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A Comparison of Various Methods for the Determination of $\dot{V}O_2$max

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Summary. Previous studies have shown that true maximal oxygen uptake ($\dot{V}O_2$max) obtained by means of cycle ergometer and step test are lower than the $\dot{V}O_2$max measured during uphill treadmill running. The predicted $\dot{V}O_2$max measured by ergometer was even lower. Four different methods for the determination of $\dot{V}O_2$max within the same group of examinees were compared: True $\dot{V}O_2$max by treadmill, ergometer, step test, and predicted $\dot{V}O_2$max (Astrand-Rhyming). This study was performed on 15 healthy non-professional sportsmen. They underwent progressive test protocols on alternating days and the results were as follows – $\dot{V}O_2$max expressed in ml O_2 kg BW/min (mean ± SD): treadmill running 63.8 ± 4.7; ergometer cycling 60.2 ± 5.6; step test 59.6 ± 5.2 and predicted $\dot{V}O_2$max 59.9 ± 6.9.

The $\dot{V}O_2$max as determined by uphill treadmill running was significantly higher than with the other methods. No significant difference was found between true $\dot{V}O_2$max determined by the ergometer and step test. However, step test and properly executed Astrand-Rhyming test again proved to be reliable and deviate from the treadmill test by only 6%. Maximal heart rate was sgnificantly higher in the treadmill and step tests than in the direct ergometer test.

Key words: Treadmill – Bicycle ergometer – Step test – Predicted $\dot{V}O_2$max

Maximal oxygen uptake ($\dot{V}O_2$max) is considered to be the best indicator of aerobic power, expressing the ability of the cardiorespiratory system to transport oxygen to active tissues and of these tissues to use it [1]. Many methods were developed for the determination of aerobic capacity, though generally uphill treadmill running or bicycle ergometer are used [12]. Numerous studies have shown that true maximal oxygen uptake obtained by means of a cycle ergometer is lower by 4–23% than the $\dot{V}O_2$max measured during treadmill running [1, 7,

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8]. However, it has been shown lately that cyclists can obtain higher $\dot{V}O_2$max values on the bicycle ergometer than on the treadmill [6]. The complexity of the direct measures as well as of the physical demands made upon the subjects led to the development of indirect methods for estimating maximal oxygen consumption based on heart rate response to submaximal work [1, 10, 12].

This study was designed to compare three direct methods (treadmill running, step test, ergometer) and one commonly used indirect method (Astrand-Rhyming) for the estimation of maximal oxygen uptake.

Material and Methods

Fifteen healthy young men whose physiological characteristics are detailed in Table 1, participated in the study. To avoid baseline differences, 32 participants of a 6-week physical fitness course were examined in a field test [11] and the 15 who obtained the highest score were chosen for the study. Three direct techniques and one indirect for the determination of maximal oxygen uptake were selected for comparison. The direct methods were: (a) modified Bruce's multistage treadmill test [3, 4], performed on a motor driven treadmill; (b) a test administered on electronic bicycle ergometer using the Siemens-Elema 380B ergometry system. The resistance was increased by 50 W (300 kpm) every 3 min from an initial load of 100 W (600 kpm) until the subject was unable to continue. A supramaximal load of 20 W was added during collection of expired air into the douglas bag; (c) a step test on a bench 32.5 cm high. The pace of stepping was increased continuously from a starting rate of 24 steps/min to a maximum of about 40–60 steps/min. This test was performed on the last day of the study in order to avoid sore muscles in unaccustomed subjects – a well-known aftermath to interfere with other tests. During the last minutes of the test the examinees were urged and motivated by the research staff to prevent a drop off in performance. The indirect method was a modified Astrand-Rhyming procedure (2). $\dot{V}O_2$max was predicted according to Astrand's nomograms by the determination of submaximal heart rate on a Siemens Elema 380B bicycle ergometer system. The examinees were tested at three successive submaximal loads (100, 150, 200 W) each lasting for 5 min. Expired air was collected during the last 30 s of every submaximal load.

All maximal experiments started with a 5 min warm up to elicit a heart rate between 150–160 beats/min, followed by a 10 min rest period. Expired air was collected in a Douglas bag during the last 30 s of the maximal exercise. The criterion of maximal effort included inability to increase rate of stepping, signs of fatique and high heart rate.

Heart rate was monitored continuously by the Nihon-Koyden (Japan) ECG utilizing a modified lead I.

All experiments were performed at sea level in a climatic chamber, at a dry bulb temp of 21° C and relative humidity (RH) of 45%.

Analysis of the expired air in the Douglas bags was performed with a paramagnetic oxygen analyzer (Beckman E_2) and an infrared CO_2 analyzer (Beckman LB_1). The respiratory valve had a dead space of 100 ml. Inner diameter of the valves, the stopcock and the tube of the bags were 28 mm. The connecting tubes had an inner diameter of 35 mm. The length of the tube from the subject

Table 1. Characteristics of the Subjects (Mean ± SE)

N	15
Age (yr)	20.2 ± 0.17
Height (cm)	180.2 ± 2.09
Weight (kg)	72.5 ± 2.45
VC (cc)	5634.0 ± 176.7
FEV_1 (cc)	4677.0 ± 154.5
FEV_1/VC (%)	84.0 ± 1.55

to the bags was approximately 50 cm in all three maximal tests. The tests were performed tow days apart, in the following order:

day 1: Treadmill running test;
day 3: Maximal ergometric test on a bicycle;
day 5: Submaximal ergometric test on a bicycle;
day 7: Maximal step test.

The data were analyzed statistically by the paired t-test. Difference was considered significant when $p < 0.05$.

Results

Mean values of maximal oxygen uptake as measured in the direct and predicted tests, O_2 pulse and heart rate are presented in Table 2. During maximal exercise the mean $\dot{V}O_2$max was 63.8, 60.2, and 59.6 ml O_2/kg BW/min and 4.57, 4.32, and 4.30 l/min for the treadmill, ergometer and step test, respectively. The mean $\dot{V}O_2$max for the predicted procedure was 59.9 ml O_2/kg BW/min. The greatest mean maximal oxygen consumption was obtained on the treadmill, about 6% above the other methods.

Comparison of the individual maximal oxygen uptake for the various methods and the linear regression lines for the results are given in Fig. 1 (A-F). The deviation of cycling, stepping, and predicted methods (l/min) from the treadmill test are evident. No significant disparity is seen between stepping and predicted or actual cycling methods. In the range of 3–6 l/min, this deviation was found to increase gradually with increase in $\dot{V}O_2$max and was greatest at 6 l/min (9% for the step test, 10% for the predicted and 11% for the direct cycling method). A paired t-test was performed between each pair of exercise procedures. This analysis was done for the $\dot{V}O_2$max, heart rate, and O_2 pulse and is summarized in Table 4. $\dot{V}O_2$max was significantly higher by the treadmill protocol than by any other test procedure. No significant difference was found between the maximal ergometer test and both the step test and predicted method. However, an analysis of the heart rate showed significantly higher maximal heart rate during treadmill running and step test than during maximal bicycle exercise. No significant difference was found between maximal heart rate in the step test and treadmill test.

Table 2. Mean (± SE) $\dot{V}O_2$max, maximal heart rate and O_2 pulse in the various test methods

Observations	Treadmill	Bicycle	Step test	Predicted
	15	15	15	15
$\dot{V}O_2$max ml O_2/kg BW/min	63.8 ± 1.30	60.20 ± 1.45	59.60 ± 1.35	59.90 ± 1.40
$\dot{V}O_2$max l/min	4.57 ± 0.17	4.32 ± 0.16	4.30 ± 0.16	4.28 ± 0.17
HR beats/min	187 ± 2	180 ± 2	188 ± 2	–
O_2 pulse ml O_2/beat	23.09 ± 1.43	23.84 ± 1.03	22.96 ± 0.92	–

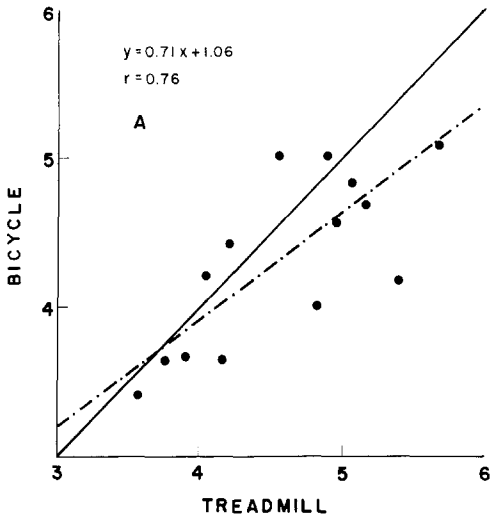

Fig. 1A. Correlation of maximal oxygen uptake ($\dot{V}O_2$max · l/min) between treadmill and bicycle tests

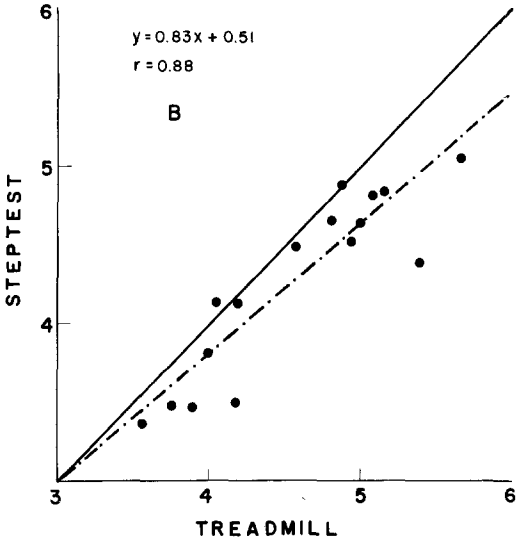

Fig. 1B. Correlation of maximal oxygen uptake ($\dot{V}O_2$max · l/min) between treadmill and step test

The mean values for the O_2 pulse computed from the maximal oxgen consumption and maximal heart rate were 23.09, 23.84, and 22.96 ml O_2/beat for the treadmill, maximal bicycle exercise, and step test, respectively. No significant difference (Table 4) was found between the O_2 pulses at the bicycle and treadmill exercises. The O_2 pulse during the treadmill test and bicycle test was significantly higher than during the step test.

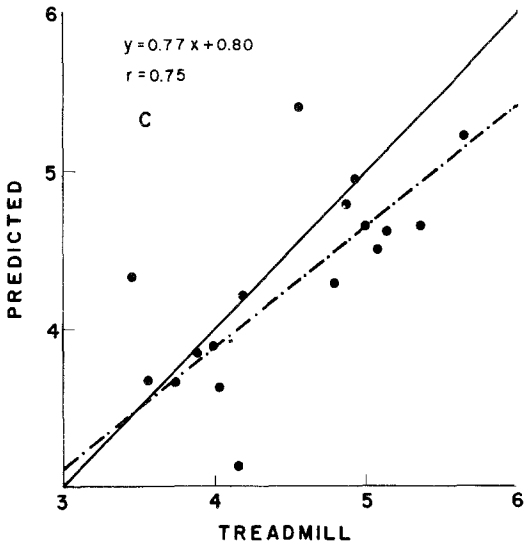

Fig. 1C. Correlation of maximal oxygen uptake ($\dot{V}O_2$max · l/min) between treadmill and predicted tests

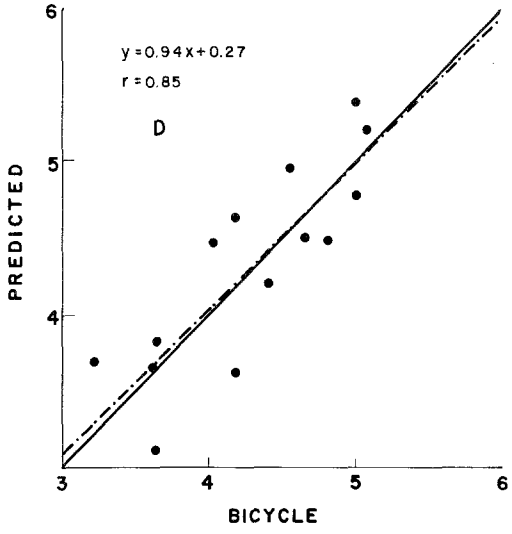

Fig. 1D. Correlation of maximal oxygen uptake ($\dot{V}O_2$max · l/min) between bicycle and predicted tests

Table 3 shows predicted values of $\dot{V}O_2$max computed from HR at the various submaximal stages. It comprises as well the true oxygen uptake measured. All three predicted values for the $\dot{V}O_2$max are similar, though at 250 W the predicted values were somewhat higher than at the other two submaximal stages. Mean maximal heart rate at this stage was 168 beats/min which is nearly the upper limit for Astrand nomogram.

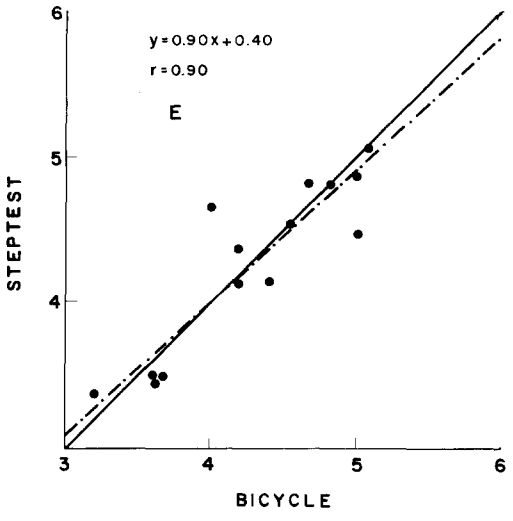

Fig. 1E. Correlation of maximal oxygen uptake ($\dot{V}_2$max · l/min) between bicycle and step tests

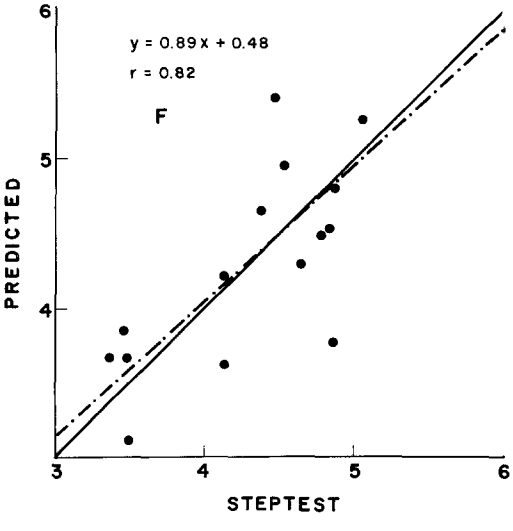

Fig. 1F. Correlation of maximal oxygen uptake ($\dot{V}O_2$max · l/min) between step test and predicted test

Table 3. Mean ± SE of true oxygen uptake and heart rate at every exercise stage of the predicted procedure and predicted $\dot{V}O_2$max values

	150 W	200 W	250 W
$\dot{V}O_2$ l/min	2.61 ± 0.07	3.31 ± 0.12	3.87 ± 0.16
$\dot{V}O_2$ ml O_2/kg BW/min	36.9 ± 1.7	47.12 ± 2.4	54.9 ± 1.4
Heart Rate beats/min	127 ± 3	151 ± 3	168 ± 3
Predicted $\dot{V}O_2$max[a] ml/kg/min	59.4 ± 2.3	59.0 ± 1.9	61.1 ± 1.7

[a] Predicted according to the nomograms of Astrand [2]

Table 4. Statistical analysis by the paired *t*-test (level of significance $p < 0.05$)

		T	B	S
$\dot{V}O_2$max l/min	T[a]	–	–	–
	B[b]	0.01	–	–
	S[c]	0.01	N.S.	–
	P[d]	0.01	N.S.	N.S.
$\dot{V}O_2$max ml/kg/min	T	–	–	–
	B	0.01	–	–
	S	0.01	N.S.	–
	P	0.01	N.S.	N.S.
HR beats/min	T	–	–	–
	B	0.0025	–	–
	S	N.S.	0.0005	–
	P	–	–	–
O_2 pulse ml/beat	T	–	–	–
	B	N.S.	–	–
	S	0.0005	0.01	–
	P	–	–	–

[a] T = treadmill; [b] B = bicycle; [c] S = step test; [d] P = predicted

Discussion

The major question in the present study was whether or not the same values for oxygen uptake can be obtained during maximal treadmill, bicycle, and step test and how these results compare with the predicted values obtained by the Astrand-Rhyming procedure.

This study confirms previous findings [5, 7] that direct maximal oxygen uptake values measured during a treadmill running test are higher than on the bicycle test. Kash found a negligible difference in $\dot{V}O_2$max between his step test method and treadmill running [9]. He pointed out that the key to the proper use of step test is a bench low enough to permit rapid stepping rates, high cardiorespiratory demands and the minimization of local muscle fatique through near elimination of anaerobic work in the legs. We tried to conform with these demands, but found nevertheless significantly lower results (6%), for the step test than for the treadmill test. However, there was no significant difference in the heart rate between the two methods.

The discrepancies in $\dot{V}O_2$max were usually attributed to differences in testing techniques, motivational factors or involvement of a smaller muscle mass during cycling, than during treadmill running. It was found by Hagberg lately that this apparent disadvantage may be eliminated by intensive training on the bicycle [6]. In his study the examinees who were members of a cycling team attained $\dot{V}O_2$max values by the bicycle-ergometer that were 3.7% higher than treadmill running values.

In our study $\dot{V}O_2$max values obtained by the treadmill technique, were 6% higher than with all other direct and predicted methods. The mean maximal

heart rate for the treadmill and step test were higher than for the direct cycle test.

The O_2 pulse, which is a good measure of cardiac performance, decreased somewhat during the step test. This decrease, compensated by increased heart rate, resulted in a $\dot{V}O_2$max similar to that obtained by the bicycle ergometer. It seems that maximal transport of oxygen is limited by the central circulation rather than by the tissues ability to utilize oxygen and that a reduced venous return during stepping up in the erect position result in reduced stroke volume and oxygen pulse which is compensated by increased heart rate.

Our study confirms that a properly performed Astrand-Rhyming predicted procedure can be a reliable measure for maximal oxygen consumption. This implies that the test be performed in three stages and the heart rate be kept between 120–170 beats/min.

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