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ORIGINAL ARTICLE

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Estimation of $\%\dot{V}O_2$ reserve from heart rate during arm exercise and running

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Abstract The purpose of the present investigation was to examine the relationship between the percent heart rate reserve (%HRR) in arm exercise and the corresponding percent oxygen uptake ($\dot{V}O_2$) reserve, and to compare this relationship to that occurring in running. Fourteen male physical education students took part in the study. Each subject performed a maximal running exercise test and a maximal arm cycling test. The subjects also performed three submaximal exercise bouts (in both exercise modes) at 30%, 60% and 80% of their HRR. The subjects were monitored for their heart rate (HR) at rest, maximal HR (HR_{max}), HR at submaximal work loads, maximal $\dot{V}O_2$ ($\dot{V}O_{2max}$), $\dot{V}O_2$ at rest and $\dot{V}O_2$ at submaximal loads. For each subject, load and exercise mode, %HRR and $\%\dot{V}O_2$ reserve were calculated (from HR_{max} and $\dot{V}O_{2max}$ as measured during running and arm cycling) and the relationship between the two was evaluated. The main finding of the present investigation is that the prediction of $\%\dot{V}O_2$ reserve in arm cycling from %HRR is grossly overestimated when calculated from HR_{max} and $\dot{V}O_{2max}$ measured during running. The prediction is better but still overestimated when calculated from HR_{max} and $\dot{V}O_{2max}$ measured during arm cycling. The findings indicate a better prediction of $\%\dot{V}O_2$ reserve from %HRR for running than for arm exercise. These findings should be taken into consideration when prescribing the target HR for arm training.

Key words Heart rate reserve · Percent $\dot{V}O_2$ reserve · RPE · Running · Target heart rate

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Introduction

In prescribing a training program for enhancing endurance and cardiopulmonary fitness, there are four aspects to consider: exercise modality, duration, frequency and intensity.

In determining exercise intensity various methods have been proposed and used. Heart rate (HR) monitoring as a criterion for exercise intensity is an important method, and one of the most accepted. With the technology that enables easy and accurate monitoring of HR, it is frequently used in many training and rehabilitation centres.

Exercise intensity is ideally prescribed to elicit a certain predetermined percentage of the subject's maximal aerobic capacity (percent $\dot{V}O_2$ reserve). Exercise intensity in the range of 55–90% of HR_{max} or 40–85% of $\dot{V}O_2$ reserve is recommended for improving cardiopulmonary fitness (American College of Sports Medicine 1998). A narrower and specific range is determined for each subject according to his individual characteristics, such as age, fitness level and medical limitations.

Using the percentage of HR_{max} ($\%HR_{max}$) to determine the target HR overestimates the exercise intensity in terms of percentage maximal oxygen consumption ($\%\dot{V}O_{2max}$). When young men are training at an intensity equal to 60–80% of their $\%HR_{max}$, they actually use a lower percentage of their $\dot{V}O_{2max}$ (Davis and Convertino 1975; Hellerstein 1973; Saltin et al. 1968). Thus, $\%HR_{max}$ is not a good predictor of the corresponding $\%\dot{V}O_{2max}$.

In 1957, Karvenon et al. (1957) introduced the concept of %HRR as a method for prescribing target HR for cardiorespiratory training. %HRR gives a closer but not exact estimation of $\%\dot{V}O_{2max}$ since, as was previously pointed out (Swain and Leutholtz 1997), comparing the range of HR from rest to the maximum with a range of $\dot{V}O_2$ from zero to the maximum introduces an error in estimating $\%\dot{V}O_{2max}$ from %HRR (Swain and Leutholtz 1997).

When accounting for the fact that $\dot{V}O_2$ at rest is not zero, it was clearly demonstrated that %HRR is very close to %$\dot{V}O_2$ reserve and thus is a direct measure of the exercise load in terms of percentage functional reserve metabolic aerobic capacity (Davis and Convertino 1975; Kilbom 1971). Swain et al. in two recent studies have shown this to be true for cycling (Swain and Leutholtz 1997) and running (Swain et al. 1998).

The above-mentioned relationships between %HR_{max}, %HRR and $\dot{V}O_2$ reserve were measured and established for exercise in which large muscle groups are involved, such as running or cycling.

Arm exercise is an important part of many cardiac fitness rehabilitation and endurance improvement programs. It is also well established that physiological and metabolic responses to arm exercise differ significantly from those of cycling or running (Barry 1985).

Thus the purpose of the present investigation was to examine the relationship between the %HRR in arm exercise and the corresponding $\dot{V}O_2$ reserve and to compare this relationship to that occurring in running.

Methods

Informed consent was obtained from 14 male physical education students who volunteered to participate in the study. The subjects reported to the laboratory four times. Sessions were spaced by intervals of 3–5 days. In two successive sessions the subjects performed treadmill running tests in which the first was a maximal test and the second a submaximal test. In the other two successive sessions the subjects performed arm cycle ergometer tests in which the first was a maximal test and the second a submaximal test. The order of the two sets of tests was balanced over subjects.

Running tests

Running tests were performed on a motor-driven treadmill (ClubTrac 3, Quinton Instrument, USA). The first running test was conducted in order to evaluate the subjects' maximal aerobic power and HR. A continuous incremental protocol was used. The initial speed was 11.2 km/h with an increase of 0.8 km/h during each subsequent 1-min stage. The grade was kept at zero until the fourth stage and then increased by 1% every stage until exhaustion occurred (muscular fatigue or severe dyspnea).

The submaximal running test consisted of three 5-min, predetermined workloads representing 30%, 60% and 80% of the subjects' HRR. These workloads were determined from the HR response at the various loads used during the maximal incremental running test. Between each 5-min workload, the subject rested until his HR had fallen to about 20 beat/min above his resting value. During the tests HR and $\dot{V}O_2$ were measured at each stage. HR at rest (HR_{rest}) and $\dot{V}O_2$ at rest ($\dot{V}O_{2rest}$) in a sitting position were determined before each test.

Arm tests

Arm tests were performed on a cycle ergometer (Fleish, Ergostate Universel, Metabo Medical and Scientific Instruments, Switzerland) in a sitting position. The ergometer was positioned so that its crank shaft was on a level with the shoulder of the subject and the arms were alternatively stretched horizontally while cranking. Pace in both arm tests was kept at 50 rev/min. In the maximal test, the starting load was 30 W and increased by 15 W every 1.5 min until exhaustion. The submaximal test consisted of three 5-min workloads representing 30%, 60% and 80% of the subjects HRR. These workloads were determined from the HR response at the various loads used during the maximal incremental arm tests. Subjects rested between workloads until the HR had fallen to 20 beat/min above resting value. During the tests HR and $\dot{V}O_2$ were measured at each stage. HR_{rest} and $\dot{V}O_{2rest}$ in a sitting position were determined before each test.

$\dot{V}O_2$, pulmonary ventilation (V_E), respiratory frequency (BF) and the respiratory exchange ratio (R) were monitored at each stage of the tests by an automated metabolic cart whose CO_2 and O_2 analysers were calibrated before each exercise session by known gas concentrations, and whose flow meter was calibrated at least once per day against a syringe with known volume (Oxycon–4, Mijnhardt Oxycon Systems, The Netherlands). HR was determined electrocardiographically. The rate of perceived exertion (RPE) was determined by using the Borg scale (Borg and Nobel 1974) which consists of 15 grades from 6 (very, very light) to 20 (very, very hard). The subjects were asked to estimate the degree of their exertion at the end of each maximal test.

Blood samples (25–30 μl) were taken from a fingertip 2–3 min upon termination of the maximal tests. The blood samples were analysed immediately to determine the lactic acid concentration using an automated lactate analyser (YSI) without a lysing agent.

The cardiorespiratory and RPE values in the submaximal tests were taken at the fifth minute of every workload. Subjects were instructed to avoid eating 3 h before each test and were given 30 min of complete rest before determining HR_{rest}. Subjects were given verbal encouragement throughout the tests.

Calculations and statistics

The physiological responses at peak arm exercise and running were compared by Student's *t*-test analysis.

For each subject the relationships between %HRR and %$\dot{V}O_2$ reserve were calculate for running and arm exercise. For arm exercise the %$\dot{V}O_2$ reserve and %HRR were calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured both in arm exercise and in running. %HRR was calculated as the percentage of $HR - HR_{rest}$ from $HR_{max} - HR_{rest}$.

$\dot{V}O_2$ reserve was calculated as the percent of $\dot{V}O_2 - \dot{V}O_{2rest}$ from $\dot{V}O_{2\,max} - \dot{V}O_{2rest}$ (Table 2).

For each individual subject three linear regression lines were calculated. One for %HRR versus %$\dot{V}O_2$ reserve in running, and two for the same relationship in arm exercise, once as calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured in running, and once as calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured in arm exercise.

Average lines were formed from individual regression lines by calculating the average intercept and the average slope from the corresponding values of the individual lines. These values were used to draw the lines presented in Fig. 3.

The individual slopes of the three regression lines (Arms1, Arms2 and Running) were compared by ANOVA with repeated measures. Student's *t*-test was used to compare the intercepts of the lines that did not differ in slope.

Results

The antropometric characteristic of the subjects are presented in Table 1.

Table 1 Physical characteristics of the subjects. Data are means (SD)

Parameter	Mean	SD
Age (years)	25.2	2.9
Height (cm)	178.7	5.6
Weight (kg)	75.2	7.8
Fat %	10.5	1.8

Physiological responses to maximal arm-cranking and running are presented Table 3.

In Fig. 1 individual data for the relationship between %HRR and the %$\dot{V}O_2$ reserve are presented for arm exercise and running. For running, the %HRR and %$\dot{V}O_2$ reserve values were calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured in running, while the %HRR and %$\dot{V}O_2$ reserve values for arm exercise were calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured in arm exercise (see Methods; Table 2).

In Fig. 2 individual data for the relationship between the %HRR and the %$\dot{V}O_2$ reserve are presented for arm exercise and running. The values were calculated both for running and arm exercise from HR_{max} and $\dot{V}O_{2\,max}$ as measured in running.

Figure 3 presents average lines calculated from the individual lines presented in Figs. 1 and 2. Average lines were formed from individual linear regression lines by calculating the average intercept and average slope from the corresponding values of the individual lines. These new values were used to draw the lines presented in Fig. 3.

The individual slopes and intercepts of the linear regression of the three calculated lines (Arms1, Arms2 and Running in Figs. 1 and 2) were compared by ANOVA with repeated measures. The slopes of the lines Running and Arms1 were not significantly different from each other (0.89 ± 0.22 and 0.94 ± 0.24 respectively), but were significantly different from the slope (0.65 ± 0.15) of the line Arms2 ($P = 0.001$ and $P < 0.001$ respectively).

The intercept of the lines Running (2.99 ± 13.39) and Arms1 (−7.26 ± 14.36) differed significantly ($P = 0.018$).

Table 2 Calculation of %HRR and %$\dot{V}O_2$ reserve. (*HR_{ex}* Heart rate at submaximal exercise, *HR_{rest}* heart rate at rest, *HR_{max}* heart rate at peak exercise, *%HRR* percent heart rate reserve, *VO_{2ex}* $\dot{V}O_2$ at submaximal exercise, $\dot{V}O_{2rest}$ $\dot{V}O_2$ at rest, $\dot{V}O_{2\,max}$ $\dot{V}O_2$ at peak exercise)

% HRR	$\frac{HR_{ex} - HR_{rest}}{HR_{max} - HR_{rest}} \times 100$
$\dot{V}O_2$ reserve	$\frac{\dot{V}O_{2ex} - \dot{V}O_{2rest}}{\dot{V}O_{2max} - \dot{V}O_{2rest}} \times 100$

Thus it can be clearly stated that the three lines (in Figs. 1, 2 and 3) are significantly different from each other.

The following regression equations describe the three lines in Fig. 3:

Arms1: $\%\dot{V}O_2\ \text{Reserve} = 0.94(\%\text{HRR}) - 7.26$

Arms2: $\%\dot{V}O_2\ \text{Reserve} = 0.65(\%\text{HRR}) - 4.15$

Running: $\%\dot{V}O_2\ \text{Reserve} = 0.89(\%\text{HRR}) + 2.99$

Discussion

The main finding of the present investigation is the difference in the prediction accuracy of %$\dot{V}O_2$ reserve from %HRR between running and arm exercise (Figs. 1, 2 and 3).

As can be seen, when %HRR and %$\dot{V}O_2$ reserve for arm exercise are calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured in running, the prediction of %$\dot{V}O_2$ reserve from %HRR is very clearly overestimated (Figs. 2, 3).

For example, during submaximal arm exercise at 60% HRR the subject uses a significantly lower percent of his $\dot{V}O_2$ reserve as measured in running. However, when %HRR and %$\dot{V}O_2$ reserve for arm exercise are calculated from HR_{max} and %$\dot{V}O_{2\,max}$ as measured during arm exercise, the prediction of the %$\dot{V}O_2$ reserve from %HRR is much better but yet not as good as the prediction for running (Figs. 1, 3).

Our findings for running are in line with previous investigations which demonstrated that while %HR_{max} overestimates the metabolic load in terms of %$\dot{V}O_2$ reserve, the %HRR gives a quite close prediction (2–4% overprediction of %$\dot{V}O_2$ reserve from %HRR) (Davis and Convertino 1975; Kilbom 1971; Swain and Leutholtz 1997; Swain et al. 1998).

The present finding may indicate that when a low muscle mass is used, the accuracy of the prediction of %$\dot{V}O_2$ reserve from %HRR is decreased. Thus, the prediction of %$\dot{V}O_2$ reserve from %HRR would be best for running, lower for cycling and still lower for arm exercise.

At maximal effort, physiological responses to running are greater than in arm exercise. At submaximal workloads, arm exercise is, however, less efficient (Vokac

Table 3 Comparison between maximal [mean (SD)] values found in running and arm exercise, maximal tests

Variable	Running		Arm exercise		% Difference Mean	*t* and *P* values
	Mean	SD	Mean	SD		
Oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$)	54.1	3.7	34.6	4.1	−36	$t = 13.6$; $P < 0.001$
Heart rate ($beats \cdot min^{-1}$)	194.4	4.6	177.8	8.6	−8.5	$t = 7.69$; $P < 0.001$
Lactic acid (mM)	11.6	1.4	9.0	1.6	−22.4	$t = 6.26$; $P < 0.001$
Ventilation ($l \cdot min^{-1}$)	145.1	17.6	105.0	18.1	−27.6	$t = 7.95$; $P < 0.001$
Rate of perceived exertion (Borg Scale: 6–20)	19.1	0.9	19.6	0.5	+2.6	$t = -2.19$; $P < 0.05$

et al. 1975). At a given power output, HR, systolic and diastolic blood pressure, the rate-pressure product, oxygen uptake and ventilation are all higher during arm exercise (Barry 1985).

$\dot{V}O_2$ at maximal effort in arm exercise in the present investigation was found to be some 36% lower than that found for running. This lower $\dot{V}O_{2\,max}$ was previously demonstrated and is explained by the smaller muscle mass involved during arm exercise (Vokac et al. 1975). However, at submaximal work loads, arm cycling results in a higher $\dot{V}O_2$ as compared to the $\dot{V}O_2$ measured when performing the same absolute work with the legs. This is true for a wide range of submaximal loads (Bevegard et al. 1966; Davis and Sargeant 1974; Stenberg et al. 1967; Vokac et al. 1975).

The excess oxygen uptake in arm exercise is due to the lower mechanical efficiency of this exercise mode, and is manifested at workloads higher than 250–300 kpm/min (Vokac et al. 1975). As work intensity rises, the mechanical efficiency decreases and is reflected by a nonlinear increase in $\dot{V}O_2$.

Arm training is an important part of rehabilitation and conditioning programs. It is generally accepted that there is a limited degree of transfer effect from leg training to arm exercise. Thus, individuals who use both upper and lower limbs in their occupational or leisure activities should be encouraged to train both arms and legs (Hellerstein and Franklin 1984).

It is clearly demonstrated that arm training can greatly increase cardiorespiratory fitness (Barry 1985). It has previously been shown that arm training can induce significant cardiovascular and physiological adaptations, such as a significant decrease in HR and a proportionate increase in stroke volume at similar $\dot{V}O_2$ during submaximal arm exercise (Mogek et al. 1978). This mode of exercise is especially beneficial for subjects with spinal cord injuries who are confined to a wheelchair. Many studies have demonstrated the cardiopulmonary improvements following upper limb exercise modes in this population (Barry 1985). The beneficial effects of arm training for normal subjects (Mogek et al. 1978; Mostardi et al. 1981) and cardiac patients (Ben Ari and Kellermann 1983; Thompson et al. 1981; Wrisley et al. 1983) have also been demonstrated.

It is however important to note that in the present study the subjects were all healthy young men. Thus further studies are needed to examine the relationship between %HRR and $\%\dot{V}O_2$ reserve in arm exercise in patients with spinal chord injury who cannot perform leg exercise.

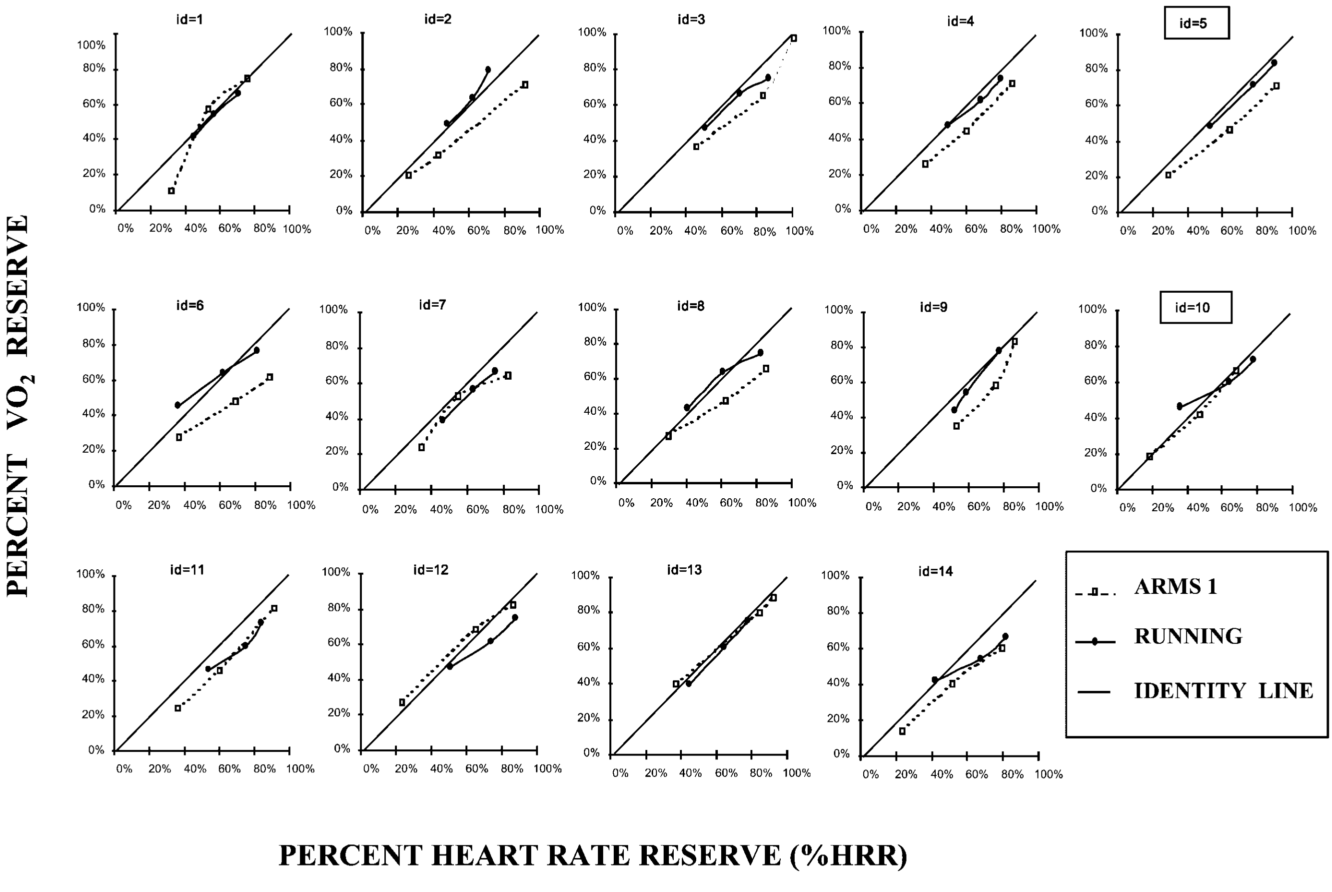

Fig. 1 The relationship between percent heart rate reserve (*%HRR*) and percent oxygen uptake ($\%\dot{V}O_2$) reserve for running and arm cycling . Values for running were calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured during running. Values for arms (*Arms1*) were calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured during arm cycling. Individual data

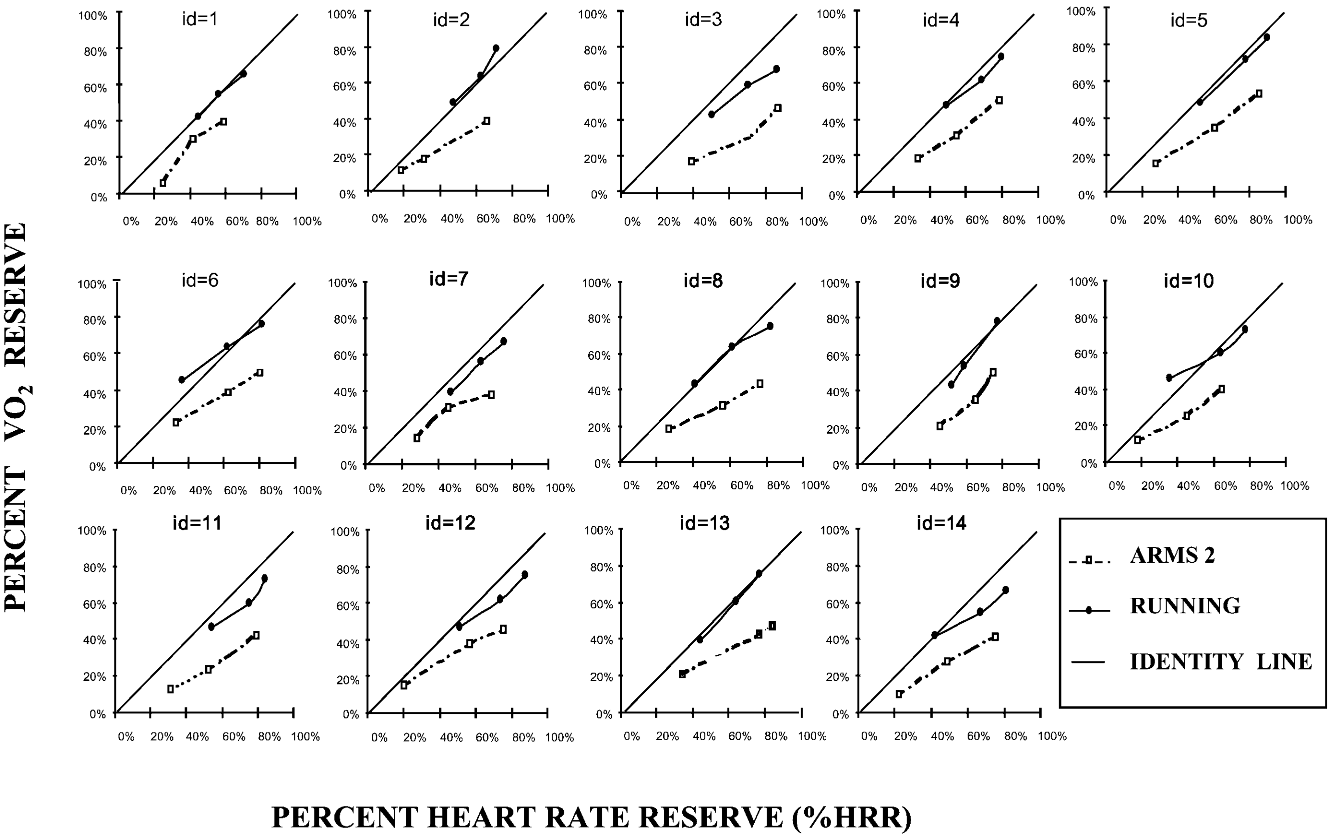

Fig. 2 The relationship between %HRR and %$\dot{V}O_2$ reserve for running and arm cycling. Values for running and arms (*Arms2*) were both calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured during running. Individual data

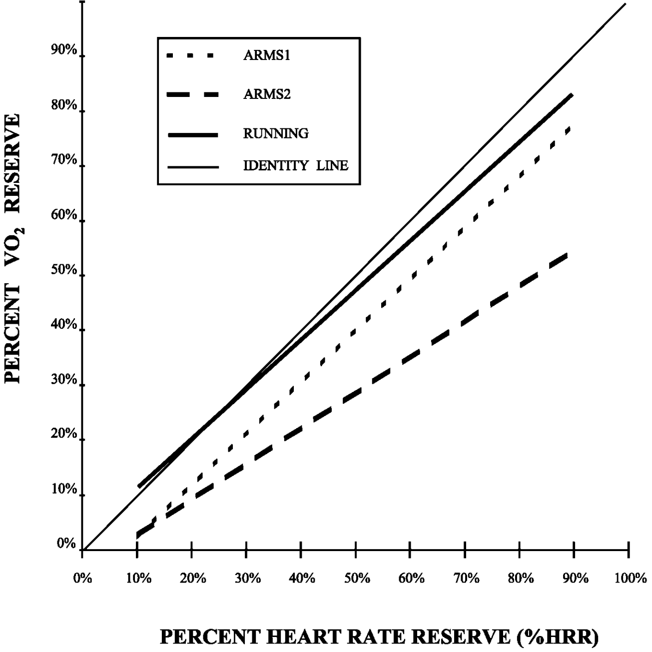

Fig. 3 The relationship between %HRR and %$\dot{V}O_2$ reserve for running and arm cycling. Average values calculated from individual lines. (*Arms1* Values calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured during arm cycling, *Arms2* values calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured during running, *Running* values were calculated from HR_{max} and $\dot{V}O_{2\,max}$ as measured during running)

In conclusion, the present findings indicate a lower accuracy for the prediction of metabolic load (%$\dot{V}O_2$ reserve) from %HRR for arm exercise than for running. The prediction of the metabolic load in arm cycling from %HRR is grossly overestimated when calculated from HR_{max} and $\dot{V}O_{2\,max}$ measured during running. In prescribing a target HR for arm training the unique physiological responses to arm training should be taken into consideration.

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