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Reliability of estimation of maximum performance capacity on the basis of submaximum ergometric stress tests in children 10–14 years old*

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Abstract. Thirty-three 10-year-old boys repeatedly performed six symptom-limited, spiroergometric exercise tests according to the vita maxima method over an observation period of 4 years. Submaximum and maximum performance parameters were assessed and their correlation was calculated. The correlation of the heart rate at 1, 2 and 3 watts/kg body weight with the values of maximum performance capacity ($watt_{max}$ and VO_2max) and with the body-weight-related, relative maximum values was statistically significant. The correlation factors for the relative values were about twice as high ($r = 0.55$) as the absolute values ($r = 0.27$). The heart rate at 1, 2 and 3 watts/kg therefore was more characteristic of the relative values, which represent the state of training, and less for the absolute performance capacity, which depends to a great extent on body weight. However, the statistically significant correlation factors were too low to estimate reliably the state of training in an individual case. The correlation of physical working capacity at an HR of 170/min (PWC 170) with the maximum ergometric Watt performance was $r = 0.80$ and therefore appears to be sufficient to estimate the maximum performance capacity in children. This is however only valid for children over the age of 11.

Key words: Maximum performance capacity – Submaximum stress test – Ergometry – Physical working capacity (PWC) 170

Introduction

For evaluation of the maximum performance capacity of the respiratory and cardiovascular systems and the aerobic metabolism of the peripheral muscles, the maximum ergometric performance capacity (in Watts) and the maximum oxygen consumption have been employed for many years. To measure these parameters of maximum performance capacity, a symptom-limited ergometric exercise test is required. Such tests are often neither possible nor desirable because of the varying motivation of the tested individuals and the greater expense due to their time-consuming nature. Test procedures therefore are often applied that permit evaluation of the maximum exercise capacity on the basis of standardized submaximum stress tests, especially when children are to be tested for sport-medical or school-medical reasons.

Many tests of circulatory function and physical performance that claim to provide an estimation of the maximum exercise capacity by analysing the heart rate response to submaximum exercise are available [10]. Our study was intended to investigate the correlation of the heart rate at standardized submaximum levels of exercise with measurements of maximum performance capacity in boys aged 10–14, in order to prove the hypothesis that submaximum stress tests also permit an adequate assessment of the maximum exercise capacity and/or the state of training in an individual case.

Subjects

Thirty-two secondary school boys underwent a spiroergometric stress test. Twenty-one boys were pupils from a physical education (PE) class with eight PE lessons per week and 11 were controls from a normal class belonging to the same age group and same school, with three PE lessons a week. The stress test was carried out on an electrically-braked bicycle ergometer. The ECG was recorded with leads V_2, V_5 and V_6 simultaneously. The heart rate was taken from the ECG at the end of every third minute. The expiratory ventilation was measured in an open system and oxygen in the expiratory gas was analysed as the difference from the room air, with continuous sampling from a mixing chamber (Siemens).

The stress test on the bicycle ergometer was symptom-limited by exhaustion. The initial load was 1 Watt/kg body weight and the increment 0.5 Watt/kg every 3 min. Exhaustion was confirmed by the maximum heart rate, by decrease of the pedalling rate below 50 rotations per min and by confirmation by the supervising physician. This tests were made at the beginning and the end of the first school year and at the end of the second to the fifth years. The PE class had an additional test at the begin of the second year. On the first test the heart

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Abbreviations: PE = physical education; kg = kilogram of bodyweight; $watt_{max}$ = maximum ergometric performance capacity; VO_2max = maximum oxygen uptake; HR = heart rate; PWC 170 = physical working capacity at an HR of 170/min; LBM = lean body mass; $\bar{x}$ = arithmetic mean; s = standard deviation

Table 1. Body weight and body height (mean ± standard deviation of the subjects, listed according to age. PE class = physical education class; SD = standard deviation

Years	PE class			Normals		
	Weight (mean ± SD)	Height (mean ± SD)	*N*	Weight (mean ± SD)	Height (mean ± SD)	*N*
10.0–10.9	35.2 ± 6.7	142 ± 6	20	36.4 ± 9.7	139 ± 8	11
11.0–11.9	38.8 ± 7.5	147 ± 7	43	39.3 ± 8.7	144 ± 8	19
12.0–12.9	42.7 ± 8.2	151 ± 8	22	45.0 ± 10.5	152 ± 8	18
13.0–13.9	46.6 ± 7.7	157 ± 9	19	49.6 ± 11.1	157 ± 8	14
14.0–14.9	53.0 ± 7.9	165 ± 9	15	55.7 ± 8.2	165 ± 7	14

rate measurement failed in the control group for technical reasons.

Parameters, derived from one single test

1. The maximum ergometric performance capacity in Watt ($watt_{max}$). The $watt_{max}$ takes into account the working time on the last step.

$$Watt_{max} = W + \frac{(s \cdot 0.5 \cdot kg)}{180}$$

W: load in Watt during the last step carried out for 3 min; s: working time in seconds on the last step; kg: body weight in kg.

2. The maximum ergometric performance capacity related to body weight: $Watt_{max}/kg$

3. The maximum oxygen uptake: $VO_2max(STPD)$

$$VO_2max = V_E \cdot Delta\,O_2$$

V_E: expiratory ventilation; $DeltaO_2$: difference between the mixed expiratory O_2 concentration and the O_2 in the room air.

4. The VO_2max related to the body weight: VO_2max/kg.

5. The heart rate (HR) at 1, 2 and 3 W/kg: HRA, HRB, HRC.

6. The physical working capacity at an HR of 170/min: PWC 170. This is computed assuming a linear correlation between work load and HR from two different steps with HR below 170/min.

$$PWC\,170 = W2 + \frac{(170 - HR2)\,Delta\,W}{Delta\,HR}$$

W2: the higher work load; Delta W: difference between the two work loads; Delta HR: difference between the two heart rates.

7. Lean body mass in kg, by the method described elsewhere [2].

Statistics

The method of the least squares was employed for the linear correlation. For this purpose the tests on both groups and of all events were taken as one sample. Comparison of the same parameters between the two groups was performed with the F test and, depending on the result, the Student *t*-test for even or uneven variances. The alternative hypothesis was accepted if $P < 0.05$. The groups were divided by age. Within 1 year a child could have done more than one test.

Results

The anthropometric data of the subjects are listed in Table 1. There was a trend to higher body weight at equal body height in the normal class.

Table 2 contains the mean values for HRA, HRB and HRC (except those of the controls of the first test), divided into age groups. From the second year of follow-up on, the mean values of the PE class were significantly lower. The values in Table 2 are normal HR values for standardized, body-weight-related work loads for different ages.

Table 3 shows the mean values of $watt_{max}/kg$, VO_2max/kg and PWC 170/kg for both groups, listed according to age. The two parameters of maximum performance capacity were significantly higher in the PE class but were not very clear, because they were not both significantly different in the second year of follow up, and none of them in the third year. The PWC 170/kg always was significantly different, but this is a parameter derived from submaximal heart rates.

Table 4 shows the $watt_{max}$, VO_2max and PWC 170 related to the lean body mass (LBM). In $watt_{max}/LBM$ and VO_2max/LBM no significant differences remained, whereas for the PWC 170/LBM from the second year on, the PE class was still better.

Table 2. Heart frequences (mean ± SD) at 1, 2 and 3 Watt/kg body weight, listed according to age. PE class = physical education class

Years		PE class		Normals	
		HF ± SD	*n*	HF ± SD	*n*
10.0–10.9	1 Watt/kg	145 ± 10	16	125	1
	2 Watt/kg	172 ± 13	16	155	1
	3 Watt/kg	197/12	14	188	1
11.0–11.9	1 Watt/kg	125 ± 12	40	132 ± 23	10
	2 Watt/kg	160 ± 14	40	165 ± 18	10
	3 Watt/kg	186 ± 14	40	191 ± 17	9
12.0–12.9	1 Watt/kg	123 ± 10 *	21	135 ± 18	11
	2 Watt/kg	156 ± 13	22	164 ± 20	10
	3 Watt/kg	182 ± 10	21	190 ± 15	9
13.0–13.9	1 Watt/kg	119 ± 10	19	133 ± 22	10
	2 Watt/kg	147 ± 14 *	19	168 ± 22	10
	3 Watt/kg	178 ± 14 *	19	190 ± 14	9
14.0–14.9	1 Watt/kg	119 ± 9 *	15	138 ± 20	9
	2 Watt/kg	150 ± 11 **	15	172 ± 19	9
	3 Watt/kg	176 ± 9 ***	15	195 ± 10	8

$^*P<0.05$, $^{**}P<0.01$, $^{***}P<0.001$

Table 3. Watt-max/kg body weight (Watt-max/kg), VO_2-max/kg and PWC 170/kg listed according to age. PE class: physical education class

Years			PE class		Normals	
			mean ± SD	*n*	mean ± SD	*n*
10.0–10.9	Watt-max/kg		3.61 ± 0.43	19	3.34 ± 0.71	10
	VO_2-max/kg		47.4 ± 7.0	19	47.1 ± 10.2	10
	PWC 170/kg		2.04 ± 0.54	17	2.69	1
11.0–11.9	Watt-max/kg		3.94 ± 0.42 **	40	3.26 ± 0.67	13
	VO_2-max/kg		56.9 ± 7.0	40	50.0 ± 13.2	13
	PWC 170/kg		2.45 ± 0.50 *	40	2.05 ± 0.70	11
12.0–12.9	Watt-max/kg		3.83 ± 0.54	22	3.48 ± 0.72	11
	VO_2-max/kg		60.6 ± 9.0	22	56.3 ± 13.5	11
	PWC 170/kg	*	2.56 ± 0.48 *	22	2.08 ± 0.69	11
13.0–13.9	Watt-max/kg		4.03 ± 0.49	19	3.61 ± 0.73	10
	VO_2-max/kg		59.7 ± 11.7 *	19	49.1 ± 9.2	10
	PWC 170/kg		2.64 ± 0.39 **	19	1.97 ± 0.69	10
14.0–14.9	Watt-max/kg		4.11 ± 0.44 *	15	3.62 ± 0.36	9
	VO_2-max/kg		57.1 ± 7.3 *	15	49.7 ± 4.7	9
	PWC 170/kg		2.76 ± 0.43 ***	15	1.91 ± 0.59	9

*$P<0.05$, **$P<0.01$, ***$P<0.001$

Table 4. Watt-max/kg lean body mass (Watt-max/kg LBM), VO_2-max/kg LBM and PWC 170/kg LBM listed according to age. PE class: physical education class

Years		PE class		Untrained	
		mean ± SD	*n*	mean ± SD	*n*
10.0–10.9	Watt-max/kg LBM	4.36 ± 0.50	19	4.08 ± 0.74	10
	VO_2-max/kg LBM	57.1 ± 7.4	19	57.2 ± 9.1	10
	PWC 170/kg LBM	2.44 ± 0.54	17	2.93	1
11.0–11.9	Watt-max/kg LBM	4.72 ± 0.46 **	40	4.00 ± 0.89	13
	VO_2-max/kg LBM	68.1 ± 5.7	40	61.2 ± 15.3	13
	PWC 170/kg LBM	2.94 ± 0.61	40	2.50 ± 0.86	11
12.0–12.9	Watt-max/kg LBM	4.80 ± 0.52	22	4.58 ± 0.74	11
	VO_2-max/kg LBM	75.8 ± 8.2	22	74.3 ± 18.7	11
	PWC 170/kg LBM	3.21 ± 0.53 *	22	2.69 ± 0.70	11
13.0–13.9	Watt-max/kg LBM	4.95 ± 0.58	19	4.76 ± 0.80	13
	VO_2-max/kg LBM	72.9 ± 11.9	19	68.0 ± 14.8	13
	PWC 170/kg LBM	3.23 ± 0.42 **	19	2.53 ± 0.73	13
14.0–14.9	Watt-max/kg LBM	4.66– 0.41	15	4.43 ± 0.56	12
	VO_2-max/kg LBM	64.6 ± 6.4	15	60.8 ± 6.5	12
	PWC 170/kg LBM	3.12 ± 0.42 **	15	2.44 ± 0.69	12

*$P<0.05$, **$P<0.01$

Table 5. Correlation matrix between the parameters derived from submaximum standardized work (HF-A, HF-B, HF-C, PWC 170, PWC 170/kg) and the parameters derived from maximum performance (Watt-max, Watt-max/kg, VO_2-max and VO_2-max/kg). HF-A, HF-B and HF-C: heart frequency at 1, 2 and 3 Watt/kg body weight

	Watt-max	Watt-max/kg	VO_2-max	VO_2-max/kg	*n*
HF-A (1 Watt/kg)	−0.287 ***	−0.545 ***	−0.295 ***	−0.468 ***	161
HF-B (2 Watt/kg)	−0.269 ***	−0.565 ***	−0.267 ***	−0.414 ***	161
HF-C (3 Watt/kg)	−0.251 **	−0.463 ***	−0.322 ***	−0.412 ***	153
PWC 170	+0.799 ***	+0.360 ***	+0.718 ***	+0.181 *	165
PWC 170/kg	+0.265 ***	+0.625 ***	+0.264 ***	+0.527 ***	165

*$P<0.05$, **$P<0.01$, ***$P<0.001$

Table 6. Correlation factors between PWC 170 and Watt-max and VO_2-max respectively, listed according to age

Years	PWC 170 vs Watt-max		PWC 170 vs VO_2-max		*n*
10.0–10.9	0.196		0.118		18
11.0–11.9	0.723	***	0.588	***	51
12.0–12.9	0.770	***	0.567	***	34
13.0–13.9	0.727	***	0.524	**	32
14.0–14.9	0.634	***	0.674	***	27

** $P<0.01$, *** $P<0.001$

Table 5 shows a correlation matrix encompassing all tests, from the values arrived at with submaximum work leads to those of the maximum performance capacity derived from the same tests. The correlations between HRA, HRB, HRC, and $watt_{max}$ and VO_2max respectively were significant but not very close (r = approx. 0.29). The correlation between HRA, HRB, HRC and $watt_{max}$/kg and VO_2mas/kg was considerably better (r = approx. 0.5). The best correlation was between PWC 170 and the maximum values (r = approx. 0.75). It is noteworthy that the Watt correlation factor was in some cases considerably better than that for VO_2.

Table 6 shows the correlation factor of PWC 170 to $watt_{max}$ and VO_2max respectively, listed according to age. One can see that in the youngest age group there was no significant correlation, whereas in the older age groups (who were the same subjects) the correlation was significant with very high factors.

Discussion

There are numerous tests for evaluating the functional capacity of the circulatory system. Many of them estimate the maximum performance capacity and/or the state of training using submaximum work loads and avoiding exhaustive stress. Such methods employ nomograms, e.g. estimating the VO_2max or computing indices, which can then be aligned with performance classes [3, 5, 6, 7, 10]. Stress tests avoiding exhaustive work are increasingly becoming part of the diagnostic programme of school and sport physicians dealing with children. Tests that measure the heart rate response to a submaximum standardized work load are the most practicable. Today ergometric procedures are the standard. The standard work load should provoke the same heart rate reaction in all subjects with the same level of circulatory function, independently of different anthropometric values. This is not the case when fixed work loads (e.g. 75 or 100 Watt) are employed for all subjects, but this condition proves right for work loads that are standardized according to body weight, e.g. 1 or 2 Watts/kg.

Compared with single step rectangular ergometric procedures, the PWC 170 includes assessment of the slope of heart rate increase in relation to the increase in work load.

It is usual to refer to a low heart rate response to a standard work load as high performance capacity and/or state of training and to a high heart rate as the opposite. In a previous paper we were able to show only poor correlation between PWC 170 and the measured maximum performance capacity in healthy elderly men and no correlation in patients with coronary heart disease [1]. In another study it has been demonstrated that VO_2max could not be predicted from the heart rate response to submaximal exercise in patients with heart failure [4]. This means that in healthy elderly people as well as in patients with coronary heart disease or heart failure a low heart rate response or a moderate slope in a single case does not necessarily indicate high performance capacity.

There are comparisons between different kinds of submaximum tests [3, 8] as well as results of submaximum ergometric tests on subjects up to the age of 14 for body-weight-standardized work loads as well as for PWC 170 [5, 9]. Up till now, however, it has not been clear how reliably these submaximum tests represent the maximum performance capacity in this fast-growing age group. In our study the same subjects were followed up, who had different numbers of PE lessons per week. Therefore the influence of age and growth on the relation of submaximum test values to the values of absolute and relative maximum performance capacity can be demonstrated very clearly.

From the 13th year of age onwards, the pupils in the PE class had significantly lower heart rates at the same body-weight-related work loads, as shown in Table 2. This would correspond to the usual interpretation of increased physical capacity compared with the normal class, as a result of the greater number of PE lessons. Surprisingly, this is not so clear, as shown in Table 3.

Consideration of the relative values related not to body weight, but to lean body mass, shows no significant differences between the different age groups (Table 5). The greatest but non-significant differences between the mean values are encountered in the 11.0–11.9-year-olds. Particularly at this age, however, the differences in heart rate response to 1, 2 and 3 Watt/kg are the least. Superior physical performance capacity therefore cannot be claimed. It can be assumed that performance capacity is not quantitatively represented precisely by the heart rate.

Therefore we investigated the correlation between HRA, HRB, HRC and PWC 170, each as a single independent variable, and the absolute and relative values of performance capacity each as a dependent variable, as shown in Table 5. All factors of correlation are statistically significantly different from zero and seem to confirm the assumption that heart rate is a good parameter of performance capacity and state of training.

It must be noted however, that the correlation factors between HRA, HRB, HRC and the relative maximum values are generally about twice as high as between HRA, HRB, HRC and the absolute values. Indeed, the maximum performance capacity is to a high degree a function of body weight (which is the basis for a normal value table for ergometric performance capacity). Therefore the effect of body weight has at first to be eliminated by forming the quotient: maximum performance capacity/body weight. The relative maximum performance capacity derived in this way is then a reliable parameter of the state of training. This state of training is defined as the deviation of the functional capacity from the normal level and is independent of the body weight. This means that all individuals in the same state of training have the same value for relative maximum performance capacity, but, depending on body weight, different values for absolute maximum performance capacity. The almost doubled values for the correlation factors between HRA, HRB, HRC and the relative maximum performance capacity demonstrate that the submaximum heart rate response to standard work loads better represents the state of training than the absolute performance capacity.

On the other hand, one can state that the correlation factors between HRA, HRB and HRC and even the relative maximum values of the performance capacity are surprisingly low. This means that these factors cannot have any relevance for practical purposes in spite of the fact that they are statistically significant. An estimation of the state of training in an individual case is therefore not reliable in children. On the basis of this rather poor correlation between HRA, HRB and HRC and the parameters of performance capacity, one can suppose that the heart rate response to submaximum work loads is not only influenced by the state of training but to a high degree also by other factors such as the tone of the sympathetic nervous system. Obviously the PE class differs mainly in having higher parasympathetic tone and thus a lower heart rate.

Quite a different situation is found using PWC 170. Table 5 shows a high correlation factor of $r = 0.8$ between PWC 170 and $watt_{max}$, so that the estimation of $watt_{max}$ by means of PWC 170 is sufficiently reliable for practical use (again the correlation factor is lower using the regression equation to estimate VO_2max). Table 6 demonstrates that this is valid for children from the age of 11 on, but not for children aged 10.9 years or younger.

Conclusion

The heart rate response to submaximum standard work loads is less characteristic of the absolute performance capacity than of the relative performance capacity related to kg body weight, which is the parameter for the state of training. The correlation factors, however, are too low for reliable estimation in an individual case, despite the fact that the factors are statistically significant. That means, that the widely used single step exercise tests based on pulse rate measurements, even if standardized, are not exact enough to be recommended for practical use in testing the individual physical fitness of children. A correlation sufficient for use in school or sport medicine exists between PWC 170 and $watt_{max}$. The PWC 170 test therefore permits estimation of the maximum performance capacity, even in an individual case. This, however, is not valid in children under 11 years of age.

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