230±0.046[a]	7.277±0.028[abc]	7.312±0.026[abcd]
20'	7.286±0.044	7.301±0.040	7.302±0.046	7.345±0.037[abc]	7.377±0.019[abc]

Statistically significant differences at $p<0.05$: [a] - 2.5% BW vs. 5.0. 7.5. 10.0, 12.5% BW, [b] - 5.0% BW vs. 7.5. 10.0, 12.5% BW, [c] - 7.5% BW vs. 10.0, 12.5% BW, [d] - 10.0% BW vs. 12.5% BW.

Discussion

During the short, maximal efforts the maximal power is produced by the optimal pedalling velocity and the force-velocity (*F-v*) dependence is described by hyperbola [52] or line [16,35,39,52]. In the work of Vandewall *et al*. [49] the force-velocity characteristic was determined on the cycle ergometer in various sport disciplines male and female players. The linear relationship between the force and pedalling rate was found in the interval of 100-200 rpm. In the work of McCartney *et al*. [35] the *F-v* characteristics were determined in 10 s efforts on the isokinetic cycle ergometer by rate of 60-160 rpm changing every 20 rpm (2 min brake between repetitions). The 30 s maximal efforts with the pedalling velocity equal: 60, 100 and 140 rpm were performed as well. The linear dependence between the torque peak and pedalling rate was found. The power-pedalling frequency relationship was parabolic. The highest power = 1826±287 W was noted by the pedalling velocity equal 140 rpm and the lowest = 1323±198 W by 60 rpm. The pedalling rate influenced the maximal power while the average power and performed work in all 30 s efforts remained similar. In the paper of Hintzy *et al.* [25] average v_o values amounted to 123.1±11.2 rpm and P_{max}/BM to 11.1±1.6

W/kg. Arsac *et al*. [1] obtained v_o=125±9 rpm and P_{max}/BM=11.5±1.7 W/kg. Hautier *et al*. [24] accomplished v_o=120±8 rpm, P_{max}=921±200 W and P_{max}/BM=14.36±2.37 W/kg. Force-velocity relationship attained in this work was presented as a line. It is coherent with other authors' results [16,28,49,52]. On the other hand, the maximal power (P_{max}) calculated from the individual *P-v* characteristics equalled 1050.6±164.1 W (12.98±2.13 W/kg) and occurred by the optimal pedalling velocity (v_o) – 107.6±11.2 rpm. The power in studies of Hautier *et al*. [24] was higher from this measurements. It could be the effect of the special training applied to subjects taking part in Hautier's *et al*. [24] experiment and of the fact that for the maximal power calculation the inertial moment of the fly-wheel was taken into account. Data fetched in this work for the cycle ergometer are in coherence with the results gained for the isokinetic [35,39,40] and non-isokinetic [1,25] cycle ergometer present in references. In the work of Dotan and Bar-Or [17] was noticed that the power is decreasing more when the load is increasing. McCartney *et al*. [35] stated that the power drop is effected by the pedalling rate. The bigger decrease of power by the higher pedalling velocity was the effect of the useful work coefficient lowering. This researches recorded during exercises the diminish of FI along with the load increase. It is in accordance with results of Vandewelle *et al*. [48] who proved that the power drop during the Wingate test depended on the effort load only in a small order. The disagreement with results of Dotana and Bar-Or [17] may be elicited by the alien technique used in trial: this research – constant work, various exercise duration; Dotan and Bar-Or work [17] – changeable work, constant time of duration.

The conception of "economical pedalling velocity" in sub-maximal efforts is defined as a pedalling rate allowing for the least oxygen intake. Paradoxically, in spite of the fact that the most economical velocity is 50-80 rpm [6,10,11,19,34,42], professional cyclist prefer the rate of 90-105 rpm during long lasting efforts [22,41]. Similar was the behaviour of non-professional cyclists [34,45]. In studies of Marsh and Martin [34] and Pugh [37] the growth of the effort power did not influence preferred pedalling rate. However, in papers of Böning *et al*. [6], Coast and Welch [10], Seabury *et al*. [42] was noticed that the economical pedalling value was growing along with the growing of performed exercise power. The economical pedalling velocity rose in Böning *et al*. [6] from 52 rpm by 50 W to 67 rpm by 200 W and in Seabyry *et al*. [42] from 42 rpm by 41 W to 62 rpm by 327 W. Coast and Welch [10] observed the linear increase of the economical pedalling velocity from 50 to 80 rpm by power growth from 100 to 300 W. In Marsh and Martin [34] the economical pedalling calculated from the second order polynomial changed insignificantly from 53.3 to 59.9 rpm by the power increase from 75 to 200 W. It seems that the pedalling rate choice (preferred/economical) does not apply in maximal efforts with maximal frequency. In this presentation, the optimal, mean pedalling rate (90.0±5.8 rpm) was calculated from the P_m-v_m and E_c-v_m individual relationship obtained in the maximal efforts with identical work amount and described by the second order polynomial equation. The above quality allowed production of the biggest mean power (768.3±83.6 W) and economical pedalling velocity (87.9±16.1 rpm) by which the lowest gross total energy was seen (228.5±55.4 kJ). Both pedalling rates did not differ crucially. It may be the prove that there exist, in maximal efforts with the same value of work, some average, economical pedalling velocity accompanied by the lowest energetic output and highest average power.

In the work of Wojcieszak *et al*. [51] the mechanical efficiency in 30 s maximal effort amounted to 13.3%. In the study of Granier *et al*. [21] the mechanical efficiency equalled 24.6% (sprinters) and 24.5% (medium-distance runners) in the Wingate test performed with the load eliciting the highest power production. Values considering 30 s maximal trial fetched in this research are lower than results of Granier *et al*. [21] and higher than in Wojcieszak *et al*. [51].

The influence of the pedalling rhythm on the mechanical efficiency in maximal efforts was described in papers of McCartney *et al*. [35]. In the study of McCartney *et al*. [35] the mechanical efficiency in 30 s maximal efforts on the isokinetic ergometer with various pedalling velocity amounted respectively: 18.7-21.5% for 60 rpm; 7.5-11.5% for 100 rpm and 1-3% for 140 rpm. According to the above authors the mechanical efficiency is related to applied load as long as the pedalling velocity is stable. The biggest power occurred by 140 rpm and the smallest by 60 rpm during the 30 s isokinetic maximal efforts with the same work amount. The power and FI growth accompanied the pedalling velocity increase. The reverse phenomenon was noted in this work for the isotonic efforts. The increase of load elicited pedalling rate decrease which effected in growth of power and fall of FI. Alike in research of McCartney *et al*. [35] the smallest values of mechanical efficiency were observed for efforts performed with the highest pedalling frequency. However, the only significant differences displayed itself between mechanical efficiency in effort with 2.5% BW (the highest pedalling) and the rest of trials. These results may contradict the McCartney's *et al*. [35] thesis that the efficiency depends on load as long as the pedalling is stable and confirm thesis of Buśko and Kłossowski [7] that mechanical efficiency is not influenced by effort power, pedalling velocity and trial lasting but only by the amount of performed work.

Heart retraction (HR) is one of the physiological indices being effected by the pedalling velocity [22] or effort power [10]. In a dissertation of Buśko and Kłossowski [7] statistically significant differences were observed only for HR_d during a 5 min effort with 150 W and both big and small velocity. Although examined performed bigger useful work in the sub-maximal effort with small pedalling rate (30 rpm) it was companioned by smaller circulation system reaction on effort (HR_d=59.5±13.7 beats/min) than in exercise with big rate – 80 rpm (HR_d=69.2±11.8 beats/min). The circulatory system reaction (HR_d) grew stronger in efforts with 250 W from 82.1±13.0 beats/min to 86.8±13.3 beats/min simultaneously with the pedalling rate from 40 to 80 rpm. Differences were statistically insignificant. In the work of Hagberg *et al*. [22] the linear growth of HR was found along with the pedalling velocity increase. In the study of Croisant and Boileau [15] the HR-pedalling rate dependence was adjusted by the smallest squares method. In the research of Cost and Welch [10] the lowest HR values in 3 min efforts with various pedalling (40-120 rpm) and power (100-300 W) were observed for 60 rpm. The effort power growth was accompanied by higher HR values. Somewhat distant results of maximal efforts were accomplished in this paper. The load increase caused the pedalling velocity diminish and as a consequence, smaller circulation system reaction. It is in a disagreement with outcomes of McCartney *et al*. [35] who described similar lactate acid concentration after 30 s maximal efforts on the isokinetic ergometer with 60, 100 and 140 rpm pedalling rate as well with the theory of Chavarren and Calbet [9] that HR is an index of exercises intensity and not the pedalling velocity effect. Presented differences of reaction on maximal efforts may flow from the work variety (isotonic and isokinetic).

In conclusion, there should be stated that the pedalling velocity change (increase of the load: 2.5-12.5% BW), in maximal efforts with identical work amount, elicited essential growth of produced power and insignificant of mechanical efficiency as well as the fatigue index and circulatory system reaction fall. The smallest changes of the acid-base balance were noted in efforts performed with the smallest pedalling velocity (loads of 12.5% BW). However, it ought to be remembered that interpretation of *F-v*, *P-v* and mechanical efficiency results must be cautious for morphological factors e.g.: muscle fibre type, also may matter. It is confirmed by results of Coyle *et al*. [12], Hautier *et al*. [24], Suzuki [44] and Tihanyi *et al*. [47] who ascertained that the optimal velocity (allowing for maximal power and mechanical efficiency production) depends on FT and ST fibres relation which practically does not change under the influence of training [20,30,46].

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