Acta Physiol Scand 1990, 138, 133–143

Differences in cardiorespiratory responses during and after arm crank and cycle exercise

V. LOUHEVAARA, A. SOVIJÄRVI*, J. ILMARINEN and P. TERÄSLINNA†
Department of Physiology, Institute of Occupational Health, Finland, *Laboratory of Clinical Physiology, Helsinki Central University Hospital, Finland, and †Department of Physical Education and Recreation, University of Kentucky, USA

LOUHEVAARA, V., SOVIJÄRVI, A., ILMARINEN, J. & TERÄSLINNA, P. 1990. Differences in cardiorespiratory responses during and after arm crank and cycle exercise. *Acta Physiol Scand* 138, 133–143. Received 1 September 1988, accepted 22 September 1989. ISSN 0001–6772. Department of Physiology, Institute of Occupational Health, Finland, Laboratory of Clinical Physiology, Helsinki Central University Hospital, Finland, and Department of Physical Education and Recreation, University of Kentucky, USA.

The differences in cardiorespiratory responses were examined during and after intermittent progressive maximal arm-crank and cycle exercise. Arm-crank exercise was performed in a standing position using no torso restraints to maximize the amount of active skeletal muscle mass. Recovery was followed for 16 min. In the tests a variety of ventilatory gas exchange variables, heart rate, the blood pressure, and the arm venous blood lactate concentration were measured in 21 untrained healthy men aged 24–45 years. At equal submaximal external workloads for arm cranking and cycling (50 and 100 W) the respiratory frequency, tidal volume, pulmonary ventilation, oxygen uptake, carbon dioxide output, the respiratory exchange ratio, heart rate, the arm venous blood lactate concentration, and the ventilatory equivalent for oxygen were higher ($P < 0.001$) during arm cranking than cycling. The maximal workload for arm cranking was 44% lower than that for cycling (155 ± 37 *vs* 277 ± 39 W, $P < 0.001$) associated with significantly ($P < 0.001$) lower maximal tidal volume (−20%), oxygen uptake (−22%), carbon dioxide output (−28%), systolic blood pressure (−17%) and oxygen pulse (−22%) but a higher ventilatory equivalent for carbon dioxide (+22%) and arm venous blood lactate concentration (+37%). However, these responses after arm-crank and cycle exercises behaved almost similarly during recovery. The high cardiorespiratory stress induced by arm work should be taken into account when the work stress and work–rest regimens in actual manual tasks are assessed, and when arm work is used for clinical testing, and in physiotherapy particularly for patients with heart or pulmonary diseases.

Key words: arm cranking, arm venous blood lactate, blood pressure, cycling, heart rate, recovery, ventilatory gas exchange.

Many agricultural, forest and manual material handling tasks as well as sport activities require substantial use of upper body muscle groups (Vrijens *et al.* 1975, Sen *et al.* 1983, Ilmarinen 1984, Kukkonen-Harjula & Rauramaa 1984). In occupational and exercise studies, it is thus sometimes necessary to assess the work capacity of the upper body (Falkel *et al.* 1986, Louhevaara *et al.* 1988). In clinical physiology and in physiotherapy arm work is also applied for disabled individuals having difficulties in using their legs for exercising (Hjeltnes 1977, Lazarus *et al.* 1981).

Evaluation of the capacity and function of the upper body is almost solely based on the recording of cardiorespiratory responses to arm-crank exercise in a sitting position (see, for example, Sawka 1986). Most investigators have

Correspondence: Veikko Louhevaara, Department of Physiology, Institute of Occupational Health, Laajaniityntie 1, SF-01620 Vantaa, Finland.

reported higher aerobic, anaerobic and heart rate responses to arm cranking than to cycling at equal submaximal power outputs, but lower peak responses and maximal power output (e.g. Christensen 1932, Åstrand *et al.* 1965, Bevegård *et al.* 1966, Vokac *et al.* 1975). In spite of increased scientific interest in the physiology of upper body exercise (Sawka 1986), no data are available about cardiorespiratory responses both during and after arm-crank exercise while standing and using no torso restraints. Furthermore, the previous data have often been obtained from physically trained, young subjects (Secher *et al.* 1974, Vrijens *et al.* 1975, Bergh *et al.* 1976, Davis *et al.* 1976), whereas the problems in work and clinical physiology and in physiotherapy usually involve untrained individuals at different ages.

It was hypothesized that the differences in cardiorespiratory responses during and after arm cranking and cycling become smaller when arm cranking is carried out in a standing position without torso restraints, i.e. when it is attempted to maximize the amount of active skeletal muscle mass during arm cranking. This test mode for arm cranking was selected because the aim of this study was to highlight the differences in conventional stress testing administered by leg exercise and performance testing simulating actual work tasks with upper body muscle groups (Louhevaara *et al.* 1988).

Consequently, the purpose of the present study was to determine the differences in ventilatory gas exchange, heart rate, the systolic blood pressure, and the arm venous blood concentration between arm cranking while standing without torso restraints and cycling in untrained healthy men at submaximal and maximal exercise levels and during recovery. This knowledge is important when physical stress is studied in manual work tasks, when the arm work is used for clinical testing, rehabilitation, and training, and to attain a better understanding of control mechanisms being involved in cardiorespiratory responses to the arm-crank exercise.

MATERIALS AND METHODS

Twenty-one untrained healthy men, aged 24–45 years, volunteered for the study. Their physical characteristics are given in Table 1. The study procedure followed the Helsinki declaration, and was accepted by the Ethical Committee of the Institute of Occupational Health. Each subject signed a statement of informed consent.

Table 1. Subjects' physical characteristics and forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1)

	$n = 21$	
	Mean	SD
Age (years)	33.3	5.9
Height (cm)	178.4	7.2
Weight (kg)	78.3	12.7
Body fat (%)	18.4	5.3
FVC (l)	5.84	0.84
FVC (% of predicted)*	104.8	11.6
FEV_1 (l)	4.93	0.67
FEV_1 (% of predicted)*	111.8	13.3

* According to Berglund *et al.* (1963).

The cycle and arm-crank exercise tests were carried out in the laboratory, with an ambient temperature of 22–24 °C and a relative humidity of 30–40%. The cycle test was followed by the arm-crank test, and they were administered on separate occasions, with an interval of 2–7 days. For one subject, the interval between the tests was 30 days. Between the cycle and arm-crank tests half of the subjects performed a work test (Louhevaara *et al.* 1988) while the rest of them accomplished it after the arm-crank test. The subjects wore shorts and sneakers during the tests.

The subjects' initial measurements comprised a determination of their anthropometric characteristics including the assessment of the body fat (Durnin & Rahaman 1967), dynamic spirometry with a water spirometer introduced by Bernstein, and a clinical examination performed by a physician and supplemented with the recording of an electrocardiogram (ECG). Before the exercise tests a plastic needle for repeated venous blood sampling was inserted in a superficial cubital vein in the forearm. The first external workload was 50 W in the cycle test and 25 W in the arm-crank test. The load was increased by 50 W or 25 W respectively, every fourth minute. At each submaximal workload, the pedalling or cranking was interrupted for 30 s after a 3-min exercise while the blood pressure was measured and a sample of arm venous blood was taken. Thereafter the pedalling and cranking were continued at the preceding exercise level to the end of the 4-min period. The blood pressure was measured and the blood samples were also collected before and after the exercise, with the subjects in a sitting position. During recovery the blood pressure was measured immediately, and thereafter every second minute after the end of the exercise, while the blood samples were taken immediately and during the minutes of 1, 4, 8, 12 and 16 after the exercise.

During arm cranking the subjects stood without torso restraints, and no attempts were made to limit the possible use of back and leg muscles. The pedalling and cranking rate was maintained at 50 r.p.m. The subjects were asked to continue exercising until exhaustion. During the last minute of exercise the resistance force of friction was kept constant, and the subjects were asked to increase the external workload (the power output) to maximum by speeding up the revolution rate as much as possible. After the exercising ended, the responses continued to be recorded for 16 min.

Calibrated, mechanically braked cycle ergometers (Monark, Monark A/S, Sweden) were used in both tests. The ergometer for the arm-crank exercise was modified from the cycle ergometer (Bohannon 1986). The crank shaft was at a constant height of 0.83 m. The pedalling and cranking rates were paced by a metronome, and registered by an inductive revolution meter connected to a printer (Printina, Misuratory Electronici, Italy).

During the tests the respiratory frequency, tidal volume, pulmonary ventilation, oxygen uptake, carbon dioxide output and the respiratory exchange ratio were continuously measured and automatically printed by a microprocessor-controlled respiratory gas exchange analyser (Morgan Exercise Test System, P. K. Morgan Ltd, UK). The measurement unit consisted of a flowmeter, a paramagnetic oxygen analyser (Morgan 500d), and an infrared carbon dioxide analyser (Morgan 800d). A low-resistance breathing valve (modified Koegel Y-valve) with a mouthpiece and a nose clip were used continuously during the entire test periods. Before every test the flowmeter was calibrated by four inspiratory strokes with a 1-litre pump, the gas analysers with two mixtures of gases of known oxygen and carbon dioxide concentrations.

The initial ECG at rest was recorded with the standard 12 leads. In the tests four CH leads were used. The ECG was monitored continuously during the entire test period on an oscilloscope, and paper recordings were obtained during the last 15 s of each minute with a three-channel ECG recorder (Mingoraf 34, Siemens-Elema, FRG). The heart rate was obtained manually from 15 successive QRS intervals of the ECG recordings. The systolic blood pressure was measured with the conventional auscultatory technique, and the cuff was located on the left arm.

The arm venous blood samples of 2.0 ml were collected through the needle into disposable syringes. The tip of the needle was inserted into approximately the middle part of the right forearm. Two separate blood samples of 25 μl were taken from the syringe for the enzymatical determination of the blood lactate concentration, using the flow injection method described by Karlsson *et al.* (1983). The mean value of the duplicates was accepted if the values differed by less than 4% (Smolander *et al.*1986). The arm venous blood samples were used for the determinations of the blood lactate concentrations due to further analysis of the responses profile of the acid–base balance in arm venous blood (Teräslinna & Louhevaara 1988).

The gross efficiency of work was calculated as the ratio of power output to aerobic metabolic (oxygen uptake) input (Powers *et al.* 1984).

The data were treated for conventional descriptive statistics. The significance of the differences was evaluated with the Student's *t*-test for paired observations.

RESULTS

At the two submaximal stages of arm-crank and cycle exercise tests when external workloads were equal (50 and 100 W), the respiratory frequency, tidal volume, pulmonary ventilation, oxygen uptake, carbon dioxide output, heart rate and the arm venous blood lactate concentration as well as the respiratory exchange ratio and the ventilatory equivalent for oxygen were significantly higher ($P < 0.001$) during arm cranking than during cycling (Figs. 1–4). At a load of 50 W, the gross mechanical efficiency was 11% during arm cranking and 16% during cycling; the difference was significant ($P < 0.001$). When the load was 100 W, the efficiencies were 15% and 20% ($P < 0.001$) respectively.

At the maximal exercise level, most parameters reflecting the power output of the work remained significantly lower during arm cranking than during cycling. The maximal external workload was 44% (155 ± 37 *vs* 277 ± 39 W, $P < 0.001$), tidal volume 20% (2.42 ± 0.30 *vs* 3.01 ± 0.53 l, $P < 0.001$), pulmonary ventilation 11% (90.4 ± 13.6 *vs* 102.0 ± 14.3 l min^{-1}, $P < 0.01$), oxygen uptake 22% (2.52 ± 0.32 *vs* 3.24 ± 0.44 l min^{-1}, $P < 0.001$), carbon dioxide output 28% (2.72 ± 0.32 *vs* 3.76 ± 0.35 l min^{-1}, $P < 0.01$), the respiratory exchange ratio 7% (1.09 ± 0.08 *vs* 1.17 ± 0.10, $P < 0.01$) and oxygen pulse 22% (14.2 ± 1.9 *vs* 18.1 ± 2.8 ml beat^{-1}, $P < 0.001$) lower during arm cranking (Figs. 1–4). On the other hand, during maximal arm cranking, the parameters reflecting anaerobic metabolism were significantly higher than during maximal cycling. The respiratory frequency was 7% (37.6 ± 5.8 *vs* 35.0 ± 5.9 breaths min^{-1}, $P < 0.05$), the arm venous blood lactate concentration 37%

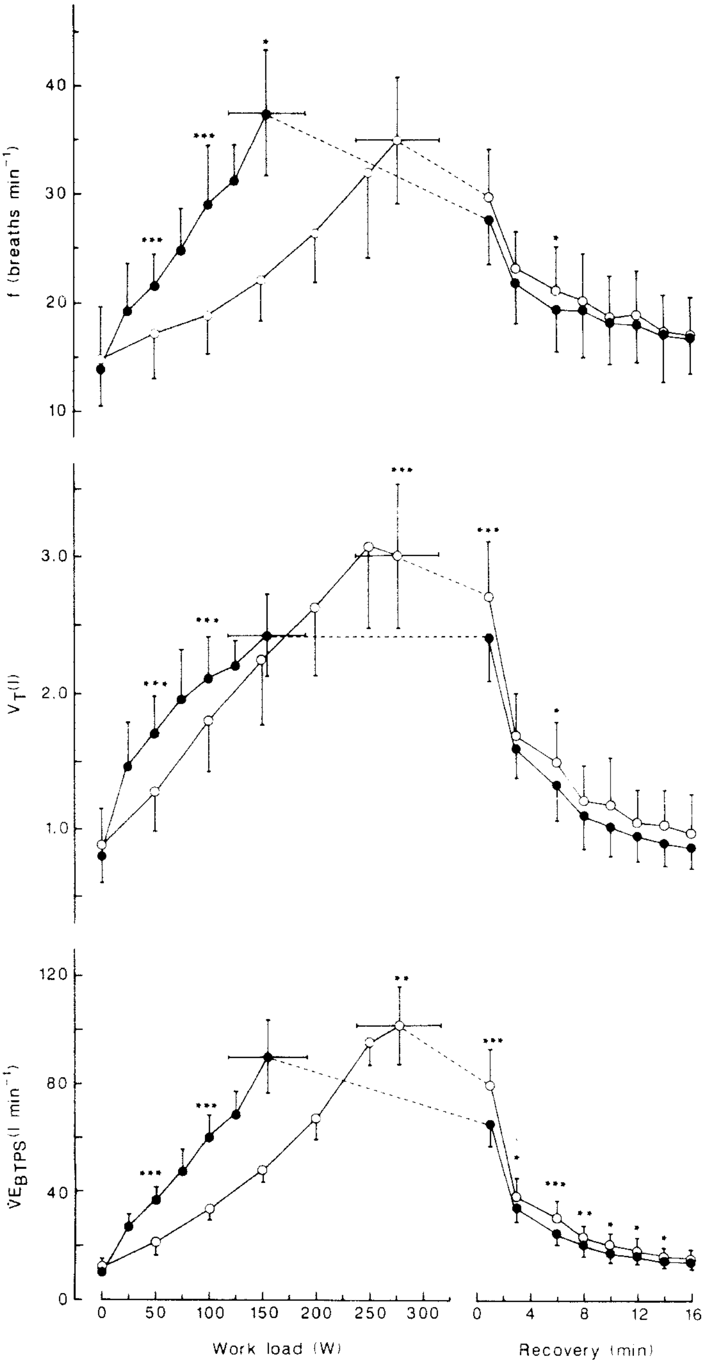

Fig. 1. Respiratory frequency (f), tidal volume (V_T) and pulmonary ventilation ($\dot{V}_{E,\,BTPS}$) in a sitting position, at submaximal exercise levels, at the maximum and during the recovery period for arm-crank (●–●) and cycle (○–○) tests. The values given are the means ± SD. At the load of *125* W for arm cranking and 250 W for cycling $n = 4$ and $n = 3$ respectively. Levels of statistical significance are expressed as * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

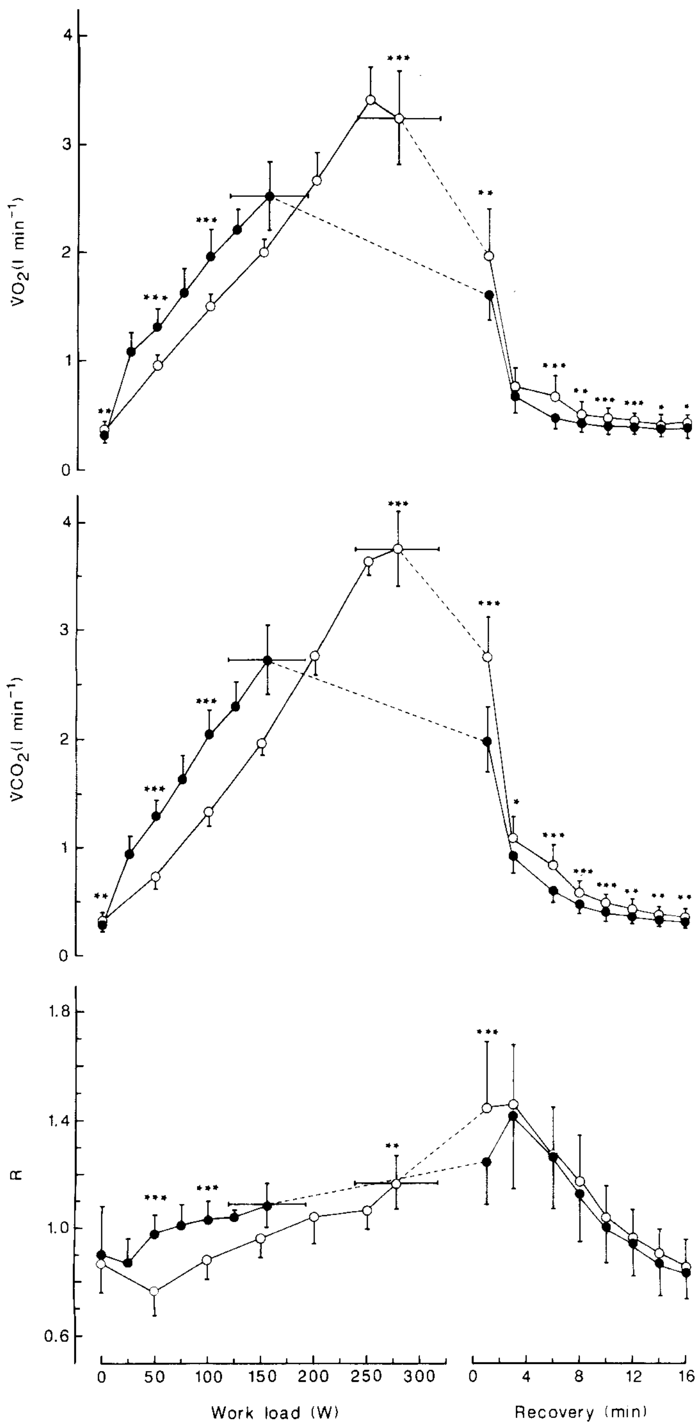

Fig. 2. Oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and the respiratory exchange ratio (R) in a sitting position, at submaximal exercise levels, at the maximum and during the recovery period for arm-crank (●–●) and cycle (○–○) tests. See also the legend to Fig. 1.

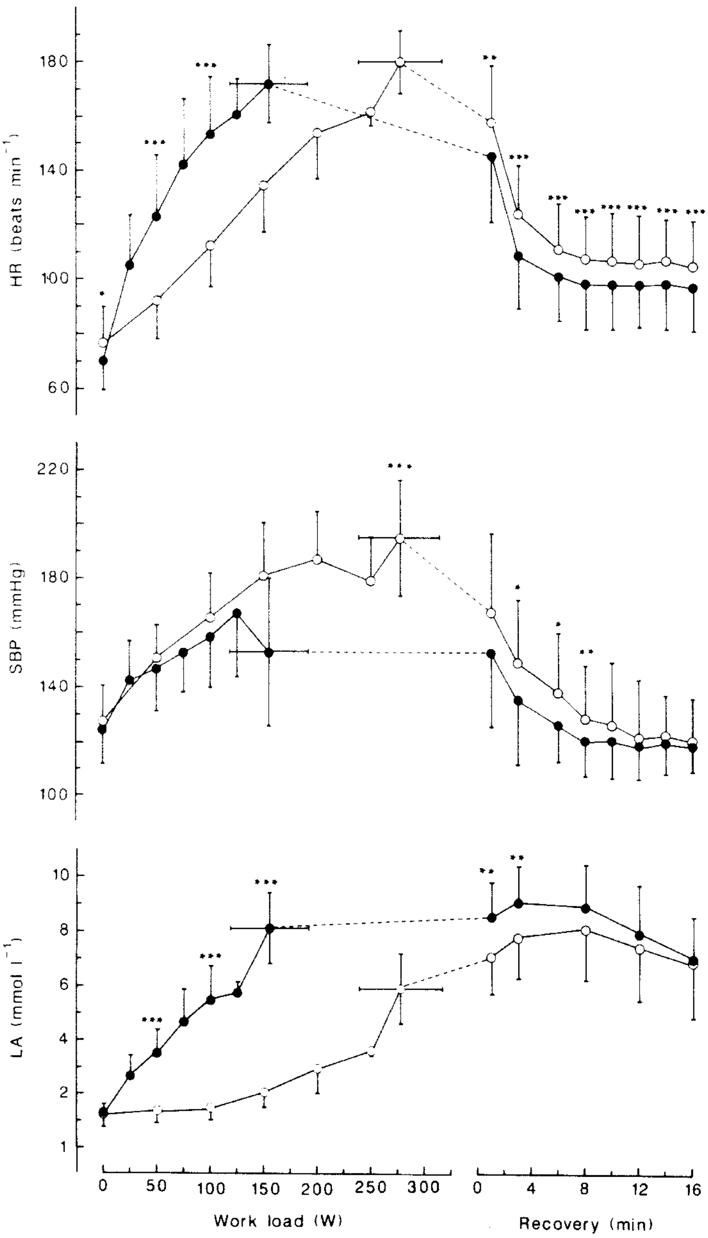

Fig. 3. Heart rate (HR), the systolic blood pressure (SBP) and the arm venous blood lactate concentration (LA) in a sitting position, at submaximal exercise levels, at the maximum and during the recovery period for arm-crank (●–●) and cycle (○–○) tests. See also the legend to Fig. 1.

(8.1 ± 1.3 *vs* 5.9 ± 1.3 mmol l^{-1}, $P < 0.001$), the ventilatory equivalent for oxygen 14% (36.1 ± 4.7 *vs* 31.8 ± 5.6 l l^{-1}, $P < 0.05$) and that for carbon dioxide 22% (33.3 ± 3.7 *vs* 27.2 ± 3.7 l l^{-1}, $P < 0.001$) higher during maximal arm cranking. There was no significant difference in the maximal heart rate while the systolic blood pressure was 17% (153 ± 27 *vs* 185 ± 22 mmHg, $P < 0.001$) lower during maximal arm cranking.

At the maximal power output, the gross efficiency was 18% during arm cranking and 25% during cycling ($P < 0.001$). At maximum

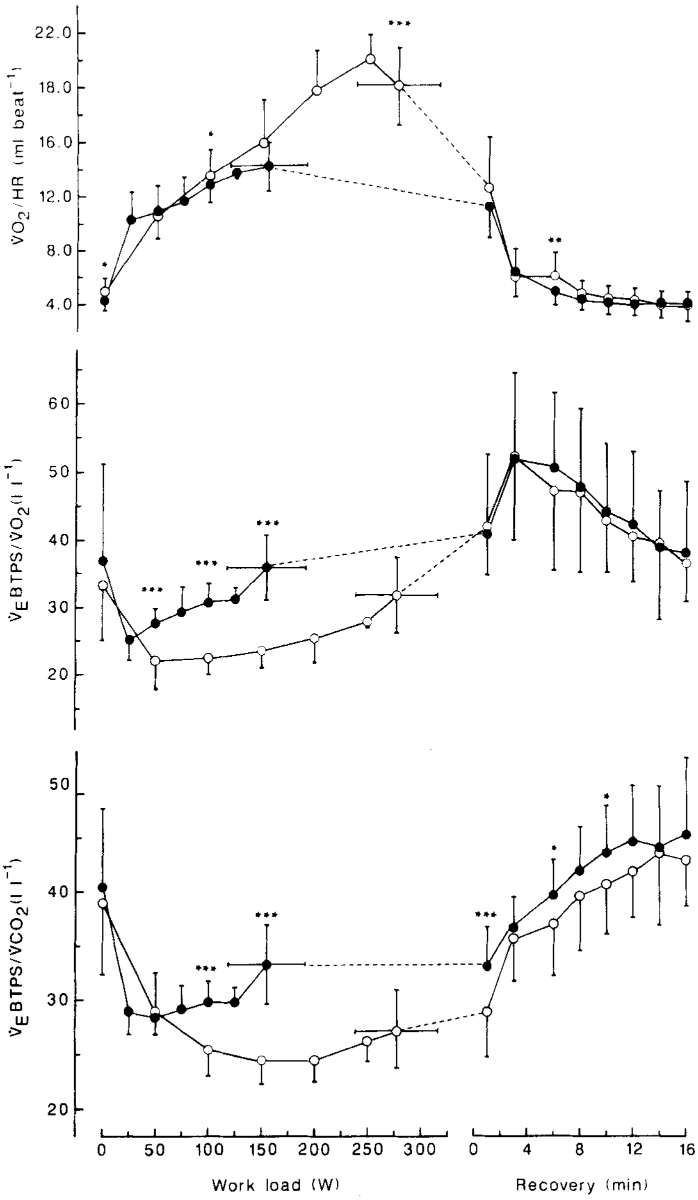

Fig. 4. Oxygen pulse ($\dot{V}O_2$/HR), the ventilatory equivalent for oxygen ($\dot{V}_{E,BTPS}/\dot{V}O_2$) and for carbon dioxide ($\dot{V}_{E,BTPS}/\dot{V}CO_2$) in a sitting position, at submaximal exercise levels, at the maximum and during the recovery period for arm-crank (●–●) and cycle (○–○) tests. See also the legend to Fig. 1.

the resistance force of friction and the revolution rate were 26 ± 3 N and 60 ± 11 r.p.m. for arm cranking and 49 ± 6 N and 57 ± 10 r.p.m. for cycling.

After 2 min of recovery in both arm cranking and cycling, no significant differences were found in respiratory frequency, tidal volume, the respiratory exchange ratio, oxygen pulse and the ventilatory equivalent for oxygen and carbon dioxide (Figs. 1–4). After a recovery of 16 min, oxygen uptake was 12% (0.38 ± 0.09 *vs* 0.43 ± 0.07 l min^{-1}, $P < 0.05$), carbon dioxide output 14% (0.31 ± 0.06 *vs* 0.36 ± 0.07 l min^{-1}, $P < 0.01$) and heart rate 8% (97 ± 16 *vs* 105 ± 16 beats min^{-1}, $P < 0.001$) lower after arm cranking than cycling. At the end of the recovery period, for both the cycle and the arm-crank test, the respiratory frequency, pulmonary ventilation, oxygen uptake, heart rate, the arm venous blood lactate and the ventilatory equivalent for carbon dioxide were significantly ($P < 0.5$–0.001) higher than the baseline values measured before the tests with the subject in a sitting position. The arm venous blood lactate level remained about fivefold higher and heart rate about 30 beats min^{-1} higher (Figs. 1–4).

DISCUSSION

Differences in body postures, the use of torso restraints, the different crank shaft heights and training status of the subjects involved in arm cranking may cause variations when the physiological responses to arm cranking are compared to those of cycling (Secher *et al.* 1974, Vrijens *et al.* 1975, Bergh *et al.* 1976). Arm-crank exercise has usually been carried out with the subjects in a sitting position with no torso restraints (Sawka 1986). In the present experiments, the arm-crank exercise was performed in a standing position without artificial torso restraints and attempts to limit the possible use of back and leg muscles while cranking. The exercise was designed to increase the amount of active skeletal muscle mass as much as possible. Furthermore, the use of efficient torso restraints may restrict blood flow and respiration (Louhevaara *et al.* 1985). On the other hand, torso restraints may reduce the amount of internal work, i.e. mainly isometric muscle work to stabilize posture and the rotational movement of upper body. Hence, the reduction of the amount of internal work may even increase the mechanical efficiency of arm cranking (Davies & Sargeant 1974, Pendergast *et al.* 1979).

At equal loads of 50 W and 100 W, arm cranking provoked minute ventilation almost twice as high as cycling. Higher ventilation was elicited by significant increases both in respiratory frequency and tidal volume, whereas Bevegård *et al.* (1966) found slightly higher values for respiratory frequency and/or tidal volume. Significantly higher submaximal responses during arm cranking when compared with cycling were also observed in oxygen uptake, carbon dioxide output, heart rate and the arm venous blood lactate concentration, the result being substantial increases in the respiratory exchange ratio as well as the ventilatory equivalents for oxygen and carbon dioxide. However, the systolic blood pressure and oxygen pulse tended to remain smaller during arm cranking than during cycling. These findings did not agree with the hypothesis of this study, and indicated that arm cranking in a standing position also had high cardiorespiratory responses at low external workloads as earlier reported, for example by Bevegård *et al.* (1966), Davies & Sargeant (1974), Vokac *et al.* (1975) and Nag (1984). Previous results on the systolic blood pressure during submaximal arm cranking have been obtained with different techniques and are somewhat controversial (e.g. Åstrand *et al.* 1965, Bevegård *et al.* 1966, Balady *et al.* 1986). The results of this study support the recent observations of Balady *et al.* (1986) when they reported slightly lower cuff arm systolic blood pressure for arm cranking than cycling at equal submaximal workloads up to 120 W.

Maximal workload during arm cranking was, on average, only 56% of that attained during maximal cycling, this outcome being associated with an 11% lower value for pulmonary ventilation and a 22% lower value for oxygen uptake. Tidal volume during maximal arm cranking remained low, restricting maximal pulmonary ventilation, which was only partly compensated for by a significantly higher maximal respiratory frequency, previously observed also by Davies & Sargeant (1974). According to the results of several investigations reviewed by Sawka (1986), the mean peak value of pulmonary ventilation has been 19% and that of oxygen uptake 27% lower during arm cranking in a sitting position than during cycling. The unexpectedly low systolic blood pressure measured immediately after the maximal arm cranking has not been reported earlier and remains unexplained. The comparison of the maximal results did not support well the hypothesis of this study.

In the present study, the arm venous blood lactate concentration at maximal exercise was significantly higher during arm cranking than during cycling. However, the results summarized by Sawka (1986) showed, on average, blood lactate values 12% lower during maximal arm cranking than during cycling. There are many possible reasons for the difference. The subjects' training status (Bergh *et al.* 1976), the place of blood sampling (Pimental *et al.* 1984) and the use of an intermittent test procedure may affect the peak blood lactate concentrations. The subjects in the present study were well motivated but physically untrained and not very familiar with cycling or arm cranking. In both tests the arm venous blood samples were taken from the same location – the superficial vein of the middle part of the right forearm – and immediately after each workload when the subjects rested. The arm venous blood samples during arm cranking represented blood directly draining the active muscles, but during cycling the blood sampling was distal to the most active muscles. The place of sampling is probably the main reason for both the higher blood lactate concentrations during arm cranking and quite low concentrations determined during cycling. Furthermore, the isometric work of arm muscles also observed in cycle exercise (Luhtanen *et al.* 1987) may have reduced peripheral blood flow and the mixing of venous blood.

The present results of gross mechanical efficiency for arm cranking (11–18%) and cycling (16–25%) at submaximal and maximal loads agree with the previous calculations (Sawka *et al.* 1983, Nag 1984, Powers *et al.* 1984, Luhtanen *et al.* 1987). Hence the internal workload in addition to considerable anaerobic work during arm cranking must be high. At the maximal load, the efficiency for arm cranking in the standing position was high, most probably reflecting the benefit induced by the increase the dynamic component of exercise due to the relatively high cranking (60 ± 11 r.p.m.) rate attained by the subjects during the last test minute (Sawka *et al.* 1983).

During submaximal arm cranking, as compared to cycling, increased internal work and the smaller active skeletal muscle mass involved during arm cranking have been thought to accelerate considerably the local accumulation of muscle metabolites because of the limited skeletal muscle blood flow (Åstrand *et al.* 1965, Secher *et al.* 1974, Reybrouck *et al.* 1975, Sawka *et al.* 1982). These substances increase minute ventilation and thus also carbon dioxide output (Åstrand 1960). Respiration may also be stimulated by the high sympathetic and proprioceptive drive associated with the arm-crank exercise (Bevegård *et al.* 1966, Vokac *et al.* 1975). The high heart rates occurring during submaximal arm cranking may also be due to a strong sympathetic stimulus, mainly caused by the extra isometric work of the upper body and the limited increase of stroke volume (Åstrand *et al.* 1965, Bevegård *et al.* 1966, Davies & Sargeant 1974, Clausen 1976). The additional isometric work required by arm cranking increases intramuscular and thorax pressures (Åstrand *et al.* 1965). Furthermore, during arm cranking perfusion pressure into the active muscle groups may be lower than during cycling (Eiken 1987). High thoracic pressure can impair venous return and preload of the heart, resulting in a decreased stroke volume during arm cranking (Bevegård *et al.* 1966, Davies & Sargeant 1974, Reybrouck *et al.* 1975).

During maximal arm cranking, the small active skeletal muscle mass, the restricted skeletal muscle blood flow and reduced cardiac output via insufficient stroke volume are the most probable reasons for the decreases in oxygen uptake, carbon dioxide output and pulmonary ventilation as well as in the attainable external workload, these being highly dependent on individual physical training status (Reybrouck *et al.* 1975, Bergh *et al.* 1976, Clausen 1976).

The recovery after maximal cycle and arm-crank exercise was followed for 16 min to consider differences in rest periods needed after arm and leg work. The differences in the ventilatory gas exchange were small, this being in agreement with the hypothesis of this study. The somewhat higher recovery values for some gas exchange parameters observed after cycling are probably due to the higher active skeletal muscle mass, inducing a greater external work and metabolic load. The arm venous blood lactate concentrations after arm cranking and cycling were equal in the latter half of the recovery period, and varied from 8.9 to 6.8 mmol l^{-1}, and about fivefold in comparison to the baseline values. The removal of lactate exceeded its release into circulation after the maximal exercise when the recovery period had progressed for 5–10 mins, as recently discussed, by, for example, Åstrand *et al.* (1986). The recovery of heart rate was significantly faster after maximal arm cranking than after cycling, possibly because of the difference in stroke volumes employed by arm cranking and cycling. However, after the 16-min recovery following arm cranking and cycling, heart rates were still substantially (about 30 beats min^{-1}) higher than the baseline values before the tests, and primarily attributed to the elevated body temperature. Probably this also affected the slow recovery of the respiratory frequency.

According to the present study, the power output of the normal male subjects during arm cranking while standing without torso restraints was markedly lower than during cycling at equal metabolic stress levels, and the recovery after arm cranking was not substantially faster than after cycling. In physically heavy work tasks, the use of upper body muscle groups should be avoided due to the resulting inefficiency and the rapid development of symptoms of local and general systemic overstrain and fatigue. When arm work is needed, the work stress and work–rest regimens should be adjusted according to the actual physiological strain, which can be indicated, for example, by simple measurements of heart rate (Vokac *et al.* 1975, Louhevaara *et al.* 1986). Furthermore, the high cardiorespiratory stress induced by arm work should be taken into account in clinical stress testing for diagnostic purposes, and when physiotherapy is planned for and guidelines for physical activity are given to disabled individuals and particularly to patients with heart or pulmonary diseases.

This study was supported by the Central Post and Telecommunications Office and the Ministry of Finance. The authors wish to thank Päivi Piirilä MD, Olli Korhonen MD, Susanna Salmio, Sirpa Leino, Eeva Tolin, and Maija Jokinen for their skilful assistance during the laboratory experiments.

REFERENCES

Åstrand, I. 1960. Aerobic work capacity in men and women with special reference to age. *Acta Physiol Scand* **49**, Suppl. 169.

Åstrand, P.-O., Ekblom, B., Messin, R., Saltin, B. & Stenberg, J. 1965. Intraarterial blood pressure during exercise with different muscle groups. *J Appl Physiol* **20**, 253–256

Åstrand, P.-O., Hultman, E., Juhlin-Dannfelt, A. & Reynolds, G. 1986. Disposal of lactate during and after strenuous exercise in humans. *J Appl Physiol* **61**, 338–343.

Balady, G.J., Schick, E.C., Weiner, D.A., Ryan, T.J., Sarno, G. & Filancia, M. 1986. Comparison of determinants of myocardinal oxygen consumption during arm and leg exercise in normal persons. *Am J Cardiol* **57**, 1385–1387.

Bergh, U., Kanstrup, I.L. & Ekblom, B. 1976. Maximal oxygen uptake during exercise with various combinations of arm and leg work. *J Appl Physiol* **41**, 191–196.

Berglund, E., Birath, G., Bjure, J., Grimby, G., Kjellmer, J., Sandqvist, L. & Söderholm, B. 1963. Spirometric studies in normal subjects. I. Forced expirograms in subjects between 7 and 70 years of age. *Acta Med Scand* **173**, 185–192.

Bevegård, S., Freyschuss, U. & Strandell, T. 1966. Circulatory adaptation to arm and leg exercise in supine and sitting position. *J Appl Physiol* **21**, 37–46.

Bohannon, R.W. 1986. Adapting a bicycle ergometer for arm crank ergometry. Suggestion from the field. *Phys Therapy* **66**, 362–363.

Christensen, E.H. 1932. Beiträge zur Physiologie schwere körperlicher Arbeit. VI. Mitteilung: Der Stoffwechsel und die respiratorischen Funktionen bei schwerer körperlicher Arbeit. *Arbeitsphysiologie* **4**, 463–478.

Clausen, J.P. 1976. Circulatory adjustments to dynamic exercise and effect of physical training in normal subjects and in patients with coronary artery disease. *Prog Cardiovasc Dis* **18**, 459–495.

Davies, C.T.M. & Sargeant, A.J. 1974. Physiological responses to standardised arm work. *Ergonomics* **17**, 41–49.

Davis, J.A., Vodak, P., Wilmore, J.H., Vodak, J. & Lurtz, P. 1976. Anaerobic threshold and maximal aerobic power for three modes of exercise. *J Appl Physiol* **41**, 544–550.

Durnin, J.V.G.A. & Rahaman, N.M. 1967. The assessment of the amount of fat in human body from measurements of skinfold thickness. *Br J Nutr* **21**, 681–689.

Eiken, O. 1987. Responses to dynamic leg exercise in man as influenced by changes in muscle perfusion pressure. *Acta Physiol Scand* **131**, Suppl. 566.

Falkel, J.E., Sawka, M.N., Levine, L., Pimental, N.A. & Pandolf, K.B. 1986. Upper body exercise performance: Comparison between women and men. *Ergonomics* **29**, 145–154.

Hjeltnes, N. 1977. Oxygen uptake and cardiac output in graded arm exercise in paraplegics with low level spinal lesions. *Scand J Rehabil Med* **9**, 107–113.

Ilmarinen, J. 1984. Physical load on the cardiovascular system in different work tasks. *Scand J Work Environ Hlth* **10**, 403–408.

Karlsson, J., Jacobs, I., Sjödin, B., Tesch, P., Kaiser, O., Sahl, O. & Karlberg, B. 1983. Semiautomatic blood lactate assay: experiences from an exercise laboratory. *Int J Sports Med* **4**, 45–48.

Kukkonen-Harjula, K. & Rauramaa, R. 1984. Oxygen consumption of lumberjacks in logging with a power-saw. *Ergonomics* **27**, 59–65.

Lazarus, B., Cullinane, E. & Thompson, P.D. 1981. Comparison of the results and reproducibility of arm and leg exercise tests in men with angina pectoris. *Am J Cardiol* **47**, 1075–1079.

LOUHEVAARA, V., SMOLANDER, J., TUOMI, T., KORHONEN, O. & JAAKKOLA, J. 1985. Effects of an SCBA on breathing pattern, gas exchange, and heart rate during exercise. *J Occup Med* 27, 213–216.

LOUHEVAARA, V., SMOLANDER, J., KORHONEN, O. & TUOMI., T. 1986. Maximal working times with a self-contained breathing apparatus. *Ergonomics* 29, 77–85.

LOUHEVAARA, V., TERÄSLINNA, P., PIIRILÄ, P., SALMIO, S. & ILMARINEN, J. 1988. Physiological responses during and after intermittent sorting of postal parcels. *Ergonomics* 31, 1165–1175.

LUHTANEN, P., RAHKILA, P., RUSKO, H. & VIITASALO, J. 1987. Mechanical work and efficiency in ergometer bicycling at aerobic and anaerobic thresholds. *Acta Physiol Scand* 131, 331–337.

NAG, P.K. 1984. Circulo-respiratory responses to different muscular exercises. *Eur J Appl Physiol* 52, 393–399.

PENDERGAST, D., CERRETELLI, P. & RENNIE, D.W. 1979. Aerobic and glycolytic metabolism in arm exercise. *J Appl Physiol* 47, 754–760.

PIMENTAL, N.A., SAWKA, M.N., BILLINGS, D.S. & TRAD, L.A. 1984. Physiological responses to prolonged upper-body exercise. *Med Sci Sports Exercise* 16, 360–365.

POWERS, S.K., BEADLE, R.E. & MANGUM, M. 1984. Exercise efficiency during arm ergometry: effects of speeds and work rate. *J Appl Physiol* 56, 495–499.

REYBROUCK, T., HEIGENHAUSER, G.F. & FAULKNER, J.A. 1975. Limitations to maximum oxygen uptake in arm, leg, and combined arm–leg ergometry. *J Appl Physiol* 38, 774–779.

SAWKA, N.M. 1986. The physiology of upper body exercise. *Exerc Sport Sci Rev* 14, 175–211.

SAWKA, M.N., MILES, D.S., PETROFSKY, J.S., WILDE, S.W. & GLASET, R.M. 1982. Ventilation and acid–base equilibrium for upper body and lower body exercise. *Aviat Space Environ Med* 53, 354–359.

SAWKA, M.N., FOLEY, M.E., PIMENTAL, N.A., TONER, M.N. & PANDOLF, K.B. 1983. Determination of maximal aerobic power during upper-body exercise. *J Appl Physiol* 54, 113–117.

SECHER, N.H., RUBERG-LARSEN, N., BINKHORST, R.A. & BONDE-PETERSEN, F. 1974. Maximal oxygen uptake during arm cranking and combined arm plus leg exercise. *J Appl Physiol* 36, 515–518.

SEN, G.R., GANGULI, A.K., ROY, G.G., PE, A. & GHAKRABARTI, D. 1983. Tea-leaf plucking-workloads and environmental studies. *Ergonomics* 21, 1963–1985.

SMOLANDER, J., KOLARI, P., KORHONEN, O. & ILMARINEN, R. 1986. Aerobic and anaerobic responses to incremental exercise in a thermoneutral and a hot dry environment. *Acta Physiol Scand* 128, 15–21.

TERÄSLINNA, P. & LOUHEVAARA, V. 1988. Arm venous blood acid-base response to maximum arm cranking (abstract). *Can J Sport Sci* 13, 33P.

VOKAC, Z., BELL, E., BAUTZ-HOLTER, E. & RODAHL, K. 1975. Oxygen uptake/heart rate relationship in leg and arm exercise, sitting and standing. *J Appl Physiol* 39, 54–59.

VRIJENS, J., HOEKSTRA, P., BOUCKAERT, J. & VAN UYTVANCK, P. 1975. Effects of training on maximal working capacity and haemodynamic response during arm and leg-exercise in a group of paddlers. *Eur J Appl Physiol* 34, 113–119.