PREDICTION OF MAXIMAL OXYGEN UPTAKE FROM SUBMAXIMAL AND MAXIMAL EXERCISE ON A SKI ERGOMETER

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ABSTRACT: The aim of the study was to assess the accuracy of prediction of maximal oxygen uptake ($\dot{V}O_{2max}$) from submaximal and maximal exercises on a ski ergometer, which imitated the work of the arms during cross-country skiing. Twenty-seven female and twenty-nine male biathletes and cross-country skiers were investigated. The subjects performed the incremental exercise test on the ski ergometer until volitional exhaustion. $\dot{V}O_{2max}$was determined directly and its predicted values were calculated from the linear relationship between $\dot{V}O_2$ and HR in a submaximal exercise extrapolated to the age-predicted HRmax; from the linear relationship between $\dot{V}O_2$ and power output at submaximal and maximal exercise; from the linear relationship between $\dot{V}O_{2max}$ and $\dot{V}O_2$ at HR=170 · min^{-1} and from the linear relationship between $\dot{V}O_{2max}$ and power output at HR=170 ·min^{-1}. The differences between measured and predicted $\dot{V}O_{2max}$ ranged from 0.3% to 1.2% (NS). Correlation coefficients between measured and predicted $\dot{V}O_{2max}$ ranged from 0.6 to 0.91 ($p<0.001$). Total error ranged from 5.91% to 11.7% and standard estimation error from 5.3% to 11.0%. The results demonstrated that $\dot{V}O_{2max}$ can be predicted from the exercise test on the ski ergometer both in the submaximal exercise from the relation between heart rate and oxygen uptake or power output and from the relation between $\dot{V}O_{2max}$ and maximal power output without oxygen uptake measurement.

KEY WORDS: prediction of maximal oxygen uptake, ski ergometer, submaximal exercise, maximal exercise

INTRODUCTION

Maximal oxygen uptake ($\dot{V}O_{2max}$) is generally believed to be the best measure of cardio-pulmonary fitness and aerobic performance. The most accurate method of $\dot{V}O_{2max}$ estimation is direct measurement of oxygen uptake during maximal exercise. This method is, however, troublesome because of the necessity of a thorough medical check-up before exercise and continuous supervision of the exercise test by a physician trained in treatment of circulatory failure. In addition, appropriate laboratory equipment for direct measurement of $\dot{V}O_{2max}$ is rather expensive and requires skilled personnel.

A variety of methods have been developed to predict $\dot{V}O_{2max}$ from submaximal or maximal exercises. They were based mostly on the linear relationship between exercise oxygen uptake ($\dot{V}O_2$) and power output as well as between $\dot{V}O_2$ and heart rate. $\dot{V}O_2$ tests have most often been conducted on a cycle ergometer, a motor driven treadmill or a rowing ergometer. The estimation of $\dot{V}O_{2max}$ without exercise tests was also proposed, for example from the ratio between HR_{max} and HR_{rest} [19], or from self-reported non-exercise predictor variables including the subject's perceived functional ability to exercise, habitual physical activity, gender and body mass index [10]. An interesting finding reported recently [6,7,8,15] was accurate prediction of $\dot{V}O_{2max}$ obtained from submaximal ratings of perceived exertion and heart rate during exercise. Of note, in the last few years, in spite of the great technical progress in construction of modern equipment to measure oxygen uptake, new methods to predict $\dot{V}O_{2max}$ have continued to be developed and are considered to be very useful, particularly in studies of large population samples [e.g. 2,6-8,12,15,17,20]. These methods were often used in the field and pre selective studies aimed at the initial determination of predispositions to endurance sports. No data, however, have been published on the prediction of $\dot{V}O_{2max}$ from the submaximal or maximal exercise test on the ski ergometer. Aerobic capacity is the major determinant of success in cross-country skiing. Measurements of $\dot{V}O_{2max}$ in cross-country skiers and biathletes is the most frequent measure of the effect of training. The aim of this study was to assess the accuracy of prediction of the maximal oxygen uptake ($\dot{V}O_{2max}$) from submaximal and maximal exercise on the ski ergometer.

MATERIALS AND METHODS

Subjects. Twenty-seven female and twenty-nine male biathletes and cross-country skiers, juniors and seniors from the national team and the direct back-up participated in the studies. Basic characteristics of the examined athletes are shown in Table 1. The subjects expressed their informed consent to participate in the investigation by signing the appropriate forms. The programme of the study was approved by the Ethical Research Committee at the Institute of Sport in Warsaw. The study was conducted during a preparatory period, at ambient temperature of 19-22ºC, in the forenoon, 1-3 hours after a light meal.

Testing procedures. The subjects performed a graded incremental exercise test on the ski ergometer [14] which imitated the work of the arms (double poling technique) during cross-country skiing. The initial workload equalled 0.5 $W \cdot kg^{-1}$, 0.7 $W \cdot kg^{-1}$, 0.8 $W \cdot kg^{-1}$ or 1.0 $W \cdot kg^{-1}$ for female juniors, male juniors, female and male adults, respectively. The workload was increased every 3 min by 0.4 $W \cdot kg^{-1}$ for women, 0.5 $W \cdot kg^{-1}$ for male juniors and 0.6 $W \cdot kg^{-1}$ for male adults until exhaustion, with 1-min intervals between stages. As a result, the exercise tests lasted from 12 min to 21 min. During the test pulmonary ventilation, oxygen uptake, and carbon dioxide output in the open system were estimated with the breath-by-breath method using the V_{max} set series 29 (Sensor Medics USA). Heart rate was recorded using the Polar sport tester recorder (Electro Oy; Finland). At the fourth minute after completion of the test, blood samples were collected from the finger pulp and the blood lactate concentration was determined using the LP400 photometer (Dr Lange; Germany). The highest values of oxygen uptake registered within 30 sec in the test were regarded as the VO_{2max}, provided that at least two of the criteria mentioned below were fulfilled:

- plateau $\dot{V}O_2$ despite an increase in workload;
- post-exercise lactate concentration in blood exceeding 8 $mmol \cdot L^{-1}$;
- respiratory quotient in excess of 1.10;
- maximal heart rate appropriate for age as calculated from the formula HR_{max} = 208.5-0.8·years of age [8].

Predicted values of $\dot{V}O_{2max}$. The predicted values of $\dot{V}O_{2max}$ were calculated from the linear regression of $\dot{V}O_{2max}$ against the values measured using the following formulas:

A. From the relationship between $\dot{V}O_2$ and W at maximal and submaximal exercise the following formulas:

(1) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 0.4394+0.0141W (submaximal and maximal) (r=0.965; p=0.0001; n=156) (females),

(2) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 0.6719+0.0125 W (submaximal and maximal) (r=0.965; p=0.0001; n=156) (males);

B. From the relationship between $\dot{V}O_2$ and W at maximal exercise the following formulas:

(3) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 1.1944+0.0092 W_{max} (r=0.82; p<0.0001) (females),

(4) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 2.1868+0.0068 W_{max} (r=0.60; p=0.006) (males);

C. From the linear relationship between $\dot{V}O_{2max}$ and W at HR=170 · min-1

(5) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 1.8073+0.0073 PWC_{170} (W) (r=0.61; p=0.0007) (females),

(6) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 2.4984+0.0073 PWC_{170} (W) (r=0.74; p<0.0001) (males);

D. From the linear relationship between $\dot{V}O_{2max}$ and $\dot{V}O_2$ at HR=170 · min-1

(7) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 1.5148+0.550 PWC_{170} ($\dot{V}O_2$ $L \cdot min^{-1}$) (r =0.63; p=0.0005) (females),

(8) $\dot{V}O_{2max}$ ($L \cdot min^{-1}$) = 1.6236+0.7127 PWC_{170} ($\dot{V}O_2$ $L \cdot min^{-1}$) (r=0.88; p<0.0001) (males);

E. From the linear relationship between $\dot{V}O_2$ and HR at a submaximal exercise extrapolated to the age-predicted HR_{max}.

The PWC_{170} values expressed in $\dot{V}O_2$ and W were calculated from the linear regression of HR against $\dot{V}O_2$ or HR against W, respectively, during submaximal exercise, interpolated to HR of 170 beats per min.

To assess the accuracy of prediction of the maximal oxygen uptake the following parameters were calculated:

- the difference between measured and estimated $\dot{V}O_{2max}$ (MD) and the statistical significance of the difference;
- Pearson's linear correlation coefficient between measured and predicted $\dot{V}O_{2max}$ (r);
- standard estimation error (SEE) according to the formula:

$$SEE = Sy \cdot \sqrt{1 - r^2}$$

where Sy = standard deviation of the predicted $\dot{V}O_{2max}$ value,
r = correlation coefficient between measured and predicted $\dot{V}O_{2max}$;

- total error (TE) according to the formula:

$$TE = \sqrt{\frac{\sum (y - Y)^2}{n}}$$

where y = the $\dot{V}O_{2max}$ value predicted for each subject,
Y = the measured value of $\dot{V}O_{2max}$,
n = number of subjects.

TABLE 1. PHYSICAL CHARACTERISTICS OF THE SUBJECTS (MEAN VALUES ± SD)

Characteristics	Women	Men
Age (years)	20.6 ±2.4	22.3±4.0
Body mass (kg)	57.2±5.1	73.9±6.3
Body height (cm)	166.2±4.8	179.4±5.9
Training experience (years)	6.7±3.2	8.7±4.2

TABLE 2. PHYSICAL FITNESS OF SUBJECTS (MEAN VALUES ± SD)

Variable	Women	Men
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	2.558 ± 0.344	4.063± 0.509
PWC_{170} ($\dot{V}O_2$ $L \cdot min^{-1}$)	1.900 ± 0.391	3.422 ± 0.627
PWC_{170} (W)	103 ±29	215 ± 17
W_{max} (W)	149 ± 31	275 ± 45

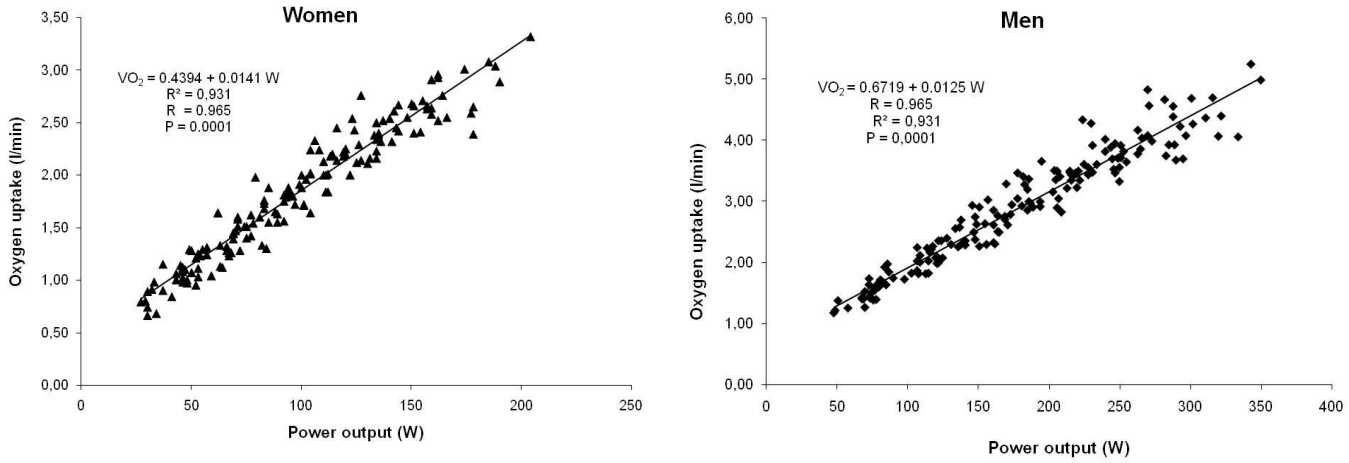

FIG 1. RELATION BETWEEN OXYGEN UPTAKE AND POWER OUTPUT IN MEN AND WOMEN EXERCISING ON THE SKI ERGOMETER. Comparison of the regression lines: intercept F=1.80, p=0.18 ns; slope F=14.04, p=0.0002

TABLE 3. COMPARISON OF MAXIMAL OXYGEN UPTAKE IN FEMALES MEASURED DIRECTLY ($\dot{V}O_{2max}$ =2.558 ± 0.344 L·min^{-1}) AND PREDICTED (MEAN VALUES ± SD)

Coefficient	Method				
	A	B	C	D	E
$\dot{V}O_{2max}$ (L·min^{-1})	2.541±0.433	2.565±0.282	2.566±0.211	2.541±0.215	2.517±0.338
MD (L·min^{-1})	0.017 ±0.251	-0.007±0.199	-0.008±0.268	0.017±0.268	0.031±0.268
MD (%)	0.68 ±9.8	- 0.29 ±7.8	-0.31±10.5	0.67±10.5	1.20±10.5
r	0.82*	0.82*	0.61*	0.63*	0.86*
SEE (L·min^{-1})	0.251	0.163	0.167	0.168	0.171
SEE (%)	9.81	6.37	6.53	6.57	6.68
TE (L·min^{-1})	0.247	0.195	0.268	0.264	0.182
TE (%)	9.65	7.62	10.50	10.30	7.11

Note: Indicated are: predicted $\dot{V}O_{2max}$ values, mean differences between measured and predicted $\dot{V}O_{2max}$ (MD), correlation coefficient (r), standard estimation errors (SEE) and total errors (TE). Percentages were calculated relatively to the directly measured $\dot{V}O_{2max}$. Details of methods A, B, C, D and E are described in Materials and Methods. * - p<0.001

TABLE 4. COMPARISON OF MAXIMAL OXYGEN UPTAKE IN MALES MEASURED DIRECTLY ($\dot{V}O_{2max}$ =4.063 ± 0.509 L·min^{-1}) AND PREDICTED (MEAN VALUES ± SD)

Coefficient	Method				
	A	B	C	D	E
$\dot{V}O_{2max}$ (L·min^{-1})	4.117 ±0.557	4.051±0.303	4.075±0.380	4.072±0.447	4.071±0.575
MD (L·min^{-1})	-0.054±0.481	0.013±0.409	- 0.012±0.340	-0.009±0.245	-0.009±0.239
MD (%)	-1.33±11.8	0.32 ±10.1	-0.30±8.4	-0.22±6.0	-0.22±5.9
r	0.61*	0.60*	0.74*	0.88*	0.91*
SEE (L·min^{-1})	0.446	0.243	0.254	0.215	0.239
SEE (%)	10.98	5.98	6.25	5.29	5.88
TE (L·min^{-1})	0.476	0.402	0.335	0.240	0.247
TE (%)	11.71	9.89	8.25	5.91	6.08

Note: Indicated are: predicted $\dot{V}O_{2max}$ values, mean differences between measured and predicted $\dot{V}O_{2max}$ (MD), correlation coefficient (r), standard estimation errors (SEE) and total errors (TE). Percentages were calculated relatively to the directly measured $\dot{V}O_{2max}$. Details of methods A, B, C, D and E are described in Materials and Methods. * - p<0.001

Significance of the differences between the measured and predicted $\dot{V}O_{2max}$ values were estimated using Student's t test for dependent data. In order to compare the regression line the differences in the slopes and the intercepts were analysed. All the statistical calculations and analyses were carried out using the Statistica 8 software.

RESULTS

As indicated in Figure 1 there was a strong correlation between oxygen uptake and power output during exercise on the ski ergometer in both men and women with the correlation coefficients being near 1.0.

Table 2 contains the directly measured $\dot{V}O_{2max}$ values as well as W_{max} and PWC_{170} in men and women. As expected, the physical

fitness of the subjects was high even when measured during exercising with their arms. The predicted $\dot{V}O_{2max}$ values, mean differences between measured and predicted $\dot{V}O_{2max}$, correlation coefficients, standard estimation errors and total errors are presented in Tables 3 and 4. Of note, there were no significant differences between the measured and predicted $\dot{V}O_{2max}$ and, on the other hand, high significance of the correlation coefficients ($p<0.001$) and moderate SEE and TE values.

DISCUSSION

The results obtained in the present study indicate that $\dot{V}O_{2max}$ can be predicted with high accuracy both from submaximal exercise tests on the ski ergometer from the relation between heart rate and oxygen uptake or heart rate and power output and from maximal exercise without oxygen uptake measurement based on the relation between $\dot{V}O_{2max}$ and maximal power output. To our knowledge it is the first attempt to predict maximal oxygen uptake from results obtained on the ski ergometer. The differences between measured and predicted $\dot{V}O_{2max}$ ranged from 0.29% to 1.2% in women and from 0.22% to 1.33% in men, and were not significantly different from zero. Similar differences between measured and predicted $\dot{V}O_{2max}$, ranging from 0.30% to 0.57 in women and from 0.12% to 1.78% in men, were obtained in our previous work [14], from exercises on the rowing ergometer. Other authors reported, generally, higher differences, ranging from 1.2% to 11% [4,5,12,20]. Mean values of the correlation coefficients between measured and predicted $\dot{V}O_{2max}$ equalled 0.74 (from 0.6 to 0.91; $p<0.001$) and were slightly lower than those recorded on the rowing ergometer (mean value of 0.76 in women and 0.86 in men) [14]. A lower mean value of the correlation coefficient of 0.69 was calculated by Carey and Frommelt [5] from the results of 24 studies of other authors. Correlation coefficients obtained with the Åstrand-Ryhming method most often ranged from 0.63 to 0.85 [3-5,12,17,20]. In some studies, however, after modification of the method, the correlation coefficient reached even as high as 0.98 [17]. Total error values in the current study equalled 7.8% (5.9% - 11.7%) and remained higher than those obtained on the rowing ergometer (4.9% - 5.9%, mean value 5.5%) [14] but considerably lower than those obtained from the exercise test on the cycle ergometer (11% - 20%, mean value 14.9%) [18]. Mean SEE values in the present study averaged 7.0% (5.3% - 11.0%) and were in general lower than those reported by other investigators from exercise tests on the cycle ergometer (6% - 15%) [1,3,10].

Accuracy of all investigated methods was similar. Relatively the best configuration of the analysed indices was obtained for method E. In fact, the MD values in this method were not significant as they were in the other methods. However, in both men and women there were the highest correlation coefficients, and SEE and TE values were lower than the average for all the methods.

The prediction of $\dot{V}O_{2max}$ with great accuracy without oxygen uptake measurement was possible because of the very strong correlation between power output and oxygen uptake. It should also be stressed that the subjects were familiar with the exercise test on the ski ergometer, which undoubtedly favourably affected the accuracy of the prediction of $\dot{V}O_{2max}$.

In conclusion, the obtained results indicate that $\dot{V}O_{2max}$ can be predicted in both men and women, from the results of submaximal and maximal exercises performed on the ski ergometer, with accuracy not less than that reported by other investigators from exercise tests on the cycle ergometer, treadmill or rowing ergometer. The most accurate values of $\dot{V}O_{2max}$ were predicted from the linear relationship between $\dot{V}O_2$ and HR in a submaximal exercise extrapolated to the age-predicted HR_{max} (method E).

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