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ORIGINAL ARTICLE

Prediction of upper extremity peak oxygen consumption from heart rate during submaximal arm cycling in young and middle-aged adults

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Abstract

Based on the strong linear relationship between heart rate (HR) and oxygen consumption, the Åstrand–Ryhming cycle ergometer test (Astrand and Ryhming in J Appl Physiol 7:218–221, 1954) is a widely used submaximal test to predict whole body maximal oxygen consumption ($\dot{V}O_{2max}$). However, a similar test predicting peak oxygen consumption ($\dot{V}O_{2peak}$) in the upper extremities is not established, and may be very useful for individuals unable to use their lower extremities or/and if separation of upper extremity aerobic capacity is sought after. Thus, the aim of the current study was to develop a submaximal test predicting $\dot{V}O_{2peak}$ in arm-cycling. Forty-nine healthy volunteers (25 women: 38 ± 13 years; 24 men: 39 ± 12 years) tested arm-cycle $\dot{V}O_{2peak}$ on a protocol with 4-min, 21-W increments to exhaustion. The data were contrasted to treadmill $\dot{V}O_{2max}$ values. Arm-cycle $\dot{V}O_{2peak}$ was 66 ± 8% of $\dot{V}O_{2max}$ ($r = 0.92$, $p < 0.001$; women: 1.9 ± 0.4 L min^{-1}; men: 3.0 ± 0.7 L min^{-1}). Arm-cycle HR and $\%\dot{V}O_2$ exhibited correlations of $r = 0.79$ and $r = 0.78$ for women and men, respectively, while corresponding correlations between work rate and $\dot{V}O_2$ were $r = 0.95$ (women) and $r = 0.89$ (men) (all $p < 0.001$). Arm-cycle $\dot{V}O_{2peak}$ prediction revealed a standard error of estimate (SEE) of 11.2% (women) and 10.2% (men), and was primarily due to individual arm-cycle maximal HR (women: 173 ± 13 beats min^{-1}; men: 174 ± 10 beats min^{-1}; correction factor: 5–7%). In conclusion, from a single 4-min stage of submaximal arm cycling, $\dot{V}O_{2peak}$ can be predicted with a SEE of 10–11%. The arm-cycle test may have important value for individuals who rely on arms in sports and occupations, and for patients with lower extremity disabilities.

Keywords $\dot{V}O_{2max}$ · Åstrand–Ryhming · Submaximal test · Arm cranking · $\dot{V}O_{2peak}$ · Heart rate · Work rate

Introduction

Maximal oxygen consumption ($\dot{V}O_{2max}$) is one of the most important measures of health (Kodama et al. 2009; Myers et al. 2002) and performance (Saltin 1990). To reach $\dot{V}O_{2max}$, the exercise has to be carried out using enough muscle mass for sufficiently taxing the oxygen transporting organs, i.e. carried out as whole body exercise to exhaustion as in walking, running or cycling. Since a $\dot{V}O_{2max}$ test is strenuous, requires expensive equipment and a qualified tester, and is relatively time consuming, simpler indirect predictions of $\dot{V}O_{2max}$ have been developed. One of the most applied such tests is the Åstrand–Ryhming cycle test, developed as early as 1954 (Astrand and Ryhming 1954), where $\dot{V}O_{2max}$ can be predicted from the correlation between work rate (WR) and heart rate (HR). However, to date, it appears that no similar test has been established for the upper extremities.

An upper extremity test may be of high value for individuals that are prevented from exercising with their lower

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extremities such as in rehabilitation medicine. The concept of testing and training upper extremities has important implications for, e.g. for amputated, paraplegics and spinal cord-injured individuals (Eerden et al. 2018). It is also important for athletes with high demands on upper body endurance (Franklin et al. 1983; Sedlock 1991; Weissland et al. 1999; Wisloff and Helgerud 1998), and occupations demanding aerobic endurance in the arms and upper body (Sawka 1986). For upper body exercises (Berg et al. 2018) or in people with diseases limiting maximal effort (Wang et al. 2008), the highest achieved oxygen uptake during a maximal test is typically referred to as peak oxygen uptake ($\dot{V}O_{2peak}$). Importantly, a submaximal test for predicting $\dot{V}O_{2max\,/peak}$ is only a test of aerobic capacity, and not physical performance as this may vary substantially between individuals and populations. Yet, it may provide the individual with information of their potential to carry out work with a certain energy cost, and provide indications of cardiovascular health if the aerobic capacity is low. It can also be very useful for the evaluation of effectiveness of a training intervention (Åstrand and Rodahl 1986).

Recognizing the history, simplicity, and broad appliance of submaximal tests for predicting $\dot{V}O_{2max}$ (Noonan and Dean 2000), it is surprising that such a test has not been established for upper extremities since they may often be the predominantly, or even only, active part of the body for many patient populations, occupations and athletes. Thus, the aims of the current study were to (1) identify relationships between WR, $\dot{V}O_2$, and HR from a graded upper extremity cycling test and create associated regression equations, and then (2) create $\dot{V}O_{2peak}$ prediction tables for men and women from a single stage of the submaximal arm cycle exercise.

Methods

Subjects

Forty-nine healthy volunteers between 20 and 60 years, 25 women (age: 38 ± 13; range 20–59 years; height: 169 ± 6 cm; body weight: 66.0 ± 6.8 kg) and 24 men (age: 39 ± 12; range 21–60 years; height: 181 ± 7 cm; body weight: 78.0 ± 9.2 kg), participated in the study. They were recruited from University students, athletes and local sport and senior sport organizations. The intention was to recruit healthy people at different levels of aerobic endurance capacity. The study was approved by the Regional Committee for Medical and Health Research Ethics; REK midt-Norge, and participants signed informed consents before the first test.

Study timeline

The study consisted of two experimental tests on two separate days. The tests were performed within a period of maximum 2 weeks. The first test was a $\dot{V}O_{2max}$ test on a treadmill, while the second test was an arm-cycling test. Subjects were instructed to not carry out severe exercise the day before the tests, not eat or drink or take any caffeine products the last 2.5 h before the tests or smoke or take oral tobacco the last 2 h before the tests.

Part 1: treadmill test

After warming up for 10 min at light to moderate intensity (HR ≤ 130 beat min^{-1}) in a treadmill with 5% inclination, the subjects progressed directly to the $\dot{V}O_{2max}$ incremental protocol. The treadmill (DK City, Taichung, Taiwan) inclination was kept constant at 5%, while speed was increased from warm-up level with 1 km h^{-1} every minute until exhaustion, in accordance with the established procedures (Helgerud et al. 2007; Wang et al. 2012), and two or more of the following criteria were used to verify that the participants reached their $\dot{V}O_{2max}$: (1) a $\dot{V}O_2$ plateau despite an increase in WR. (2) Respiratory exchange ratio (RER) value ≥ 1.10. (3) ≤ 5 beats min^{-1} from individual's maximal heart rate (HR_{max}) if HR_{max} was known. (4) Blood lactate concentration ($[La^-]_b$) ≥ 7 mmol L^{-1}. Encouragement to continue the test as long as possible was given from the tester. Measurements of pulmonary gas exchange were recorded every 10 s using Cortex Metamax II portable metabolic test system with an oxygen concentration Zirconium sensor and an infrared carbon dioxide sensor (Cortex Metamax Portable Metabolic Test system, Leipzig, Germany). Manufacturer-reported volume range is 0.0–14.0 L s^{-1} (accuracy 1.5%), while oxygen and carbon dioxide concentration sensors are reported to have a range of 0–25 vol.% (accuracy < 0.1 vol.%) and 0–10 vol.% (accuracy < 0.1 vol.%). The Cortex Metamax II portable metabolic test system has previously been validated against the classic Douglas bag technique (Larsson et al. 2004). Prior to the tests, the volume transducer was calibrated with a 3-L standardized calibration syringe (Hans Rudolph Jäger GmbH, Germany). The gas concentration sensors were calibrated with ambient air and a chemically standardized calibration gas with 16% oxygen, 4% carbon dioxide and 80% nitrogen (SensorMedics Corporation, USA). HR was continuously measured throughout the test by Polar Sporttester (Polar electro Oy, Finland) and the average HR during the last 30 s of the test was recorded. Within 1 min after the test, $[La^-]_b$ was measured using blood from the subjects' fingertips and analyzed by an

YSI 1500 Sport, lactate analyzer (Yellow Springs Instruments Co, USA). The overall rating of perceived exertion (RPE) was noted at the same time using the Borg scale (Borg 1982).

Part 2: arm cycle test

The subjects were familiarized to the arm cycle ergometer (Monark Ergomedic 891 E, Monark Exercise AS, Sweden) before the test started and this introduction to the arm cycling also served as a warm-up. The subjects were placed in a seated position on a typical chair when cycling. Height was adjusted by foam rubber pillows so the participants were sitting with their arms in shoulder height and slightly flexed. The legs were not braced and the feet were placed flat on the floor. Progressing into the incremental arm cycling protocol, the test was split into stages of 4 min with 21 W higher load for each stage, starting at 21 W (adding 300 g load). In between the stages, the subjects rested for 1 min while blood was drawn from the fingertip for $[La^-]_b$ measurements. The crank rate was set to 70 (±2) repetitions per minute (rpm) throughout the test and was visible to the subjects during the arm cycling. The test was terminated when subjects, despite instructions to keep their position and encouragement to continue, were unable to maintain the desired rpm for ten consecutive seconds. The same equipment was used for measuring $\dot{V}O_2$, HR, and $[La^-]_b$ during the arm cycle test and the treadmill test. HR was recorded the last 30 s of each load and the peak heart rate (HR_{peak}) was noted at the time of exhaustion.

As $\dot{V}O_2$ divided by body weight will underestimate the large and overestimate the small individuals, respectively, allometric scaling was applied in the analyses to account for the subjects' different body dimensions in accordance with the recommended procedures (Helgerud 1994; Hoff et al. 2005). Thus, $\dot{V}O_2$ is given in absolute values (L min^{-1}), relative to body weight (mL min^{-1} kg^{-1}) and relative to allometrically scaled body weight (mL min^{-1} $kg^{-0.67}$).

Calculations and statistical analysis

A linear line of fit was modelled for the $\dot{V}O_2$–WR relationship from a linear regression equation. As a result, predictions of arm cycle $\dot{V}O_2$ was made given the knowledge of arm cycle WR:

$$\dot{V}O_2 = a \cdot \mathrm{WR} + b,$$

where a is the slope of the line and b is the intersection with the y-axis. Similarly, a linear line of fit was also modelled for the $\%\dot{V}O_{2peak}$–HR relationship, such that predictions of arm cycle $\%\dot{V}O_{2peak}$ were made from the knowledge of submaximal arm cycle HR:

$$\%\dot{V}O_{2peak} = a \cdot \mathrm{HR} + b.$$

Thus, for an individual arm cycling at a given WR, with a given HR, information of $\dot{V}O_2$ and which $\%\dot{V}O_{2peak}$ this corresponded to was provided. Finally, $\dot{V}O_{2peak}$ was estimated as

$$\dot{V}O_{2peak} = \left(\dot{V}O_2 / \%\dot{V}O_{2peak}\right) \times 100.$$

The arm cycle $\dot{V}O_{2peak}$ prediction may also be adjusted for individual arm cycle HR_{peak}, if this is known: $\dot{V}O_{2peak}$ prediction individual HR_{peak} percentage deviation from current data sample average HR_{peak}.

Means and standard deviations were computed for all the measured variables. Repeated measures analyses of variance (ANOVA) were used to calculate statistical differences between genders and treadmill and arm cycling testing modalities. Linear Pearson correlation regression analyses were applied to detect relationships between variables, and correlations are given as r values throughout the results. Statistical significance was accepted at $p < 0.05$. Statistical analyses were performed using Statistical Package for Social Sciences (IBM SPSS version 24). The graphs were constructed using GraphPad Prism 8 (California, USA).

Results

Part 1: relationship between arm cycle $\dot{V}O_{2peak}$ and treadmill $\dot{V}O_{2max}$

The subjects achieved 66 ± 8% (men: 67 ± 8; women: 65 ± 9%) of VO_{2max} in the arm cycle test while they reached 91 ± 4% (men: 91 ± 3%); women: 90 ± 5%) of HR_{max}. The strong association ($r = 0.92$; $p < 0.001$) between arm cycle VO_{2peak} and treadmill VO_{2max} had the linear regression equation: treadmill $\dot{V}O_{2max}$ (L min^{-1}) = 1.25 arm cycle $\dot{V}O_{2peak}$ (L min^{-1}) + 0.65, illustrated in Fig. 1. In the arm cycle

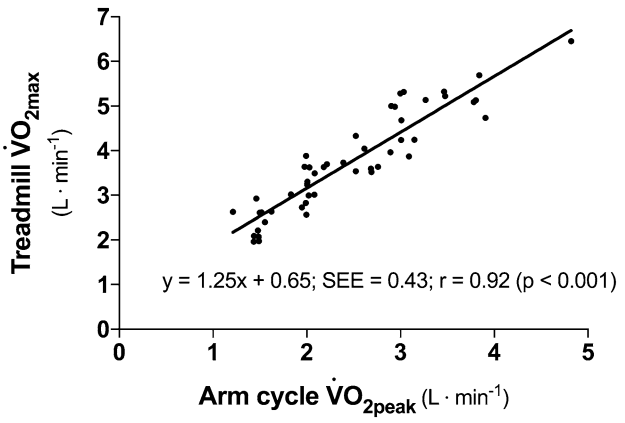

Fig. 1 Linear relationship between treadmill $\dot{V}O_{2max}$ and arm cycle $\dot{V}O_{2peak}$ for women ($n = 25$) and men ($n = 24$). *SEE* standard error of estimate

test, 21–105 W were completed by all men. For the subsequent WRs the number of male subjects that completed were 126 W ($n=22$); 147 W ($n=16$); 168 W ($n=6$); 189 W ($n=4$); 201–222 W ($n=1$). For females, the number of subjects that completed the WRs were 21–42 W ($n=25$); 63 W ($n=24$); 84 W ($n=19$); 105 W ($n=9$); 126 W ($n=4$); 147 W ($n=2$). Maximal test values for physiological variables are shown in Table 1, and submaximal variables in Table 2, respectively.

Part 2: arm cycle test

The linear WR–$\dot{V}O_2$ relationship during submaximal arm cycle work had the linear regression equation: $\dot{V}O_2$ (L min^{-1}) = 0.017 WR (watt) + 0.548 and is shown in Fig. 2 ($p<0.001$). No differences were observed between women and men in the WR–$\dot{V}O_2$ relationship. From this relationship, an estimated $\dot{V}O_2$ can be seen for a given WR (Table 2), and $\dot{V}O_2$ can be estimated from relevant increments of 25 W (Table 3). The submaximal HR–$\dot{V}O_2$ relationships ($p<0.001$) are shown in Fig. 3 and had linear regression equations of HR (beats min^{-1}) = 47 $\dot{V}O_2$ (L min^{-1}) + 75 (women) and HR (beats min^{-1}) = 39 $\dot{V}O_2$ (L min^{-1}) + 58 (men). The relationships ($p<0.001$) between HR and percentage $\dot{V}O_{2peak}$ is shown in Fig. 4, and had a linear regression equations of $\dot{V}O_{2peak}$ (%) = 0.48 HR (beats min^{-1}) − 5.43 and $\dot{V}O_{2peak}$ (%) = 0.41 HR (beats min^{-1}) + 7.11 for women and men, respectively. Predictions of $\dot{V}O_{2peak}$, based on the linear relationships shown in Figs. 2 and 4, are given for women in Table 4 and for men in Table 5, and returned standard error of estimates of 11.2% and 10.2% for women and men, respectively. The variation in $\dot{V}O_2$ on a given WR is due to differences in work economy among the subjects, and this variation is also included in the prediction of %$\dot{V}O_{2peak}$ from HR. The variation in work economy is thus included in the final $\dot{V}O_{2peak}$ prediction. Data are presented separately for women and men since the results were different ($p<0.01$). If arm cycle HR_{peak} is known, correction factors (Table 6) can be applied to improve the prediction accuracy. In contrast, the results showed no association between age and $\dot{V}O_{2peak}$ in arm cycling for neither men nor women, thus no age-related correction was made.

Discussion

Predictions of aerobic capacity based on submaximal WR and HR have been a simple and useful strategy when direct testing is not available. Despite the broad application of submaximal tests, a standardized test for the upper extremities has not been established, and the aim of the current study was to develop an arm cycling test for predicting $\dot{V}O_{2peak}$ in the upper extremities using the Åstrand–Ryhming protocol. The main findings were that participants were able to reach ~ 2/3 of their $\dot{V}O_{2max}$ when arm cycling, strong correlations between HR, WR and $\dot{V}O_2$ were present, and predictions of $\dot{V}O_{2peak}$ returned standard errors of ~ 10–11%. The results of the current study can be applied when predicting $\dot{V}O_{2peak}$ from submaximal HR and WR during arm cycling, and will return smaller errors compared with the well-recognized Åstrand–Ryhming cycle test (Astrand and Ryhming 1954). Given the putative value of assessing $\dot{V}O_{2peak}$ in individuals who rely on their arms for propulsion, these data may be very useful.

Table 1 Physiological parameters at treadmill running and arm cycling

	Women ($n=25$)		Men ($n=24$)	
	Treadmill	Arm cycle	Treadmill	Arm cycle
$\dot{V}O_2$				
L min^{-1}	2.90 ± 0.61†	1.87 ± 0.42	4.58 ± 0.84†,*	3.06 ± 0.68*
mL kg^{-1} min^{-1}	44.2 ± 9.1†	28.4 ± 6.8	58.7 ± 8.3†,*	39.1 ± 7.9*
mL kg$^{-0.67}$ min^{-1}	178.0 ± 35.9†	114.5 ± 26.2	250.5 ± 36.9†,*	167.1 ± 33.8*
HR_{max} (beats min^{-1})	192 ± 12†	173 ± 13	191 ± 9†	174 ± 10
$[La^-]_b$ (mM)	7.5 ± 1.8	6.1 ± 1.0	8.2 ± 1.5†	7.3 ± 1.3
RER	1.10 ± 0.04	1.06 ± 0.06	1.10 ± 0.05†	1.04 ± 0.05
V_E (L min^{-1})	98.4 ± 21.4†	79.8 ± 20.8	150.6 ± 26.5†,*	128.7 ± 27.9*
WR_{peak}		81 ± 24		135 ± 31*
TTE (min)		15 ± 5		25 ± 6*

Data are mean ± standard deviation

$\dot{V}O_2$ oxygen consumption, *HR* heart rate, $[La^-]_b$ blood lactate concentration, *RER* respiratory exchange ratio, V_E total pulmonary ventilation, WR_{peak} highest achieved work rate (WR) in the arm cycling test, *TTE* total exercise time, breaks excluded

*Significant difference from women ($p<0.05$). †Significant different from arm cycling values ($p<0.05$)

Table 2 Physiological parameters in the submaximal arm cycling tests

	Work rate (W)	Women ($n=25$)	Men ($n=24$)
$\dot{V}O_2$			
L min^{-1}	21	0.9 ± 0.1	1.1 ± 0.2
	42	1.1 ± 0.1	1.3 ± 0.2
	63	1.5 ± 0.2	1.6 ± 0.2
	84	1.8 ± 0.2	1.9 ± 0.2
	105	2.4 ± 0.1	2.4 ± 0.2
mL min^{-1} kg^{-1}	21	13.2 ± 1.8	13.6 ± 2.1
	42	17.0 ± 1.3	16.7 ± 1.8
	63	22.7 ± 1.9	20.9 ± 3.5
	84	28.7 ± 2.7	24.8 ± 2.5
	105	37.5 ± 3.8	31.5 ± 3.4
mL min^{-1} kg$^{-0.67}$	21	52 ± 6	57 ± 8
	42	70 ± 8	69 ± 7
	63	91 ± 8	88 ± 13
	84	113 ± 10	103 ± 10
	105	147 ± 11	148 ± 20
HR (beats min^{-1})	21	107 ± 20	92 ± 13
	42	128 ± 19	107 ± 18
	63	149 ± 26	124 ± 25
	84	156 ± 14	138 ± 21
	105	170 ± 13	147 ± 20
$[La^-]_b$ (mM)	21	1.8 ± 0.9	1.4 ± 0.4
	42	2.7 ± 0.7	1.9 ± 0.5
	63	3.9 ± 1.4	2.7 ± 1.2
	84	4.3 ± 1.0	3.4 ± 1.1
	105	5.4 ± 0.4	4.3 ± 1.1
RER	21	1.00 ± 0.07	0.93 ± 0.06
	42	1.02 ± 0.06	1.00 ± 0.07
	63	1.05 ± 0.06	1.00 ± 0.08
	84	1.03 ± 0.04	1.01 ± 0.06
	105	1.05 ± 0.05	1.00 ± 0.05
V_E (L min^{-1})	21	27.0 ± 5.4	30.9 ± 5.7
	42	38.0 ± 5.3	38.3 ± 6.7
	63	55.1 ± 11.3	54.7 ± 26.6
	84	66.3 ± 15.7	61.7 ± 10.0
	105	92.1 ± 13.3	78.5 ± 10.4

Data are presented as mean ± standard deviation

$\dot{V}O_2$ oxygen consumption, *HR* heart rate, $[La^-]_b$ blood lactate concentration, *RER* respiratory exchange ratio, V_E total pulmonary ventilation

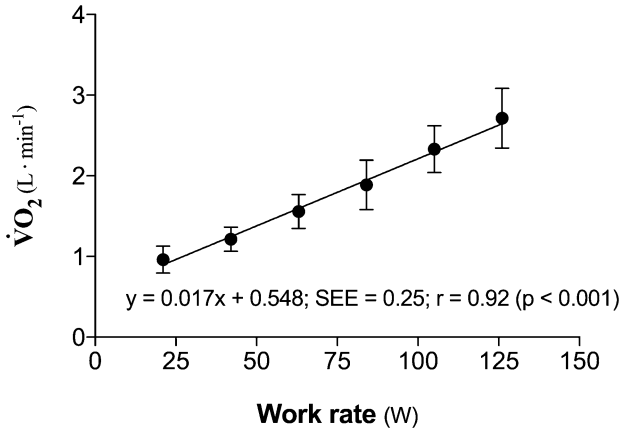

Fig. 2 Linear relationship between arm cycle $\dot{V}O_2$ and work rate during submaximal loads for women and men combined ($n=49$). *SEE* standard error of estimate

Table 3 Predicted oxygen consumption ($\dot{V}O_2$) from work rate (W) during arm cycling

Watt (W)	$\dot{V}O_2$ (L min^{-1})	
	Women	Men
25	0.9	1.2
50	1.3	1.5
75	1.8	1.9
100	2.2	2.3
125	2.6	2.7
150	3.0	3.0
175	3.4	3.4

Prediction is based on the equation: $\dot{V}O_2 = 0.017_{watt} + 0.477$ (women) and $\dot{V}O_2 = 0.015_{watt} + 0.781$ (men)

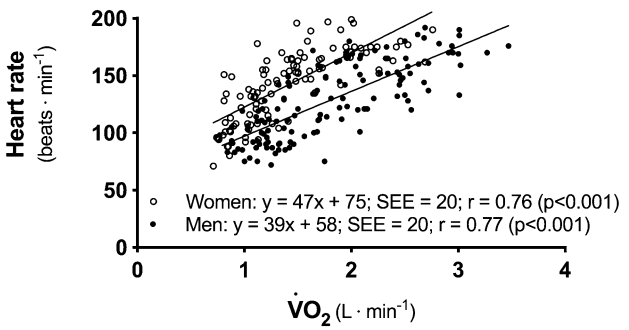

Fig. 3 Linear relationships between heart rate and arm cycle $\dot{V}O_2$ for women ($n=25$) and men ($n=24$). Submaximal work rates are 21, 42, 63, 84 and 105 W. *SEE* standard error of estimate

Part 1: arm cycling vs. treadmill

In the current study, both women and men achieved 66% of VO_{2max} in arm cycling to exhaustion. These results are in accordance with previous arm cycling studies documenting results between 65 and 80% (Bar-Or and Zwiren 1975; Franklin 1985; Sawka et al. 1983b; Weissland et al. 1999). Albeit, individuals who use upper body muscles in a work situation or in sports will often get closer to their VO_{2max} (Arabi et al. 1997). Of importance, a treadmill test was chosen for comparison with the arm cycle

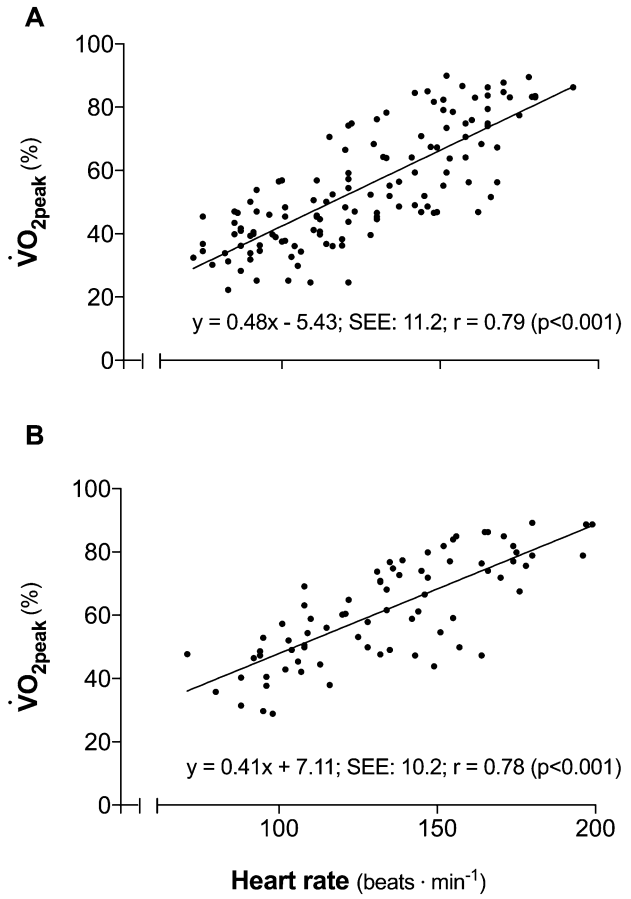

Fig. 4 Linear relationship between percentage of $\dot{V}O_{2peak}$ and heart rate for **a** women ($n = 25$) and **b** men (24) at submaximal work rates. *SEE* standard error of estimate

Table 4 Predicted arm cycling (70 rpm) peak oxygen consumption ($\dot{V}O_{2peak}$) from heart rate (HR) in women

HR (beats min^{-1})	$\dot{V}O_{2peak}$ (L min^{-1})				
	25 W	50 W	75 W	100 W	125 W
110	1.7	2.5	3.3	4.1	5.0
112	1.7	2.5	3.3	4.1	4.9
114	1.7	2.4	3.2	4.0	4.8
116	1.6	2.4	3.2	3.9	4.7
118	1.6	2.3	3.1	3.8	4.6
120	1.6	2.3	3.0	3.8	4.5
122	1.5	2.3	3.0	3.7	4.4
124	1.5	2.2	2.9	3.7	4.4
126	1.5	2.2	2.9	3.6	4.3
128	1.5	2.2	2.8	3.5	4.2
130	1.4	2.1	2.8	3.5	4.2
132	1.4	2.1	2.8	3.4	4.1
134	1.4	2.1	2.7	3.4	4.0
136	1.4	2.0	2.7	3.3	4.0
138	1.4	2.0	2.6	3.3	3.9
140	1.3	2.0	2.6	3.2	3.8
142	1.3	1.9	2.5	3.2	3.8
144	1.3	1.9	2.5	3.1	3.7
146	1.3	1.9	2.5	3.1	3.7
148	1.3	1.8	2.4	3.0	3.6
150	1.2	1.8	2.4	3.0	3.6
152	1.2	1.8	2.4	2.9	3.5
154	1.2	1.8	2.3	2.9	3.5
156	1.2	1.7	2.3	2.9	3.4
158	1.2	1.7	2.3	2.8	3.4
160	1.2	1.7	2.2	2.8	3.3
162	1.1	1.7	2.2	2.8	3.3
164	1.1	1.7	2.2	2.7	3.3
166	1.1	1.6	2.2	2.7	3.2
168	1.1	1.6	2.1	2.7	3.2
170	1.1	1.6	2.1	2.6	3.1

Predictions are based on the linear relationship between (1) $\dot{V}O_2$ (L min^{-1}) and work rate (W) and (2) $\%\dot{V}O_{2peak}$ (L min^{-1}) and HR, at submaximal loads

test in the current study. As subjects typically attain 4–8% higher oxygen uptake during uphill treadmill running or walking compared to cycling (Astrand 1976), this likely made the deviation between whole body $\dot{V}O_{2max}$ and arm cycle $\dot{V}O_{2peak}$ larger. Indeed, the higher $\dot{V}O_2$ that typically is attained on a treadmill was the reason why this test, and not cycling, was used as a whole body $\dot{V}O_{2max}$ standard in the present study. Albeit, this also prevented a direct comparison with the classical Åstrand–Ryhming cycle test (1954). Notably, the results in the present study showed a strong ($r = 0.92$) correlation between treadmill VO_{2max} and arm ergometer VO_{2peak}. While this association is in accordance with some previous findings (Sawka 1986), returning correlations of $r = 0.70$–0.94, it is somewhat contradictory to the conclusion in a review article stating that it is not possible to estimate upper extremity VO_{2peak} from lower extremity tests (Franklin 1985). Although our data indicate a strong relationship between $\dot{V}O_{2max}$ on the treadmill and $\dot{V}O_{2peak}$ when arm cycling, the SEE was 0.43 L min^{-1} (Fig. 1), suggesting that an estimate would not be very accurate. The main reason to predict $\dot{V}O_{2max}$ from the arm cycling is the role of $\dot{V}O_{2max}$ as an important measure of health and performance. $\dot{V}O_{2max}$ is also a critical factor in prevention and rehabilitation of several diseases. The strong correlation between whole body $\dot{V}O_{2max}$ and arm cycle $\dot{V}O_{2peak}$ in the present study may be explained by the possibility that the trained individuals also exercised their upper extremities. Indeed, several of the test subjects that reached a high $\dot{V}O_{2max}$ reported that they trained cross-country skiing. As expected, due to the lower vascular conductance in upper extremities (Calbet et al. 2015), the difference in HR at the end of the arm cycle and treadmill

Table 5 Predicted arm cranking (70 rpm) peak oxygen consumption ($\dot{V}O_{2peak}$) from heart rate (HR) in men

HR (beats min^{-1})	$\dot{V}O_{2peak}$ (L min^{-1})					
	25 W	50 W	75 W	100 W	125 W	150 W
110	2.2	3.0	3.7	4.4	5.2	5.9
112	2.2	2.9	3.6	4.3	5.1	5.8
114	2.2	2.9	3.6	4.3	5.0	5.7
116	2.1	2.8	3.5	4.2	4.9	5.6
118	2.1	2.8	3.4	4.1	4.8	5.5
120	2.0	2.7	3.4	4.0	4.7	5.4
122	2.0	2.7	3.3	4.0	4.6	5.3
124	2.0	2.6	3.3	3.9	4.5	5.2
126	1.9	2.6	3.2	3.8	4.5	5.1
128	1.9	2.5	3.2	3.8	4.4	5.0
130	1.9	2.5	3.1	3.7	4.3	4.9
132	1.9	2.5	3.1	3.7	4.3	4.9
134	1.8	2.4	3.0	3.6	4.2	4.8
136	1.8	2.4	3.0	3.5	4.1	4.7
138	1.8	2.3	2.9	3.5	4.1	4.6
140	1.7	2.3	2.9	3.4	4.0	4.6
142	1.7	2.3	2.8	3.4	3.9	4.5
144	1.7	2.2	2.8	3.3	3.9	4.4
146	1.7	2.2	2.7	3.3	3.8	4.4
148	1.6	2.2	2.7	3.2	3.8	4.3
150	1.6	2.1	2.7	3.2	3.7	4.2
152	1.6	2.1	2.6	3.2	3.7	4.2
154	1.6	2.1	2.6	3.1	3.6	4.1
156	1.6	2.1	2.6	3.1	3.6	4.1
158	1.5	2.0	2.5	3.0	3.5	4.0
160	1.5	2.0	2.5	3.0	3.5	4.0
162	1.5	2.0	2.5	3.0	3.4	3.9
164	1.5	2.0	2.4	2.9	3.4	3.9
166	1.5	1.9	2.4	2.9	3.4	3.8
168	1.4	1.9	2.4	2.8	3.3	3.8
170	1.4	1.9	2.3	2.8	3.3	3.7

Predictions are based on the linear relationship between (1) $\dot{V}O_2$ (L min^{-1}) and work rate (watt) and (2) $\%\dot{V}O_{2peak}$ (L min^{-1}) and HR, at submaximal loads

tests was smaller than the difference in $\dot{V}O_2$, and the participants reached about 91% of their HR_{max} during arm cycling.

Comparing submaximal $\dot{V}O_2$ during arm cycling with previous studies applying cycling exercise, our data revealed that the former is performed at a greater $\dot{V}O_2$ cost. Åstrand and Ryhming (1954) documented $\dot{V}O_2$ at, e.g. 50 W to be 0.9 L min^{-1} during cycling while in the present study, the average $\dot{V}O_2$ cost at the same WR was 1.3 L min^{-1} (women) and 1.5 L min^{-1} (men). The divergence between lower and upper extremity $\dot{V}O_2$ costs for a given submaximal work was apparent also for heavier WRs. The higher $\dot{V}O_2$ cost for arm cycling could be explained by the lower vascular conductance (Calbet et al. 2015), poor oxygen extraction and less oxidative fibers (Calbet et al. 2005), poor training status compared with lower extremities (Nyberg et al. 2017), or involvement of isometric stabilization musculature (Franklin et al. 1983; Price and Campbell 1997; Sawka et al. 1983a). Our data also showed a difference in $\dot{V}O_2$ between women and men, indicating that women have better arm cycling economy than men at the same submaximal load. Although this difference was not apparent for higher loads, it could be a result of few women being able to carry out the heavier WRs.

Table 6 $\dot{V}O_{2peak}$ predictions in Tables 4 and 5 should be multiplied with the correction factors below if HR_{peak} for arm cycling is known

HR_{peak}	Correction factor
205	1.17
200	1.14
195	1.11
190	1.08
185	1.05
180	1.03
175	1.00
170	0.97
165	0.95
160	0.92
155	0.90

Corrections are based on the individual's HR_{peak} percentage deviation from the current data sample's average HR_{peak}

Part 2: submaximal predictions of $\dot{V}O_{2peak}$ from heart rate

The association between arm cycle HR and $\dot{V}O_2$ also demonstrated a linear relationship following the submaximal work. The standard errors of estimate, of ~ 10–11% were somewhat smaller than the ~ 15% observed for lower extremity cycling in the Åstrand–Ryhming test (Astrand and Ryhming 1954), implying that the arm cycle test may certainly be applied for arm cycle $\dot{V}O_{2peak}$ predictions. A challenge for both these tests, cycling and arm cycling, is the variance in HR_{max} for individuals with similar age. However, to date, there appears to be no better approach for submaximal tests. Although the results in our study showed no significant correlation between arm cycle HR_{peak} and age, the error still exists because of the individual differences in HR_{peak} within age groups. In accordance with this notion, our results revealed standard deviations in HR_{peak} of 13 beats min^{-1} (women) and 10 beats min^{-1} (men), implying correction factors of 7% and 5%, respectively (Table 6). Indeed, the variability in absolute HR response, due to age, fitness, and intrinsic genetic factors has previously been forwarded as a limitation to the application of the Åstrand–Ryhming cycle test. With a standard error of 15%, when hundred subjects are predicted to have a $\dot{V}O_{2max}$ of 3.0 L min^{-1}, five of them will have a true $\dot{V}O_{2max}$ of < 2.1 L min^{-1} or > 3.9 L min^{-1} (Legge and Banister 1986), leading to a substantial error with possibly large clinical implications. It is also previously claimed that the Åstrand and Ryhming nomogram is over- and underestimating VO_{2max} for trained and untrained individuals, respectively (Grant et al. 1999). It was indicated that the reason for this was the inclusion of active young subjects in the cycle test. Thus, to avoid this skewness in the current study, we included trained and untrained subjects with various ages.

Importantly, the $\dot{V}O_{2max}$ achieved during the treadmill test revealed a typical age-related reduction of ~ 1% per year, in accordance with the previous literature (Storen et al. 2017). Interestingly, the influence of age was not evident in the arm cycle test, and this may be explained by the fact that cellular aging is typically manifested in the lower, but not to the same degree in upper extremities (Kanda et al. 1996). As a consequence, it was not necessary to calculate an aging factor for the $\dot{V}O_{2peak}$ prediction in the current study, as has previously been done for the Åstrand–Ryhming cycle test (Astrand and Ryhming 1954).

Protocol type

It would seem that intermittent protocols (employing rest periods between exercise bouts) could minimize the effect of accumulated local fatigue and thus elicit higher values for $\dot{V}O_{2peak}$ than continuous protocols (Franklin 1985). Continuous protocols, however, provide an obvious advantage of requiring less time to administer than intermittent protocols. But, intermittent protocols may have a particular application for arm cycling because exercise termination is frequently associated with local muscle fatigue. The combination of power, exercise duration and crank rate should be carefully chosen to obtain an optimal evaluation during exhaustive events. The majority of the test subjects in the present study had not tried arm cycling earlier, which probably affected the test results. This could be a reason for not achieving higher results in $\dot{V}O_{2peak}$ in comparison to $\dot{V}O_{2max}$ as previous results have indicated. We would recommend familiarizing the subject to the arm cycle ergometer before the test starts, this can also serve as a warm-up. A power is then chosen that will require a $\dot{V}O_2$ about 15–20% higher than the warm-up load, using Table 3. If the subject at the end of the first minute on the selected power has difficulty in keeping up the pedaling and starts to hyperventilate markedly, the power must be lowered to allow the subject to continue for a total of 4 min. If, on the other hand, the subject, after a minute or two, appears to have higher capacity than predicted, the workload could be slightly increased. Then another 4-min WR has started. Notably, higher crank rates (rpms) have been documented to yield higher $\dot{V}O_2$ costs compared with lower crank rates (Sawka et al. 1983a). The applied protocol in the current study utilized 70 rpm as this previously has been advocated as preferable because of extended test time, postponement of acute local neuromuscular fatigue, increased physiological strain, and allowance of more total work to be completed (Price and Campbell 1997; Smith et al. 2001).

Study limitations and practical implications

Recognizing that a large sample size is always sought after, the 49 subjects included in the current study were carefully chosen to be representative for future utilization of the test. Although the Åstrand–Ryhming cycle test included a higher number of subjects (86 males and females), it has, despite being applied to healthy and non-healthy groups differing in age and fitness, been criticized for only including students between 20 and 30 years of age (Legge and Banister 1986). By including participants with various fitness level and age, we aimed to increase its applicability. Yet, as some variation in the accuracy of both predicted and measured $\dot{V}O_{2peak}$ should be expected from one sample to another, the test would have benefitted from validation of an additional data set, preferably from another laboratory.

Given the relatively low SEE, the results in the current study may be used with caution for predictions of individuals' upper extremity aerobic capacity, and evaluation of the effectiveness of a training program for the upper extremities. Of notice, as physical function may be considerably different in individuals, depending on health status and the work being performed, it is limited to only predict $\dot{V}O_{2peak}$, e.g. patient populations may have different physical restrictions, muscular and oxygen transport limitations, and differences in gender distribution. It would have required a very high and carefully selected number of patients to take the potential impact of pathology on $\dot{V}O_{2peak}$ into consideration. However, a predicted $\dot{V}O_{2peak}$ may provide a useful indication about the ability to perform work, and may also be an indicative of health status, especially for patients that can only use their upper extremities. In that situation, their upper extremity $\dot{V}O_{2peak}$ becomes similar to their whole body $\dot{V}O_{2peak}$. One group that may find the test particularly useful is spinal cord-injured patients. Recognizing that these patients typically should be considered as healthy in their upper extremities and also have a good upper body fitness level, the prediction tables in our study may be very useful for assessing $\dot{V}O_{2peak}$. However, it may have less relevance for predicting wheelchair mobility as the functional translation between the two different modalities is shown to be poor (Brurok et al. 2011; Laskin et al. 2004). The results in the current study may also be useful for athletes participating in sports that rely on the arms, such as in, e.g. rock climbing, rowing, double poling in cross country skiing, and kayaking. Finally, the test may also be useful for individuals in occupations that are dominated by upper extremity work.

An upper extremity $\dot{V}O_{2peak}$ test carried out in accordance with the protocol of the present study should include arm cycling at 70 rpm for 4 min, at a single-stage submaximal constant load, well below WR_{max} and HR_{peak}. The HR should ideally be between 100 and 140 beats min^{-1}, and is measured the last 30 s of the single-stage 4-min interval. The VO_{2peak} can be predicted from the measured HR using Table 4 for women and Table 5 for men. If HR_{peak} is known, correction factors in Table 6 may be applied. The result can be divided by body weight to provide results in mL kg^{-1} min^{-1}, and if an inter-individual comparison of the result is needed, the result can be divided on allometrically scaled body weight to yield the values in mL $kg^{-0.67}$ min^{-1}.

Conclusion

A submaximal standardized test based on HR and WR may be a practical and cost-effective strategy to predict $\dot{V}O_{2peak}$ in the upper extremities, and thus provide important information of health and performance. To the best of our knowledge, no such tests had been developed to date, and we aimed to establish an arm cycling test in the current study. The results revealed that arm cycle $\dot{V}O_{2peak}$ can be predicted from a single-stage 4-min WR with a standard error of ~ 10–11% for women and men. Providing a relatively low prediction error, the test may be used with caution as a useful indication for healthy individuals as well as in patients, particularly those who rely on their arms for daily propulsion.

Author contributions JH and JH conceived and designed research; BEØ and EW conducted experiments; BEØ and EW analyzed data; BEØ, EW and JH, wrote the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

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