Physiological responses to asynchronous and synchronous arm-cranking exercise

Abstract The purpose of this study was to examine mechanical efficiency (ME) and physiological responses during asynchronous (the pedal arms oriented in opposing directions) arm-cranking exercise (AACE) and compare these responses to those obtained during synchronous (the pedal arms oriented in the same direction) arm-cranking exercise (SACE). Ten male subjects participated in the study and performed two exercise tests, one AACE and the other SACE in counterbalanced order. Each test consisted of submaximal (30, 60 and 90 W) and maximal exercise. At 30 W, gross ME was significantly lower during SACE compared to AACE, whereas at 60 W and 90 W no differences between the two types of exercise could be observed. We found that at lower power output levels the flywheel mass and its moment of inertia may have induced more body movements for compensation, which may have been more pronounced during SACE than during AACE. At higher levels of power output this flywheel mass effect was less, which explained the lack of differences in ME at these levels. Physiological responses to maximal AACE or SACE exercise were not significantly different. The results indicated that there were no differences in physiological responses of these two types of exercise at higher exercise intensities. However, at lower levels of power output ME seemed to decrease, most likely as a result of the flywheel-mass effect, which was more pronounced during SACE.

Key words Upper body exercise • Maximal exercise • Submaximal exercise • Gross mechanical efficiency

Introduction Since many industrial tasks and rehabilitation programmes involve the use of the upper part of the body, an increasing interest in upper-body exercise can be noticed in occupational and rehabilitation medicine as well as in laboratory tests (Franklin 1985; Kemper et al. 1990; Shephard 1991; Casaburi et al. 1992; Davis 1993). In addition, wheelchair-dependent individuals have to turn to upper-body exercise for daily ambulation. Recently, several studies have been directed towards physiological responses during upper-body exercise, i.e. in pulmonary patients (Carter et al. 1992), in cardiac patients (Franklin 1989), in individuals with a spinal-cord injury (Hopman et al. 1992), during wheelchair propulsion (Van Der Woude et al. 1988) and in comparison to lower-limb exercise (Sawka 1986).

Up to the present, however, no study has been directed towards the examination of the physiological responses of different types of arm-cranking exercise, i.e. asynchronous and synchronous arm-cranking. During asynchronous arm-cranking exercise (AACE) the pedal arms of the flywheel are oriented in opposing directions 180° relative to each other, which is the most common situation for arm-cranking exercise in laboratory or clinical tests. During synchronous arm-cranking exercise (SACE) the pedal arms are oriented in the same direction, 0° relative to each other, which is of interest for wheelchair propulsion. This study was conducted because it is important, for routine laboratory and clinical cardiorespiratory assessment as well as for daily ambulation of wheelchair dependent people, to clarify the differences between the mechanical efficiencies and physiological responses of these two types of exercise.

The purpose of this study was, therefore, to examine the differences in physiological responses between maximal AACE and SACE, and, in addition, to establish mechanical efficiency (ME) during different intensity levels of submaximal AACE and SACE.

Methods Subjects Ten male able-bodied subjects participated in this study after giving their written informed consent. The study was approved by...
Fig. 1 The exercise protocol, including submaximal (submax) and maximal exercise (max test)

the Faculty Ethics Committee. All the subjects were healthy, used no medication and their activity levels varied from hardly any exercise to highly trained individuals.

Protocol

The subjects visited the laboratory twice within 1 week and performed submaximal and maximal arm exercise (Fig. 1). Submaximal exercise was performed at 30 W, 60 W and 90 W. Each period of exercise lasted 5 min with a 6-min recovery period in-between.

Submaximal exercise was followed by a maximal exercise test. Power output increased every minute by 10 W until exhaustion, with a crank revolution frequency of 65 rpm (Washburn and Seals 1983). The test was concluded when, even after verbal encouragement by the examiner, the revolutions per minute fell below 60. Heart rate (HR) above 170 beats · min⁻¹ and respiratory exchange ratio (R) above 1.00 were used as objective criteria for maximal exercise (Sawka 1986). The participants were only informed about the performances achieved after the second test. The tests were performed once with synchronous and once with asynchronous arm cranking. Each type of test was assigned in random order, using a counterbalanced design. On all occasions, temperature in the experimental room was maintained between 20 and 22 °C with a relative humidity of 50%–60%.

Apparatus

Exercise was performed using an electro-magnetic arm ergometer (type Angio, Lode, Groningen, The Netherlands). The subjects sat on a stool and the axis of the arm-crank ergometer was adjusted to shoulder level (Sawka 1986). The feet were positioned on the ground at premarked places to maintain high reproducibility of the posture of the subjects.

During AACE, the pedal arms of the flywheel were oriented in opposing directions, 180° relative to each other, whereas during SACE the pedal arms of the flywheel were oriented similarly, 0° relative to each other (Fig. 2).

Measurements

During the maximal as well as the submaximal exercise tests, oxygen uptake (VO₂) and carbon dioxide output (VCO₂) were measured by an automated gas analysis system (Oxycon IV, Mijnhardt, Bunnik, The Netherlands). This system contains a gas-meter, a paramagnetic O₂ analyser and an infrared CO₂ analyser, which were calibrated before each exercise test with gas-mixtures analysed using the Scholander technique (Hopman et al. 1992). The subjects breathed via a two-way Hans Rudolph valve which was connected to the automated gas analysis system.

Electrocardiograms (ECG) were recorded and HR was monitored, continuously. The HR was calculated from the ECG records afterwards.

The electromyogram (EMG) activity of the rectus abdominus and triceps brachii muscles was measured during all of the tests using surface electrodes. Measurements were used as a qualitative indication for muscle activity during the different types of exercise.

The gross ME was calculated during submaximal steady-state exercise by dividing the internally liberated mechanical power, which was assumed to be equal to VO₂, into external power output (W): ME = W/(VO₂ × 340), in which 340 W has been shown to be the power equivalent for 1 l O₂·min⁻¹ (Gaesser and Brooks 1975; Stainsby et al. 1980; Van Der Woude et al. 1988; Linden et al. 1993).

Statistical analysis

A paired Student's t-test was applied to assess the significance of differences in the physiological responses between AACE and SACE during maximal and submaximal exercise. A two-tailed p<0.05 was considered to be statistically significant.

Results

The characteristics of the ten subjects were: mean age 29 (SD 3.9) years, mean body mass 76 (SD 6.2) kg, mean body height 1.82 (SD 0.15) m, mean sport participation 6.4 (SD 5.9) h week⁻¹.

During submaximal exercise the ME was significantly different between AACE and SACE at the 30-W exercise intensity. At 60 and 90 W, however, no significant differences in ME were noted between AACE and SACE (Fig. 3).

Table 1 presents the physiological responses to maximal AACE and SACE. All the subjects met at least one of the two criteria for maximal performance, so their efforts can be considered to be maximal. No significant differences were found in the peak power output (Wpeak), peak oxygen uptake (VO₂peak), peak heart rate (HRpeak) and peak respiratory exchange ratio (Rpeak) between AACE and SACE.

A typical example of EMG activity in the rectus abdominus and triceps brachii muscles is shown in Fig. 4. Abdominal muscle activity seemed to be higher during SACE compared to AACE at the same power output. The triceps brachii muscle showed activity during almost the whole cycle-time with SACE, whereas with AACE the activity of these muscles seemed to be more related to a certain phase in the cycle.

Table 2 presents the peak responses for test 1 and test 2. The Wpeak and VO₂peak were significantly higher during the second test whereas HRpeak and Rpeak.
Fig. 3 The gross mechanical efficiency (ME) (percentage) at power outputs (W) of 30 W, 60 W and 90 W for asynchronous arm cranking exercise (AACE) and synchronous arm cranking exercise (SACE). *P < 0.05.

Table 1 Physiological responses to maximal asynchronous arm cranking exercise (AACE) and synchronous arm cranking exercise (SACE) in ten men. W Power output, VO2 oxygen uptake, HR heart rate, R respiratory exchange ratio, P level of statistical significance (n = 10)

<table>
<thead>
<tr>
<th></th>
<th>AACE</th>
<th>SACE</th>
<th>P</th>
</tr>
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<tbody>
<tr>
<td>W (W)</td>
<td>154</td>
<td>157</td>
<td>0.65</td>
</tr>
<tr>
<td>VO2 (l·min⁻¹)</td>
<td>2.84</td>
<td>2.76</td>
<td>0.56</td>
</tr>
<tr>
<td>HR (beats·min⁻¹)</td>
<td>176</td>
<td>171</td>
<td>0.06</td>
</tr>
<tr>
<td>R</td>
<td>1.14</td>
<td>1.13</td>
<td>0.76</td>
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showed no differences between the first and the second test. No significant differences were observed in ME between test 1 and test 2.

Discussion

Whereas previous research has in the main been directed towards the examination of physiological responses to arm-cranking exercise (ACE) and wheelchair propulsion (Van der Woude et al. 1988; Linden et al. 1993), in the present study attention has been focused on two different forms of arm-cranking exercise, i.e. asynchronous versus synchronous, which is of interest for wheelchair propulsion as well as for laboratory tests.

The values of gross ME found in the present study (Table 2) are in agreement with previously reported values during ACE in able-bodied subjects (Cummins and Gladden 1983; Powers et al. 1984; Hopman et al. 1992). Results have indicated that ACE has a higher

ME compared to hand-rim wheelchair propulsion (11%–15% vs 8%–10%, respectively; Van der Woude et al. 1988). Linden et al. (1993) have reported even lower values for net ME during forward (5.6%) and reverse (6.1%) wheelchair propulsion at 30 W. However,
these investigators have determined ME only at \( W \) between 15–30 W. The \( W \), however, markedly affects ME (Van der Woude et al. 1988), which may in part explain the low values found by Linden et al. (1993). The result of the present study also confirmed the relationship between \( W \) and ME. Noteworthy is the low ME at 30 W, which was significantly lower during SACE compared to AACE and may be explained by the flywheel mass and the moment of inertia at this low \( W \) (Binkhorst and Vissers 1983). This seems to affect the motion during SACE more than during AACE. At a higher \( W \) the flywheel-mass effect is less and no differences were found in ME between SACE and AACE.

The physiological responses to maximal AACE found in this study are in agreement with previously reported values on able-bodied subjects (Sawka 1986; Hopman et al. 1992). It has been suggested that SACE may provide benefits in achieving higher \( W \) using the trunk as a fulcrum to generate force, whereas during AACE the trunk only has a function in stabilising the body. In addition, differences in physiological responses or maximal \( W \) may be expected based on substantial differences in the way the arm muscles are used during force delivery while rotating the flywheel asynchronously or synchronously and based on differences in the compensatory muscle activity of the legs and trunk between both types of ACE. This was confirmed by differences in EMG activity – an early onset of activity of the abdominal muscles during SACE and activity of the triceps muscles for about 75% of the cycle-time during SACE and only for 50% during AACE.

However, results of this study indicated that there were no differences in physiological responses and \( W_{\text{peak}} \) between SACE and AACE for able-bodied subjects with normal use of leg, trunk and arm muscles. Additional research is needed to examine whether or not this holds true for wheelchair users, such as individuals with spinal cord injuries who can only use part of their trunk muscles and have no control over their leg muscles.

It is worth noting that subjectively (asked after finishing both tests) seven out of the ten subjects felt AACE to be easier than SACE, whereas only one subject found SACE to be easier.

The differences between the first and second test cannot be explained by a learning effect of the first test, since all the subjects had participated in other studies and were used to ACE. In addition, ME did not change, which confirms in another way that the observed differences were not based on an improvement in skills. However, these results once more show the importance of a counterbalanced design for a study in which two or more tests are compared.

In conclusion, during maximal exercise the physiological responses were not significantly different between AACE and SACE. The ME did not appear to be different between the two types of exercise at higher \( W \), however ME showed a decrease at lower \( W \) most likely due to a flywheel-mass effect, which was more pronounced during SACE than during AACE.

Acknowledgement The authors gratefully acknowledge the support of Lode (Groningen, The Netherlands) by providing the arm ergometer and the technical assistance of Mr. A.C.A. Vissers.

References