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Aerobic and functional capacity in a group of healthy women: reference values and repeatability

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Summary

Twenty-five randomly selected, low or moderately fit and healthy women (22–44 years) rated their perceived physical capacity and performed an incremental cycle exercise test with respiratory gas analysis. The aerobic and functional capacity did not decrease with age. However, $\tau\dot{V}O_2$ increased with age. The mean value of the perceived physical capacity was 10 metabolic equivalents and that of $\dot{V}O_{2max}$ 2075 ml min^{-1}. The increasing anaerobic metabolism was determined at three points DX (where the rate of $\dot{V}CO_2$ increase just exceeds the rate of $\dot{V}O_2$ increase), PX (where $\dot{V}CO_2/\dot{V}O_2 = 1{\cdot}0$) and PQ (where ventilation increase disproportionately in relation to $\dot{V}CO_2$). The mean $\dot{V}O_2$ (% of $\dot{V}O_{2max}$) at DX, PX and PQ were 1263 (63%), 1528 (73%) and 1620 (78%) ml min^{-1}, respectively. The mean value of $\Delta\dot{V}O_2/\Delta W$ was 10·2 ml min^{-1} W^{-1} while that of $\tau\dot{V}O_2$ was 0·578 (age) + 15·6. Ten women performed a test and re-test on two consecutive days, and eight of these performed another re-test 4 weeks later. The repeatability was analysed and the variations were expressed as 2 SD of the differences between the tests. The variation was greater for the 4-week re-test than the day-to-day re-test regarding $\dot{V}O_{2max}$, $\dot{V}O_2$ at DX, PX and PQ, $\Delta\dot{V}O_2/\Delta W$ and HR. The variation in $\dot{V}O_{2max}$, PX and $\Delta\dot{V}O_2/\Delta W$ for the 4-week re-test was more than twice that of the previously reported 4-week variation for men. The considerable variation, especially for 4-week re-testing for women should be considered when evaluating the effects of exercise and rehabilitation.

Introduction

Reference values and values of repeatability are necessary to interpret the results of exercise testing, both in evaluating the level of fitness and in evaluating the effects of exercise and rehabilitation. An appropriate set of reference values is a function of the subject population, including age, height, weight, sex and physical activity, and may vary from one country to another.

Aerobic capacity can be determined from gas analysis during an exercise test. The most common and reliable measurement is the maximal oxygen uptake ($\dot{V}O_{2max}$). To gain information about the functional capacity, the contribution of supplementary anaerobic metabolism can be estimated. In addition, the time constant of $\dot{V}O_2$ ($\tau\dot{V}O_2$) and the amount of O_2 required at each load ($\Delta\dot{V}O_2/\Delta W$) gives further information about the aerobic profile. It may also be useful to obtain knowledge about some submaximal variables. Furthermore, it is important to have knowledge concerning the test subject's level of physical activity, and this can be achieved by using a questionnaire. It is also possible to let the subjects rate their perceived capacity (present or previous) and compare this with the capacity actually demonstrated during an exercise test.

When combined these measurements provide a broad knowledge base on different aspects of the aerobic capacity and improve the ability to define the subject's capacity, to prescribe suitable exercise and to evaluate the effects of an exercise (Hagberg *et al.*, 1980; Babcock *et al.*, 1994; Phillips *et al.*, 1995). The combination of measurements also has been shown to improve our ability to diagnose cardiopulmonary and peripheral diseases (Hansen *et al.*, 1987; Sue *et al.*, 1988; Itoh *et al.*, 1989; Whipp & Ward, 1990; Koike *et al.*, 1992; Mettauer *et al.*, 2000; Gitt *et al.*, 2002; Toyofuku *et al.*, 2003).

We have recently presented a scale which can be used to determine the perceived capacity (Wisén *et al.*, 2002) and a set of methods to analyse data from gas measurements from a single progressive exercise test on a cycle, which also included a period of constant load (Wisén & Wohlfart, 2004a,b). In those studies we focused on a group of healthy men ($n = 19$) and reported the 5–6-week repeatability of the measurements. Integrated measurements of aerobic capacity and repeatability in healthy women including reference values have to our knowledge, not previously been reported. However, several studies have reported maximal values (Hansen *et al.*, 1984; Jones *et al.*, 1985; Åstrand & Rodahl, 1986; Possner *et al.*, 1987; Wasserman *et al.*, 1994; Farazdaghi & Wohlfart, 2001). Reference values of the anaerobic and ventilatory threshold (in % of $\dot{V}O_{2max}$), $\tau\dot{V}O_2$ and $\Delta\dot{V}O_2/\Delta W$ are given in the literature, but not separately for men and women (Wasserman *et al.*, 1994; Cooper & Storer, 2001). Only a few studies of day-to-day repeatability in groups of women were found (Foster *et al.*, 1986; Wergel-Kolmert & Wohlfart, 1999; Wergel-Kolmert *et al.*, 2001), but no studies on long-term repeatability.

The aims of this study were to describe the integrated aerobic and functional capacity in a group of healthy women and to give reference values. We also investigated the day-to-day and the 4-week repeatability of aerobic and functional capacity. Furthermore, the repeatability of some variables at rest and at submaximal and maximal load was studied.

Method

Subjects

Twenty-five healthy women, uniformly distributed in age (22–44 years), participated. To analyse the repeatability of the measurements 10 of the women performed a second test the day after the first test, and eight of these women performed a third test 4 weeks after the first test.

Initially a letter of invitation was sent to 118 women randomly recruited from the municipal population register. As stated in the invitation, the participants had to be healthy, with no cardiac or lung disease, not being obese, not on regular medication, and had to be able to perform a maximal exercise test. A total of 31 women accepted the invitation. Six subjects dropped out, three due to illness and three for social reasons. Prior to the test the women were asked structured questions about their health and medical status, level of physical activity and were also asked to rate their perceived physical capacity (Wisén *et al.*, 2002). Of the 25 women 10 agreed to participate in two re-tests. Two of the subjects were unable to perform the third test due to illness.

The Ethics Committee of Lund University Hospital approved the study. Prior to the test the participants received written and oral information, and signed informed consent forms. The same investigators supervised the tests, and all tests were performed at the same laboratory. The participants were instructed not to take part in any sporting activities 48 h before the test, not to eat 3 h before the test and not to drink coffee or any beverage containing caffeine 2 h before the test. The participants were also asked not to smoke 2 h before the test. They were also asked not to change their general level of activity between the test sessions. Prior to the test, it was ascertained whether the subject had followed the pretest instructions.

Prior to each of the tests, body weight was determined on an ordinary physician's beam scale, with the participant dressed in light underwear and wearing no shoes. Height was measured to the nearest cm and the body mass index (BMI = weight in kg/height^2 in m) was calculated. Venous blood samples were drawn for analysis of B-haemoglobin (Hb). Based on a questionnaire, the physical requirements for the subject's profession and the physical activity level during leisure and exercise were recorded (Saltin & Grimby, 1968). The characteristics of the subjects are given in Table 1. As can be seen, most of the 25 subjects had a moderate activity level at work, some were sitting but none performed hard work. None of the subjects was inactive during leisure time, their level of activity being some or regular. Nearly all of the women performed regular exercise, and most of them at moderate intensity. The physical requirements at work and activity level during leisure time changed to a lower level between the first test and 4-week re-test due to unemployment for one woman.

Table 1 Characteristics of the subjects given as mean (SD) and range. Weight, BMI and B-haemoglobin (Hb) are given for each of the repeated tests. Physical requirements for the subjects' profession and level of leisure and exercise activity from a questionnaire are given.

	25 women	10 women (test 1/test 2)	8 women (test 1/test 3)
Age (years)	34·8 (7) 22–44	33·5 (8·0) 22–44	35·6 (7·5) 22–44
Weight (kg)	62·9 (8) 50–80	66·3 (6·8) 55–78/66·3 (6·6) 55–78	67·8 (6·2) 61–78/67·3 (6·5) 59–78
Height (cm)	166 (6) 153–181	166 (6)	167 (7)
BMI (weight/height^2)	22·4 (3) 19–28	24·3 (2·7) 20–28/24·3 (2·7) 20–28	24·3 (2·2) 21–28/24·1 (2·4) 20–28
Hb (g l^{-1})	129 (13) 89[a]–154	128 (11) 102–146/126 (11) 100–141	128 (13) 102 –146/124 (11) 101–136

	Number of subjects	Test 1	Test 3
Workload (not working/sitting/sitting, standing/walking, handling material/hard work)	1/6/12/6/0	0/0/4/4/0	1/0/4/3/0
Leisure activities (inactive/some physical activity 4–6 h per week/regular physical activity/regular hard physical activity)	0/13/11/1	0/5/3/0	1/4/3/0
Exercise (no exercise/almost no exercise/regular at low intensity/regular at moderate intensity/regular at high intensity)	0/2/7/13/3	0/2/3/3/0	0/2/3/3/0

[a]One subject showed a low Hb, 89 g l^{-1}, which could be due to a small blood sample or to anaemia. This subject was not excluded because all the parameters tested were close to the mean values of the group. The subject did not participate in the repeated tests.

Exercise test and respiratory gas exchange

The exercise test was performed on an ergometer cycle (Rodby 380; Siemens-Elema, Solna, Sweden). The handlebars and seat were individually adjusted, their positions documented and applied on the re-test occasions. A pedalling rate of 60 rpm was maintained during the test. The test started with a power output of 30 W, which was increased by 5 W/30 s. A period of 4-min constant load was included in the ramp exercise test. The constant load was set at a heart rate (HR) of 125 ± 5 bpm or at a respiratory exchange ratio (RER) just below 1·0. The constant load was documented and applied on the re-test occasions. The ECG was continuously monitored, and the blood pressure (BP) and the rating of perceived exertion (RPE) (Borg, 1982) were determined every 2 min, according to clinical routine in Lund.

Continuous respiratory gas analysis and volume measurements were performed breath-by-breath during the exercise test using an Oxycon® gas analyser (Oxycon Champion; Jaeger, Höchberg, Germany). Ambient air was inspired via the facemask and expired air passed out through the flow/gas sensor. Time-based mean values of $\dot{V}O_2$, $\dot{V}CO_2$, volume of ventilation ($\dot{V}_E$) and HR were recorded every 10 s as raw data. Data collection included a 2-min resting phase prior to the test, to allow the participant to become accustomed to breathing through the mask and to register resting values. The test was terminated when the test subject in a general sense reached volitional exhaustion or reported a rating of 18–20 on the Borg scale. A 3-min postexercise phase was recorded in order to follow the recovery.

Volume calibration and calibration of the gas analysers using reference gases, as well as the transit time of gas from the mouthpiece through the tubes and the gas sensor, was carried out daily under the supervision of medical engineers at the department. Prior to each test, zero adjustment of the gas analysers was performed automatically (for details see Wisén & Wohlfart, 2004b).

Data analysis

Rating of perceived capacity (RPC) was performed using a scale, based on metabolic equivalents (METs) from 1 to 20. Selected activities, such as walking, running and cycling, are linked to some of the intensities. The subject was asked to choose the highest intensity of activity that could be maintained for half an hour, and the corresponding MET was registered. A MET between the different activities presented could also be chosen. A predicted maximal MET was calculated based on the rating and age correction using the following equation (Wisén *et al.*, 2002):

$$MET_{pred} = (5{\cdot}08 + 0{\cdot}70\, MET_{RPC})/[1 + (e^{0{\cdot}059(age-87{\cdot}2)})] \quad (1)$$

Raw data for $\dot{V}O_2$, $\dot{V}CO_2$ and HR from the exercise test and gas analysis were filtered using a low-pass filter available in Matlab® (The Math Works Inc., Natick, MA, USA) (Wisén & Wohlfart, 2004b), and resting, submaximal and maximal values were recorded. Ratings of perceived exertion were registered during submaximal and maximal exercise intensities.

The increasing contribution of the anaerobic metabolism was determined by measuring $\dot{V}O_2$ at three different time-points during the incremental exercise test. PX was defined as the last point at which the filtered value of $\dot{V}CO_2$ crossed the filtered value of $\dot{V}O_2$ during the exercise test. The point at which the slope of the $\dot{V}CO_2$ versus time curve started to increase at a higher rate than the $\dot{V}O_2$ versus time curve during the exercise test (DX) was determined using the derivative of a polynomial fit. The point at which the slope of the equivalent of CO_2, i.e. $\dot{V}_E/\dot{V}CO_2$, ($EQCO_2$), became >0 during the exercise test (PQ) was determined in an analogous way, using derivatives of polynomial fits (Wisén & Wohlfart, 2004b). DX, PX and PQ were determined by computer and the graphs were visually inspected. Occasionally, DX, PX and PQ were not in accordance with the criteria described above (the points had been incorrectly selected by the computer and occurred early in the exercise test). In those cases the points were adjusted by hand using an offset programme.

The values of $\tau\dot{V}O_2$ and $\Delta\dot{V}O_2/\Delta W$ were determined by applying equations to the results obtained from the exercise test described above (for details see Wisén & Wohlfart, 2004a).

$$\dot{V}O_2(n+1) = \Delta t/\tau[\dot{V}O_{2ss}(n) - \dot{V}O_2(n)] + \dot{V}O_2(n) \quad (2)$$

where Δt is the time interval between each recorded value, τ the time constant of $\dot{V}O_2$ and

$$\dot{V}O_{2ss} = bP + \dot{V}O_{2rest} \quad (3)$$

where b is the slope of the relation $\dot{V}O_2$ versus load (P), i.e. $\Delta\dot{V}O_2/\Delta W$.

Statistics

Data recorded breath-by-breath by the gas analyser (Oxycon Champion®) and time-based averages (10 s) were further analysed on a personal computer. Signal processing, analysis of data, and the generation of preliminary graphs were performed in Matlab®. The age relations were described by linear regression. The mean values, SDs and ranges of selected variables were calculated with Microsoft Excel®. The repeatability of the measurements obtained from each of the exercise sessions was compared by plotting the differences between the individual measurements against their mean value (Bland & Altman, 1986). The statistical significance of the differences between the repeated measurements were calculated using ANOVA, and the intraclass correlation coefficients ($ICC_{1\cdot1}$) were calculated as ICC = (BMS − WMS)/(BMS + WMS), where BMS is the variability between subjects and WMS is the variability in the measurements within subjects. A significance level of $P = 0{\cdot}05$ was chosen. Variation between tests is expressed as the SD or as the coefficient of repeatability (COR = 2 SD). Graphs were created in Sigmaplot® (SPSS Inc., Chicago, IL, USA).

Results

Aerobic and functional capacity – reference values

Twenty-five women (aged 22–44 years) rated their perceived capacity on the RPC scale and performed a maximal incremental cycle exercise test while continuous measurements of gas exchange were made.

It can be seen from the trend line in Fig. 1a that the rated perceived capacity had a tendency to decline with increasing age. Similarly, the maximal load and HR had a tendency to correlate negatively with age (Fig. 1b,c). However, the values of $\dot{V}O_{2max}$, $\dot{V}O_2$ at DX and $\dot{V}O_2$ at PQ did not change with age, while the value of $\dot{V}O_2$ at PX tended to increase slightly with age (Fig. 1d). An increase in the time constant, $\tau\dot{V}O_2$ ($P = 0{\cdot}05$) and $\Delta\dot{V}O_2/\Delta W$ with increasing age was also seen (Fig. 1e,f). The correlation coefficients and the regression equations are given in the figure.

The mean (SD) of the maximal load achieved was 185 (26) W and the mean value of HR_{max} was 180 (10) bpm. The achieved mean maximal values of aerobic capacity are given in Table 2. The reference values for $\tau\dot{V}O_2$ for each age group: 20–29, 30–39 and 40–44 years were 30, 33 and 43 s, respectively. Continuous reference values (based on age) can be calculated using the linear equations shown in Fig. 1e,f.

The mean of the rated perceived capacity, RPC, was 10 METs, which corresponds to a VO_2 value of 35 ml min^{-1} kg^{-1}. An age correction (see Method) was made to the rated value and the resulting predicted value of MET (MET_{pred}) was compared with MET values calculated from the maximal load achieved in the test (MET_{test}). It can be seen in Fig. 2 that the mean of the difference between MET_{pred} and MET_{test} (2 SD) was 0·9 (3·4) MET.

Repeatability of aerobic and functional capacity

The mean values of aerobic and functional capacity obtained from the day-to-day and the 4-week re-tests are given in Table 3. The mean values of the variables did not differ significantly between any of the tests.

The absolute differences in $\dot{V}O_2$ at DX, PX, PQ and $\dot{V}O_{2max}$ (test 2 − test 1, i.e. the day-to-day or day-to-day variation, and test 3 − test 1, i.e. 4-week variation) versus the mean of each of the pairs of tests are shown in Fig. 3a–d. The mean of the difference (dotted line) did not differ from zero in any of the measurements. The COR (2 SD, dashed lines) were between 5·0 and 7·3 ml min^{-1} kg^{-1} for the day-to-day tests for $\dot{V}O_2$ at DX, PX, PQ and VO_{2max}. The variations were greater for the 4-week re-tests, especially for $\dot{V}O_2$ at PX and VO_{2max} (14·1 and 10·6 ml min^{-1} kg^{-1}, respectively). However, the variations in the differences between the tests for the maximal load were the same for the day-to-day re-test and the 4-week re-test. The correlations between the tests expressed as the ICC are presented in Table 3.

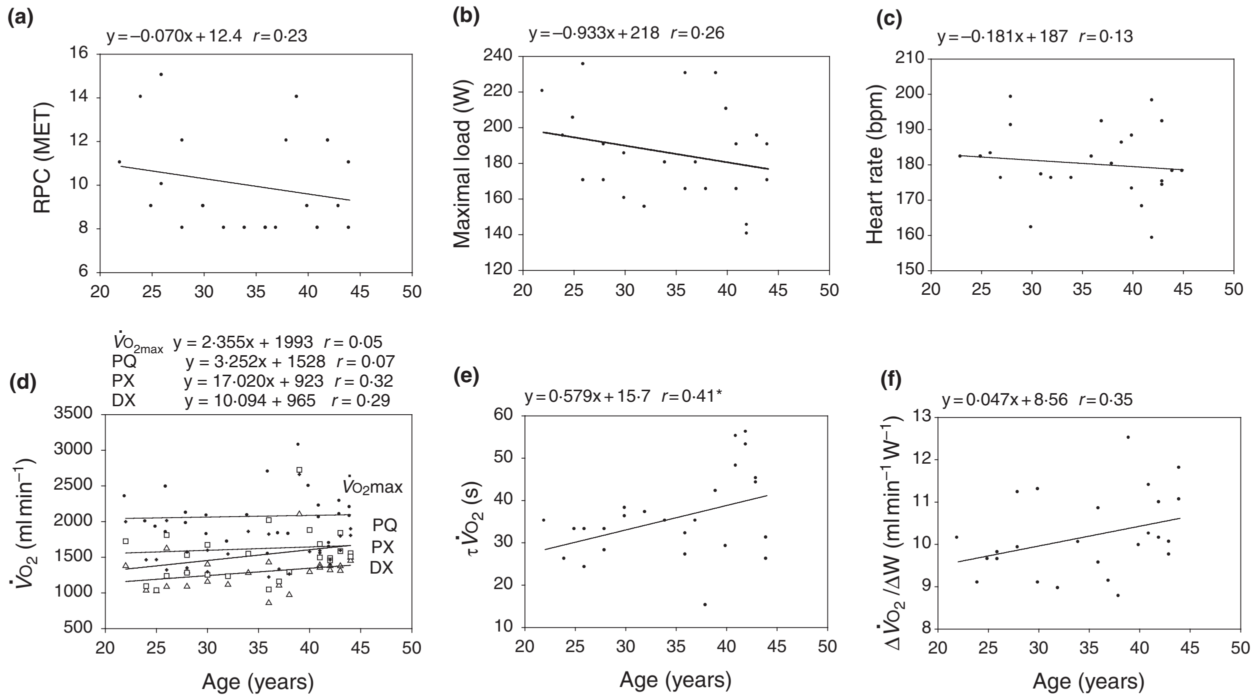

Figure 1 Results of aerobic and functional capacity for all 25 women as a function of age. Rating of perceived capacity (RPC) (a), maximal load, achieved in an incremental cycle test (b), and maximal HR versus age (c). It can be seen from the trend line that the variables in panels a, b and c show a tendency to decrease with age. $\dot{V}O_2$ versus age at maximum and at different anaerobic thresholds DX, PX and PQ (d). Note that the values of $\dot{V}O_{2max}$ and $\dot{V}O_2$ at DX and at PQ did not change in relation to age while $\dot{V}O_2$ at PX tends to increase with age. The time constant $\tau\dot{V}O_2$ increased significantly with age (e) and $\Delta\dot{V}O_2/\Delta W$ tends to increase with age (f). Equations for calculating age-related mean values are given together with the correlation coefficients.

Table 2 Aerobic capacity in women aged 22–44 years (n = 25).

	Mean (SD)
RPC (METs)	10·0 (2·2)
Vo_{2max} (ml min^{-1})	2075 (348)
Vo_{2max} (ml min^{-1} kg^{-1})	33·3 (6·5)
DX (Vo_2 ml min^{-1} at DX)	1263 (250)
DX in % of Vo_{2max}	63
PX (Vo_2 ml min^{-1} at PX)	1528 (367)
PX in % of Vo_{2max}	73
PQ (Vo_2 ml min^{-1} at PQ)	1620 (316)
PQ in % of Vo_{2max}	78
τVo_2 (s)	35·8 (10·1)
$\Delta Vo_2/\Delta W$ (ml min^{-1} W^{-1})	10·2 (1·0)

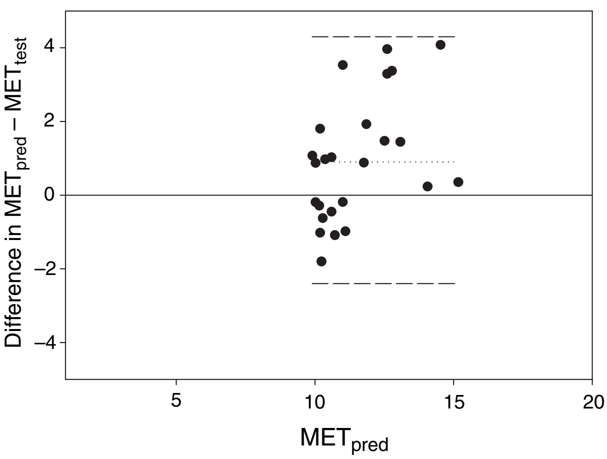

Figure 2 Predicted MET (MET$_{pred}$, based on the RPC scale and an equation) minus MET$_{test}$ (calculated from W_{max}) against MET$_{pred}$ for each individual (dots). The mean of the difference was 0·9 MET (dotted line). The variation shown by the dashed lines (2 SD) was 3·4 MET. The capacity predicted from the RPC scale was thus, in general, slightly higher than the maximal MET calculated from the load, during the test.

Similarly, the repeatability for $\tau\dot{V}o_2$ and $\Delta\dot{V}o_2/\Delta W$ is shown in Fig. 4 a,b. The mean of the differences between the repeated tests did not significantly differ from zero (dotted line). The COR in $\tau\dot{V}o_2$ was similar for the day-to-day re-test (20 s) and the long-term re-test (18 s). The variation of $\Delta\dot{V}o_2/\Delta W$ was lower in the day-to-day test (1·8 ml min^{-1} W^{-1}) than for the 4-week test (3·2 ml min^{-1} W^{-1}). The correlation between these tests (ICC) were not significant (Table 3).

The SDs of the differences between the tests are given in Table 3 as a supplement to Figs 3 and 4.

RER is plotted versus $\dot{V}o_2$ for each of the three tests in Fig. 5 for one subject. It can be seen that the first two tests were similar with the regard to the rise in RER and that $\dot{V}o_2$ at PX (vertical line) and $\dot{V}o_{2max}$ were also very similar. In the third test, the rise in RER was markedly faster, combined with an earlier occurrence of PX and a lower value of $\dot{V}o_{2max}$. The faster rise in RER was also combined with a lower value of $\Delta\dot{V}o_2/\Delta W$. This pattern of distinctly different curves at one of the tests was seen in five of the eight subjects tested. No co-variation was seen between the RER curves and the time constant.

The mean difference (2 SD) in the blood concentrations of Hb was −2·70 (6·8) and −0·25 (7·6) g l^{-1} for the day-to-day and 4-week tests, respectively. The subjects participating in the day-to-day test did not menstruate at that time. Five of the women performed the third test at the same time of their menstrual cycle, two of the women had contraceptives coils that led to amenorrhoea and one woman was postmenopausal.

Repeatability of resting, submaximal and maximal values

During the incremental exercise test the load was kept constant for 4 min. The mean values of these constant loads for the day-to-day re-test and the 4-week re-test are given in Table 4. The mean values of the maximal load did not differ significantly in either the short- or 4-week re-tests.

In Table 4, the mean values of $\dot{V}o_2$, HR at rest (sitting on the cycle) are given together with submaximal and maximal values of $\dot{V}o_2$, HR and RPE. These mean values did not differ significantly between either the day-to-day or the 4-week re-tests, except for the submaximal RPE and HR at the 4-week re-test.

In Fig. 6 the difference in $\dot{V}o_2$, HR and RPE (test 2 − test 1 and test 3 − test 1) is plotted versus the mean for each individual at rest, at submaximal and at maximal load. The mean of the differences (dotted lines) for $\dot{V}o_2$ and RPE did not differ significantly from zero, but the mean of the difference in HR was below zero in both the short- and 4-week re-tests.

In general, the COR was greater for the 4-week re-test (long-dashed lines) than for the day-to-day re-test (short-dashed lines). However, the COR at maximal load and maximal RPE, as well as submaximal HR, was the same in both the day-to-day and 4-week re-tests (note that the means of the difference are not the same and thus the lines of 2 SD are different for HR and slightly different for RPE despite equal absolute values of 2 SD).

The values of the COR are given in Table 4 as a supplement to Fig. 6.

Data analysis

The computerized determinations of the points DX, PX and PQ were visually inspected and adjusted in 17, 19 and 14 of the 43 recordings, respectively, in order to fulfil the criteria described in Method.

Discussion

The subjects were recruited from the municipal register via a letter of invitation. It is possible that the subjects who volunteered were slightly fitter than those who did not wish to participate. However, we made an effort to describe the activity level of the subjects included, which indicates that a major proportion of the participants had a low or moderate level

Table 3 Day-to-day and 4-week repeatability of aerobic capacity measurements.

	Repeatability, day-to-day (n = 10)	Repeatability, 4-week (n = 8)
RPC (METs)		
Mean (SD)	–	8·9 (1·5)
Test 1/test 2	–	9·3/8·6
SD of the difference between the tests	–	1·3
ICC	–	0·82*
$\dot{V}O_{2max}$ (ml min^{-1})		
Mean (SD)	2060 (313)	2049 (291)
Test 1/test 2	2038/2083	2070/2028
SD of the difference between the tests	229	358
ICC	0·78*	0·51
$\dot{V}O_{2max}$ (ml min^{-1} kg^{-1})		
Mean (SD)	31·2 (4·3)	30·5 (4·4)
Test 1/test 2	30·9/31·5	31·6/30·4
SD of the difference between the tests	3·4	5·3
ICC	0·72*	0·55*
DX ($\dot{V}O_2$ ml min^{-1} at DX)		
Mean (SD)	1237 (199)	1219 (172)
Test 1/test 2	1211/1263	1249/1189
SD of the difference between the tests	167	187
ICC	0·72*	0·55*
PX ($\dot{V}O_2$ ml min^{-1} at PX)		
Mean (SD)	1465 (300)	1468 (250)
Test 1/test 2	1418/1513	1481/1455
SD of the difference between the tests	227	444
ICC	0·73*	0·18
PQ ($\dot{V}O_2$ ml min^{-1} at PQ)		
Mean (SD)	1562 (254)	1554 (266)
Test 1/test 2	1549/1574	1588/1520
SD of the difference between the tests	221	272
ICC	0·64*	0·61*
$\tau\dot{V}O_2$ (s)		
Mean (SD)	30 (4)	30 (4)
Test 1/test 2	29/30	29/31
SD of the difference between the tests	10	8
ICC	0·17	0·02
$\Delta\dot{V}O_2/\Delta W$ (ml min^{-1} W^{-1})		
Mean (SD)	10·3 (0·8)	10·1 (0·6)
Test 1/test 2	10·1/10·4	10·3/9·9
SD of the difference between the tests	0·9	1·6
ICC	0·48	0·24

Mean values of test 1 and test 2 and mean (SD) for the two tests are given. The SD of the individual differences between the tests is presented. No significant differences between measures were shown using ANOVA. Intraclass correlation coefficients (ICC) are given, *significant correlation.

of activity, none was completely sedentary and only a few had a regular high activity level.

Aerobic and functional capacity – reference values

The aerobic capacity is frequently reported to decline linearly with age (Åstrand, 1960; Hansen *et al.*, 1984; Jones *et al.*, 1985; Åstrand & Rodahl, 1986; Possner *et al.*, 1987). The results of this study did not confirm this linear decrease, although a non-significant tendency towards a linear decrease could be seen for RPC, maximal load and HR. It is desirable to continue the collection of reference values and include subjects with older ages especially if the purpose is to make comparisons with values from cardiopulmonary patients (who in general are older than our subjects). A slow decline in load and HR at younger ages and a faster decline at older ages has been reported by Farazdaghi & Wohlfart (2001) who fitted an exponential function to the data based on age. Thus, if older ages had been included the same decline would probably have been seen. Due to the non-significant decline of the parameters versus age we did not divide our subjects into age groups, but presented the reference values for the age range 22–44 years as a single unit. Reference intervals have earlier been reported as the mean ± 20% (Nordesjö & Landelius, 1975; Cooper & Storer, 2001). An interval from 80 to 120% of the mean gave values very close to ±1 SD for the variables in Table 2. This means that a number of test values in this study were outside the reference interval, indicating values lower or higher than average

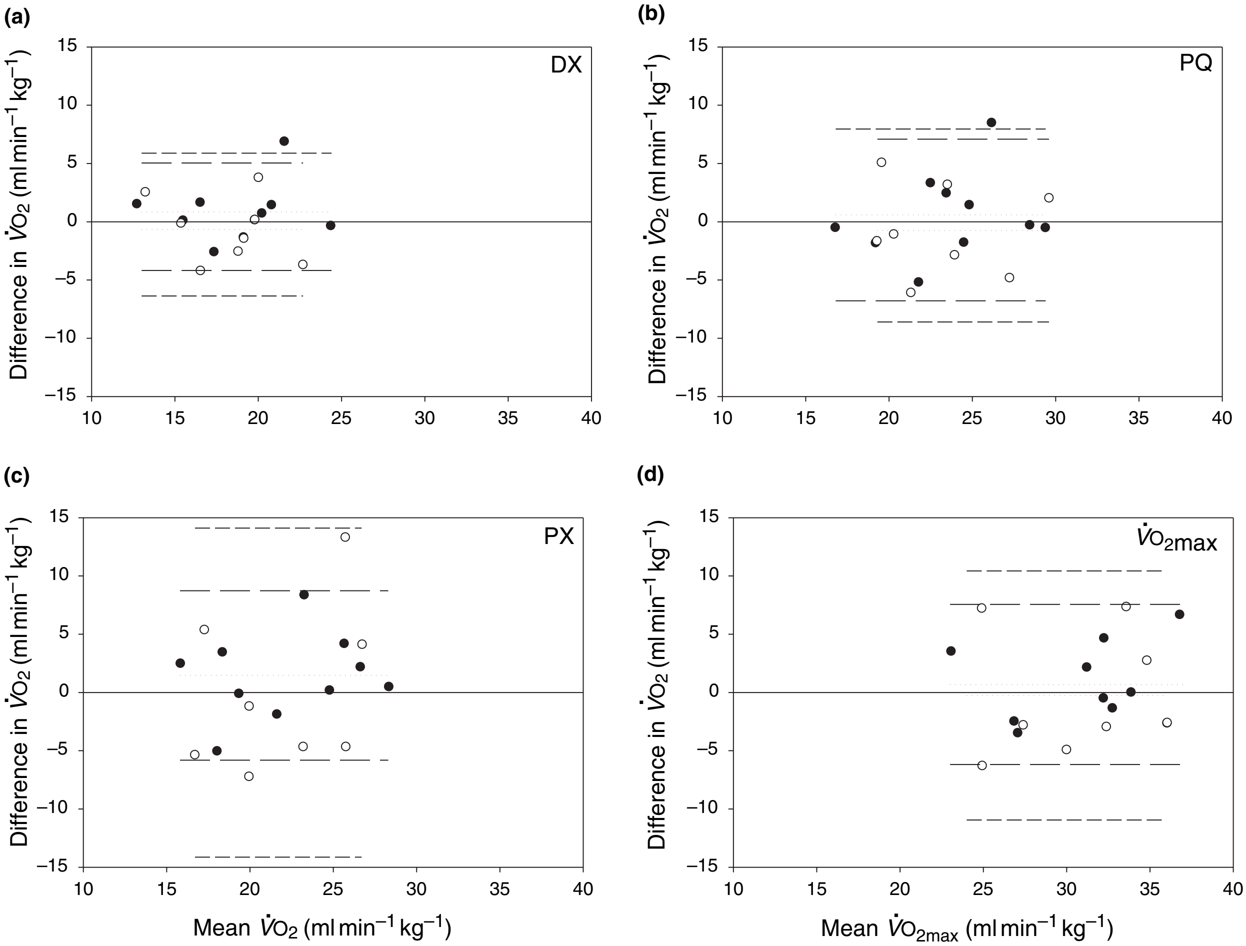

Figure 3 Day-to-day and 4-week repeatability of aerobic function and capacity. Test 2 − test 1 (n = 10, dots) and test 3 − test 1 (n = 8, open circles) versus the mean of each variable, for each of the subjects. The mean of the difference is shown (dotted line) and 2 SDs are shown by pairs of horizontal lines (long-dashed for day-to-day re-test, short dash for 4-week re-test). Panel (a) shows the repeatability of $\dot{V}O_2$ at DX and panels b, c and d the corresponding values for PX, PQ and $\dot{V}O_{2max}$. In all panels 2 SD was greater for the 4-week re-test than for the day-to-day re-test.

(normal). Another possibility is to express a reference interval as ±2 SD, which consequently will include 95% of the subjects. The choice of how to use a reference value or interval will depend on the reason for testing, is it for diagnostic purpose, evaluating level of fitness or an exercise period?

A significant increase in $\tau\dot{V}O_2$ with age was seen, and therefore age-based reference values are given, as well as an equation to calculate continuous reference values. An equation is also provided for $\Delta\dot{V}O_2/\Delta W$ as a function of age as the correlation with age was very close to significant. Increasing values of $\Delta\dot{V}O_2/\Delta W$ could possibly be explained by an increase in fat metabolism, which increases oxygen consumption, compared with carbohydrate metabolism. The tendency towards increasing values of $\dot{V}O_2$ at PX with age (Fig. 1, panel d) support this hypothesis. The age-based equations are also given for the other parameters but as these did not show the same age- dependent changes the mean values can be utilized as reference values.

Several comparisons were made with reference values from other studies. The values for $\dot{V}O_{2max}$ in this study was 98% when expressed in l min^{-1} and 92% when expressed in ml min^{-1} kg^{-1} of the reference values (in decades) given by Åstrand (1960).

The maximal load and maximal HR observed in this study were 91 and 99%, respectively, of the reference values given by Farazdaghi & Wohlfart (2001). The trend line for HR_{max}, 220 − age (Åstrand & Rodahl, 1986) was markedly above the trend line of HRmax in this study for the age range 22–40 years, the lines crossed at 40 years, and the trend line 220 − age was then lower. Another trend line, 208 − 0·7 (age) (Tanaka *et al.*, 2001) was markedly lower than the trend line in our study. The lower HRmax trend line was probably caused by limited exertion while the exertion at the highest load in our study was 18–19 on the RPE scale.

The three different points characterizing the increasing contribution of anaerobic metabolism (DX, PX and PQ) were expressed in units of $\dot{V}O_2$. In absolute values, the values of $\dot{V}O_2$ at DX, PX and PQ were lower for women than those found earlier for men (Wisén & Wohlfart, 2004b), although, expressed as a percentage of $\dot{V}O_{2max}$ the women had higher values than the men, 63, 73 and 78% at DX, PX and PQ, respectively, compared

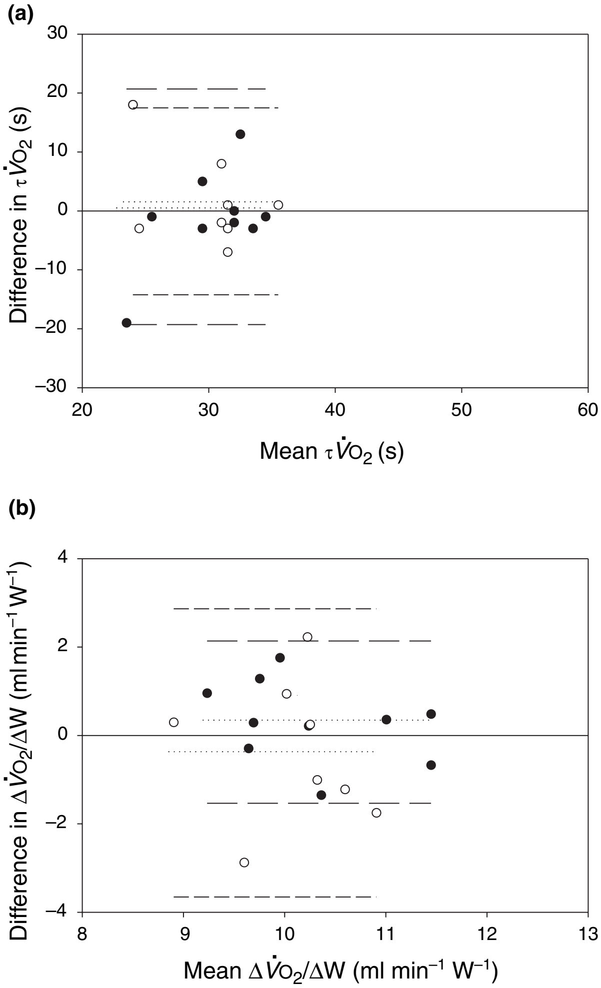

Figure 4 Day-to-day and 4-week repeatability of $\tau\dot{V}O_2$ (a) and $\Delta\dot{V}O_2/\Delta W$ (b). The difference in the short-term (dots) and long-term (open circles) re-tests versus the mean of each variable is shown. 2 SD was greater for the 4-week re-test (short-dashed lines) than for the day-to-day re-test (long-dashed lines) for $\Delta\dot{V}O_2/\Delta W$, but for $\tau\dot{V}O_2$ the case was the opposite.

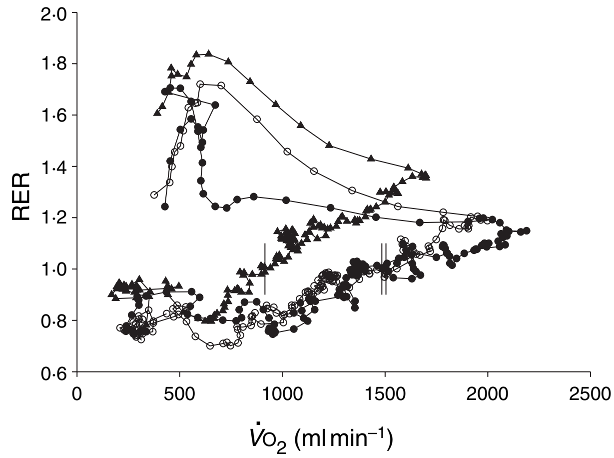

Figure 5 RER versus $\dot{V}O_2$ (n = 1) during the incremental exercise test, on the first occasion (dot), the re-test next day (open circles) and at the re-test 4 weeks later (triangles). During the tests $\dot{V}O_2$ increased up to a maximum and concurrently after a slight decrease, RER increased and passed PX (vertical lines). After maximal $\dot{V}O_2$, the RER continued to increase. As can be seen, the first two tests gave similar results while at the third test the loop of RER increased at a faster rate and $\dot{V}O_{2max}$ was lower.

with the values 54, 68 and 70% for the men. For comparison, Bunc & Heller (1993) reported a ventilatory threshold (VT = $\dot{V}_E$ versus $\dot{V}O_2$ linear model) for young and adult female athletes of between 74 and 85%.

Wasserman *et al.* (1994) have described an increase in anaerobic threshold (AT = $\dot{V}CO_2$ versus $\dot{V}O_2$ linear model) expressed as a percentage of $\dot{V}O_{2max}$ with increasing age (52, 55 and 58% at 20, 30 and 40 years of age, respectively) due to a greater decrease in $\dot{V}O_{2max}$ than in $\dot{V}O_2$ at AT (Wasserman *et al.*, 1994). As mentioned above, we did not see any decline in $\dot{V}O_{2max}$ with age in this study.

The mean value of $\Delta\dot{V}O_2/\Delta W$ was similar for these women and the men in our previous study (10·2 and 10·8 ml min W^{-1}, respectively) (Wisén & Wohlfart, 2004a). Similar mean values of $\Delta\dot{V}O_2/\Delta W$ as in this study were also reported for sedentary women (Neder *et al.* 2001). Higher values are seen in athletes and lower values in, for instance, cardiopulmonary disease (Hagberg *et al.*, 1980; Chilibeck *et al.*, 1996; Cooper & Storer, 2001). Likewise, the mean value of $\tau\dot{V}O_2$ was similar for these women and the men in our previous study (36 and 38 s, respectively) (Wisén & Wohlfart, 2004a). The time required to reach steady state can be estimated to be around 2·5 min ($4\tau\dot{V}O_2$).

Values estimated from the RPC scale or calculated from the maximal load, as well as the predicted capacity for 10-year age groups, have been reported earlier (Wisén *et al.*, 2002). RPC in terms of METs allows calculation of the expected capacity expressed as $\dot{V}O_2$ by multiplying by 3·5 (and the subject's body weight if ml min^{-1} is the desired unit). In this study, the rating gave a slightly higher (ns) mean value of $\dot{V}O_{2max}$ than the mean value obtained in the cycle test (35 and 33 ml kg min^{-1}). In addition, when the rated capacity was corrected for age (according to Wisén *et al.*, 2002), the predicted RPC in METs (MET_{pred}) was higher than the value obtained (in METs) from the cycle test (calculated from W). The difference between MET_{pred} and MET_{test} was 3·4 METs which corresponds to a variation (2 SD) in VO_2 of about 12 ml kg min^{-1}. This is around 35% of the mean VO_{2max} of the subjects which might seem high. However, the day-to-day variability of VO_{2max} is 21% and the 4-week repeatability 32%. From that perspective the RPC thus gives a rough estimate of the present or previous capacity, which nevertheless can be useful in both choosing an appropriate exercise protocol and in interpreting an exercise test result.

Repeatability of aerobic and functional capacity

In order to evaluate the effects of exercise or rehabilitation, it is of the utmost importance to have knowledge concerning the

Table 4 Day-to-day ($n = 10$) and 4-week repeatability ($n = 8$) of resting values measured with the subject sitting on the cycle, submaximal and maximal values.

	Load (W)	$\dot{V}O_2$ (ml min^{-1})	HR (bpm)	RPE
Day-to-day				
Rest 1	–	287 (40)	89 (12)	–
Rest 2	–	298 (31)	80 (9)	–
ICC	–	0·33	0·39	–
Submax 1	81 (12)	1131 (213)	132 (8)	12 (2)
Submax 2	81 (12)	1189 (173)	128 (6)	12 (2)
ICC	–	0·82*	0·31	0·60*
Max 1	186 (23)	2038 (323)	184 (7)	18 (1)
Max 2	184 (26)	2083 (343)	183 (5)	18 (1)
ICC	0·93*	0·78*	0·72*	0·72*
COR, rest	–	(82)	(18)	–
COR, submax	–	(212)	(16)	(3)
COR, max	(18)	(458)	(8)	(2)
4-week				
Rest 1	–	292 (43)	88 (13)	–
Rest 3	–	264 (52)	79 (10)	–
ICC	–	0·22	0·35	–
Submax 1	83 (13)	1169 (223)	134 (6)	13 (2)
Submax 3	83 (13)	1122 (165)	124 (9)	12 (2)
ICC	–	0·57*	0·11	0·74*
Max 1	186 (25)	2070 (356)	185 (7)	19 (1)
Max 3	187 (30)	2028 (327)	179 (7)	19 (0)
ICC	0·96*	0·50	0·11	0·24
COR, rest	–	(116)	(24)	–
COR, submax	–	(368)	(16)	(2)
COR, max	(18)	(716)	(18)	(2)

Mean values (SD) from each of the two tests and coefficient of repeatability (COR, 2 SD of the differences between the tests) are given. A significant difference between measures (ANOVA) were observed at 4-week repeatability of submaximal HR and RPE, while no significant differences were observed between measures among the other parameters. Intraclass correlation coefficients (ICC) are given, *significant correlation.

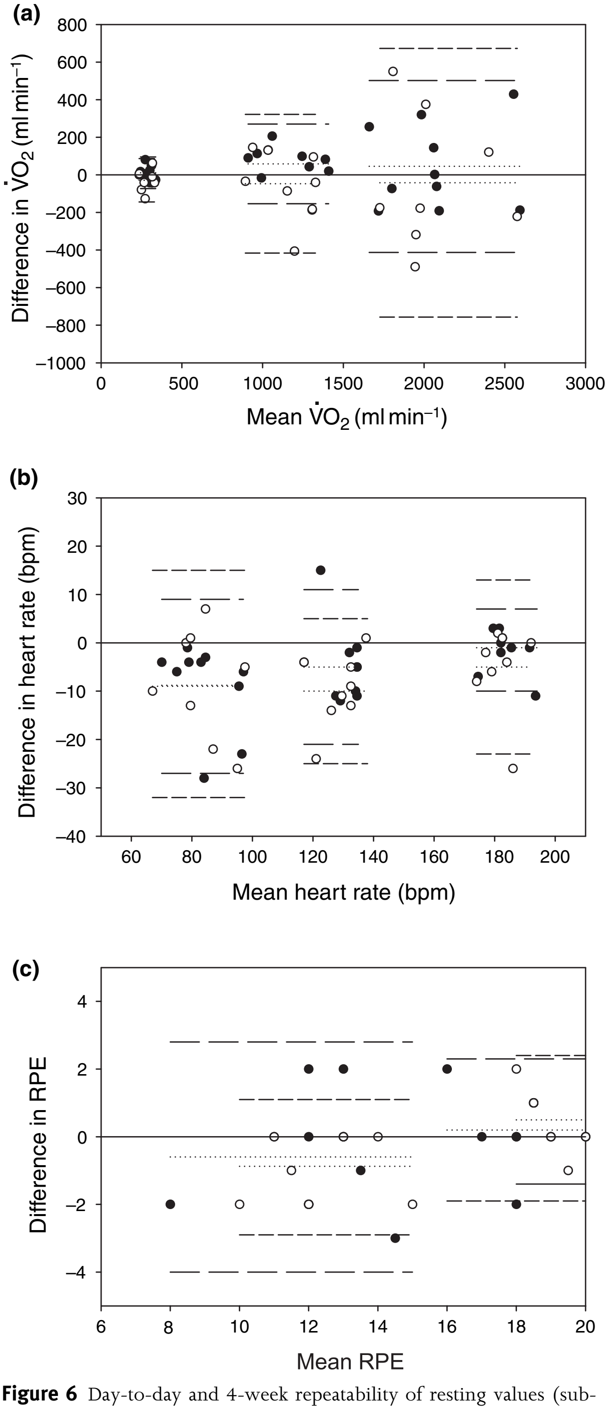

Figure 6 Day-to-day and 4-week repeatability of resting values (subjects sitting on the cycle), submaximal and maximal values. The difference (test 2 – test 1, dots) and (test 3 – test 1, open circles) is plotted against the mean of the measurements for: (a) $\dot{V}O_2$, (b) HR and (c) RPE. The mean of the difference (dotted lines) and 2 SD (pairs of long-dashed lines for day-to-day re-test and short-dashed lines for 4-week re-test) are shown. In general, the variation was greater at the 4-week re-test than at the day-to-day re-test, except for RPE at submaximal level.

normal test–re-test variation, especially in the 4-week period. The tests were performed under standardized conditions with extra caution paid to avoid changes in activity pattern and rigorous controls of health during the intervening period, as described in Method, but nevertheless variations were observed. The variations were greater after 4 weeks than in the day-to-day re-test, except for time constant, $\tau\dot{V}O_2$. Due to the small range of $\tau\dot{V}O_2$ and $\Delta\dot{V}O_2/\Delta W$ the ICC between the two tests were not significant. In a case like this, ICC may be a less informative measure. As pointed out by Bland & Altman (1986) an absolute repeatability is in general clinically more useful.

A limitation in this study is the small number of healthy subjects participating in the repeated tests. It is likely that the individual variations are much larger in clinical populations. Thus, the individual variations shown indicate the need for further enlarged studies in order to demonstrate the findings with greater impact.

The variation in the blood content of Hb (2 SD) between the day-to-day tests and the 4-week tests corresponds to a difference in oxygen in the blood of about 10 ml l^{-1}. This indicates that the oxygen content available at maximal work could vary by about 200 ml. [Each gram of Hb binds 1·33 ml oxygen: a maximal HR of 180 bpm and an arbitrary maximal stroke volume of 120 ml gives 6·8 g l^{-1} 1·33 ml · (180 bpm · 120 ml) = 195 ml.] This means that a part of the variations of $\dot{V}O_2$ observed at test–re-test might originate from a varying content of Hb.

No relation was observed between the stage of menstrual cycle and Hb; subjects with amenorrhoea and the subject who was postmenopausal showed equally high variations. The time interval of 4 weeks between the tests was chosen so that the women would be at the same stage in their menstrual cycle. However, it seems possible that alterations of Hb might affect the repeatability if the tests are performed at different stages of the menstrual cycle.

The variation in the 4-week re-tests for women was more than twice that for men studied previously (Wisén & Wohlfart, 2004a,b) regarding $\dot{V}O_{2max}$ expressed as ml min^{-1} and ml min^{-1} kg^{-1}, $\dot{V}O_2$ at PX and $\Delta\dot{V}O_2/\Delta W$. However, the variations were less in the group of women regarding $\dot{V}O_2$ at DX, PQ and $\tau\dot{V}O_2$.

When comparing the women's variations in the day-to-day tests with the 4-week re-test the variation in $\dot{V}O_{2max}$, $\dot{V}O_2$ at PX and $\Delta\dot{V}O_2/\Delta W$ for the 4-week re-test was 1·5–2 times greater than for the day-to-day re-test.

In Figs 3 and 4 outliers can be seen. These subjects also showed a greater variation in raw-data distribution during the test. In order to describe the differences the three tests were analysed by plotting the RER versus $\dot{V}O_2$ for each subject (Fig. 5). As can be seen the increase in CO_2 production during test 3 was accompanied by a lower value of $\dot{V}O_2$ at PX and a lower value of $\dot{V}O_{2max}$ compared with tests 1 and 2. (Interestingly, there were positive correlations between $\Delta\dot{V}O_2/\Delta W$ and $\dot{V}O_2$ at both PX and maximum.) Greater CO_2 production may be due to a higher metabolism of carbohydrates or may indicate lactate production. The reverse situation, i.e. lower CO_2 production and lower RER has been reported during the luteal phase of the menstrual cycle (Redman *et al.*, 2003). Similar plots for the group of men (Wisén & Wohlfart, 2004b) did not show such extreme variations in the RER curves as in the group of women.

Only a few earlier tests of repeatability concerning women were found in the literature. The $\dot{V}O_{2max}$ and HR were found to be reproducible based on means and correlation, although the repeatability of the ventilatory threshold (VT, $\dot{V}_E$ versus $\dot{V}O_2$ which correspond to DX in our study) was found to be less applicable for women in the eighth and ninth decades of life. The latter for the reason that the ventilatory threshold could not be detected and one of the proposed reasons may be the very low $\dot{V}O_{2max}$ obtained (about 13 ml min^{-1} kg^{-1}) (Foster *et al.*, 1986). This difficulty to detect the threshold might be of relevance for all with low $\dot{V}O_{2max}$ at all ages and especially in diseases, but were not observed in our study.

In conclusion, considerable variations were observed in the aerobic function and capacity of women, especially at a 4-week re-test which must be considered when repeated tests are made to evaluate exercise or rehabilitation in women.

Repeatability of resting, submaximal and maximal values

The resting value of $\dot{V}O_2$ showed less variation in the group of women than in a group of men previously studied (Wergel-Kolmert *et al.*, 2002). The variations in both submaximal and maximal $\dot{V}O_2$ values were twice as high for the women than for the men at 4-week re-test. The variations in the maximal load were almost the same for the men and the women. The HR varied as much at rest (sitting on the cycle) as at submaximal load in both women and men, whereas the variation in maximal HR for women was twice that for men. Obviously, no gender difference was seen for maximal RPE.

The submaximal variation in $\dot{V}O_2$ was similar to earlier reported day-to-day variations in women (Wergel-Kolmert *et al.*, 2001), while the re-test variation in submaximal HR and $\dot{V}O_{2max}$ were markedly higher in this study. The variation in submaximal and maximal HR must be considered when submaximal HR-based exercise tests are performed to predict $\dot{V}O_{2max}$. Submaximal values of HR and RPE are often used when monitoring exercise intensity and the variation reported here indicates that a range of values for HR or RPE may be more suitable than a fixed value.

Conclusions

Reference values of aerobic function and capacity for women aged 22–44 years are reported. $\dot{V}O_{2max}$, maximal HR and load were compatible with earlier reported values. Values of $\dot{V}O_2$ at DX, PX and PQ were found to be lower for women than for men in absolute values, but higher when expressed as a percentage of $\dot{V}O_{2max}$. The time constant of $\dot{V}O_2$ and $\Delta\dot{V}O_2/\Delta W$ were similar to the values reported for men.

Day-to-day and 4-week repeatability of aerobic function and capacity measurements showed a greater variation at the 4-week re-tests. This can partly be explained by variations in Hb and variations in $\dot{V}CO_2$. The 4-week repeatability in the group of women was more than twice that for men regarding $\dot{V}O_{2max}$, PX and $\Delta\dot{V}O_2/\Delta W$, but lower for DX, PQ and $\tau\dot{V}O_2$.

The variation of resting, submaximal and maximal values of $\dot{V}O_2$ and HR were greater at the 4-week re-test. The variations in RPE_{max} were the same at both short- and 4-week re-tests.

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References

Åstrand I. Aerobic work capacity in men and women with special reference to age. *Acta Physiol Scand* (1960); **49**(Suppl. 169): 45–59.

Åstrand PO, Rodahl K. *Textbook of Work Physiology Physiological Bases of Exercise* (1986), pp. 189–198, 332–337. McGraw-Hill Book Co., Singapore.

Babcock MA, Paterson DH, Cunningham DA. Effects of aerobic endurance training on gas exchange kinetics of older men. *Med Sci Sports Exerc* (1994); **26**: 447–452.

Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* (1986); **1**: 307–310.

Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exc* (1982); **14**: 377.

Bunc V, Heller J. Ventilatory threshold in young adult female athletes. *J Sports Med Phys Fitness* (1993); **33**: 233–238.

Chilibeck PD, Paterson DH, Petrella RJ, Cunningham DA. The influence of age and cardiorespiratory fitness on kinetics of oxygen uptake. *Can J Appl Physiol* (1996); **21**: 185–196.

Cooper CB, Storer TW (eds). Response variables. In: *Exercise Testing and Interpretation, a Practical Approach* (2001), pp. 96–148. Cambridge University Press, Cambridge.

Farazdaghi GR, Wohlfart B. Reference values for the physical work capacity on a bicycle ergometer for women between 20 and 80 years of age. *Clin Physiol* (2001); **21**: 682–687.

Foster VL, Hume GJ, Dickinson AL, Chatfield SJ, Byrnes WC. The reproducibility of VO2max, ventilatory, and lactate thresholds in elderly women. *Med Sci Sports Exerc* (1986); **18**: 425–430.

Gitt AK, Wasserman K, Kilkowski C, Kleeman T, Kilkowski A, Bangert M, Schneider S, Schwarz A, Senges J. Exercise anaerobic threshold and ventilatory efficiency identify heart failure patients for high risk of early death. *Circulation* (2002); **106**: 3079–3084.

Hagberg JM, Hickson RC, Ehsani AA, Holloszy JO. Faster adjustment to and recovery from submaximal exercise in the trained state. *J Appl Physiol* (1980); **48**: 218–224.

Hansen JE, Sue DY, Wasserman K. Predicted values for clinical exercise testing. *Am Rev Respir Dis* (1984); **129**: S49–S55.

Hansen JE, Sue DY, Oren A, Wasserman K. Relation of oxygen uptake to work rate in normal men and men with circulatory disorders. *Am J Cardiol* (1987); **59**: 669–674.

Itoh H, Koike A, Taniguchi K, Marumo F. Severity and pathophysiology of heart failure on the basis of anaerobic threshold (AT) and related parameters. *Jpn Circ J* (1989); **53**: 146–154.

Jones NL, Makrides L, Hitchcock C, Chypchar T, McCartney N. Normal standards for an incremental progressive cycle ergometer test. *Am Rev Respir Dis* (1985); **131**: 700–708.

Koike A, Hiroe M, Adachi H, Yajima T, Nogami A, Ito H, Takamoto T, Taniguchi K, Marumo F. Anaerobic metabolism as an indicator of aerobic function during exercise in cardiac patients. *J Am Coll Cardiol* (1992); **20**: 120–126.

Mettauer B, Zhao QM, Epailly E, Charloux A, Lampert E, Heitz-Naegelen B, Piquard F, di Prampero PE, Lonsdorfer J. VO(2) kinetics reveal a central limitation at the onset of subthreshold exercise in heart transplant recipients. *J Appl Physiol* (2000); **88**: 1228–1238.

Neder JA, Nery LE, Peres C, Whipp BJ. Reference values for dynamic responses to incremental cycle ergometry in males and females aged 20 to 80. *Am J Respir Crit Care Med* (2001); **164**(8 Pt 1): 1481–1486.

Nordesjö LO, Landelius J. Clinical evaluation of physical work capacity. *Scand J Clin Lab Invest* (1975); **35**(Suppl. 143): 64.

Phillips SM, Green HJ, MacDonald MJ, Hughson RL. Progressive effect of endurance training on VO2 kinetics at the onset of submaximal exercise. *J Appl Physiol* (1995); **79**: 1914–1920.

Possner JD, Gorman KM, Klein HS, Cline CJ. Ventilatory threshold: measurement and variation with age. *J Appl Physiol* (1987); **63**: 1519–1525.

Redman LM, Scroop GC, Norman RJ. Impact of menstrual cycle phase on the exercise status of young, sedentary women. *Eur J Appl Physiol* (2003); **90**: 505–513.

Saltin B, Grimby G. Physiological analysis of middle-aged and older former athletes. *Circulation* (1968); **38**: 1104–1115.

Sue DY, Wasserman K, Moricca RB, Casaburi R. Metabolic acidosis during exercise in patients with chronic obstructive pulmonary disease. Use of the V-slope method for anaerobic threshold determination. *Chest* (1988); **94**: 931–938.

Tanaka H, Monahan KD, Seals DR. Age-predicted maximal heart rate revisited. *J Am Coll Cardiol* (2001); **37**: 153–156.

Toyofuku M, Takaki H, Sugimachi M, Kawada T, Goto Y, Sunagawa K. Reduced oxygen uptake increase to work rate increment (Delta/DeltaWR) is predictable by response to constant work rate exercise in patients with chronic heart failure. *Eur J Appl Physiol* (2003); **90**: 76–82.

Wasserman K, Hansen JE, Sue DY, Whipp BJ, Casaburi R. Normal values. In: *Principles of Exercise Testing and Interpretation* (eds Harris, JM, Stead, L, DiRienzi, D, DeNardo, M) (1994), pp. 112–131. Williams & Wilkins, Philadelphia.

Wergel-Kolmert U, Wohlfart B. Day-to-day variation in oxygen consumption and energy expenditure during submaximal treadmill walking in female adolescents. *Clin Physiol* (1999); **19**: 161–168.

Wergel-Kolmert U, Agehall A, Rosenberg N, Wohlfart B. Day-to-day variation in oxygen consumption at submaximal loads during ergometer cycling by adolescents. *Clin Physiol* (2001); **21**: 135–140.

Wergel-Kolmert U, Wisén A, Wohlfart B. Repeatability of measurements of oxygen consumption, heart rate and Borg's scale in men during ergometer cycling. *Clin Physiol Funct Imaging* (2002); **22**: 261–265.

Whipp BJ, Ward SA. Physiological determinants of pulmonary gas exchange kinetics during exercise. *Med Sci Sports Exerc* (1990); **22**: 62–71.

Wisén AGM, Wohlfart B. Determination of both the time constant of $\dot{V}O_2$ and $D\dot{V}O_2/DW$ from a single incremental exercise test – validation and repeatability. *Clin Physiol Funct Imaging* (2004a); **24**: 1–9.

Wisén AGM, Wohlfart B. A refined technique for determining the respiratory gas exchange responses to anaerobic metabolism during progressive exercise – repeatability in a group of healthy men. *Clin Physiol Funct Imaging* (2004b); **24**: 1–9.

Wisén AGM, Farazdaghi RG, Wohlfart B. A novel rating scale to predict maximal exercise capacity. *Eur J Appl Physiol* (2002); **87**: 350–357.