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ENERGY EXPENDITURE AND HEART RATE IN DRIVING A WHEEL-CHAIR ERGOMETER

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ABSTRACT. Twenty young healthy females have been studied, driving a wheel-chair ergometer and an arm ergometer to determine the mechanical efficiency and the heart rate response. Technical details about the wheel-chair ergometer with variable settings are given. The results show that the mechanical efficiency in driving a wheel-chair is rather low, around 7–8 per cent, and may thus give a relatively high load on the circulatory system. The placement of the rim wheel influences the efficiency and heart rate only slightly. The mechanical efficiency was somewhat higher when the rim wheels were in the posterior position. The lowest heart rate in relation to the O_2 uptake was with the rim wheels in anterior, low position and similar to that during exercise with the arm ergometer.

In Gothenburg, several research teams are trying to analyse the factors which are of significance in connection with the design of wheel-chairs and which affect the possibilities of wheel-chair-bound persons to use a wheel-chair. As a step in these investigations, the research teams started in 1968 to perform physiological studies in which the mechanical efficiency and heart rate response were determined at different work loads and size and position of the rim wheels. For this purpose, the investigators constructed a special test wheel-chair in which the position of the wheels and their size could be changed and in which the wheel-chair work was varied through various loads. For the purpose of comparison, work was also performed on an arm ergometer.

The main questions to be investigated were:

1. The mechanical efficiency in driving a wheel-chair ergometer?
2. The influence of the work load on the mechanical efficiency?
3. The influence of the position of the wheels on the mechanical efficiency?
4. Oxygen uptake and heart rate in driving a wheel-chair ergometer?

The test wheel-chair

The investigation was carried out using a test wheel-chair consisting of a seat unit and a driving unit. The seat unit is constructed so that the angle of the seat in the horizontal plane as well as the inclination of the back support in relation to the seat can be adjusted as required. The distance between the seat and the foot supports can be adjusted to the height of the person tested to ensure sufficient support in driving the wheel-chair (cf. Fig. 1).

The driving unit consists of wheel-chair wheels with driving rims. The distance between the driving rims can be varied, i.e. it can be adjusted to the sitting width required by the wheel-chair-bound subject (cf. Fig. 2). The seat unit and the driving unit can be adjusted to each other so that the wheels can be placed at any height in relation to the seat and at any distance from the back support.

The two driving wheels are connected to a flywheel with a circumference of 163 cm and of the type used in von Döbeln's bicycle ergometer. The flywheel brake works on a friction basis (Fig. 3). The test equipment has been calibrated by the Department of Machine Elements at Chalmers Institute of Technology, Gothenburg.

This construction of the test wheel-chair eliminated the sources of error which can be caused by course instability in driving a wheel-chair. Only

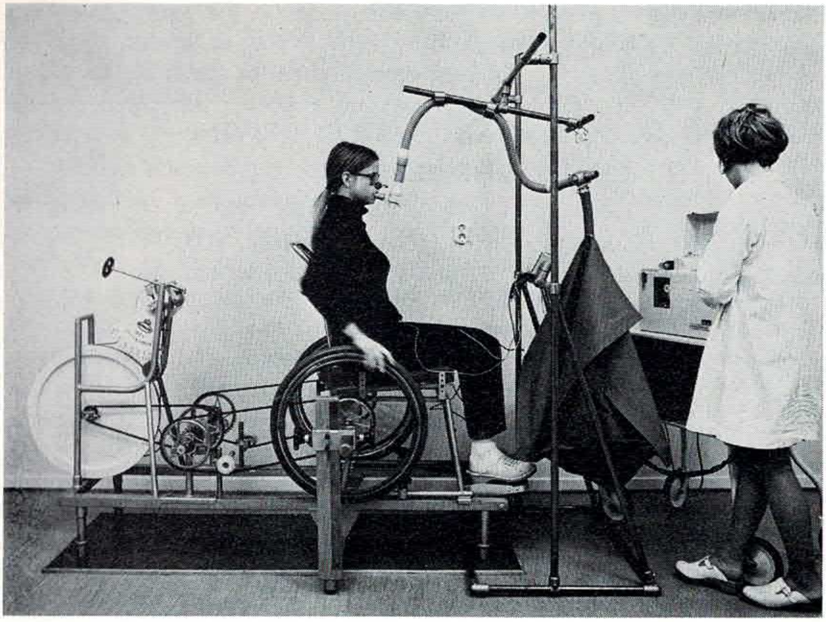

Fig. 1. Experimental set up. The angle of the seat, the inclination of the back support and the distance between the seat and the foot supports can be individually adjusted.

factors which are directly related to the driving function will be determined.

Bicycle ergometer

In order to make possible a comparison with the wheel-chair work, the subjects tested also had to perform cranking on an ergometer for arm exercises, constructed by O. Höök several years ago and used among others by Stenberg et al. (5, 6).

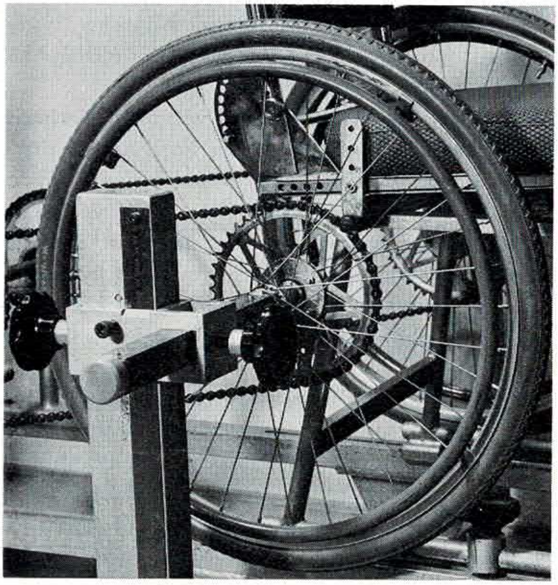

Fig. 2. The seat unit and the driving unit can be adjusted to each other. The wheels can thus be placed at variable height in relation to the seat and at variable distance from the back support.

TEST PERSONS

The primary objective of the investigation was to study the load involved in wheel-chair work and how different constructions of the wheel-chair affected the performance of the wheel-chair-bound subject. It was therefore important to eliminate the sources of error which could be caused by physiological and other factors in the subjects tested and which could change the test conditions, e.g. reduced vital capacity, partial paralyses or instability. Therefore, only persons who were not handicapped were used in the investigations. Twenty healthy female students of physiotherapy took part in the investigation. The mean age of the test persons was 22.4 ± 1.69; the body height 168.3 ± 4.69 cm and the body weight 57.9 ± 4.58 kg. None of the test persons had any previous experience in wheel-chair driving when they took part in the preliminary experiments.

The registration of heart rate and oxygen uptake

The heart rate was calculated on the basis of ECG-recordings. The analyses of the expired air were made after the air had been collected in

Douglas bags for between 3 and 6 min at each work load. The volume of gas was measured in a dry gasometer and the analyses of the oxygen and carbondioxide was performed by means of the micro-Scholander technique.

The mechanical efficiency was calculated according to the formula:

$$\frac{\text{external work load} \times 100}{(\dot{V}_{O_2} \text{ at exercise} - \dot{V}_{O_2} \text{ at rest})\ 4.9 \times 427}$$

where the external work load was expressed in kpm/min and $\dot{V}_{O_2}$ in l/min.

The oxygen uptake at rest was calculated according to Carpenter. The caloric equivalent of oxygen was assumed to be 4.9 kcal per liter oxygen.

Conventional statistical methods and a 5% significance level were used.

Test conditions

In the main investigation, all 20 test persons had to carry out the different work steps in four work positions. In each work position, there were two loads. Thus, for each test person 8 different recordings were obtained. The four work positions were:

1. The rim wheels of the test chair in a posterior position and at a high level, approximately corresponding to the position of the wheels in the traditional rear-wheel-operated wheel-chair.
2. The rim wheels in an anterior position but at the same height as under 1 above.
3. The rim wheels in the same anterior position as under 2 above, but at such a height that the upper edge of the wheel was on the same level as the upper surface of the seat.
4. The arm ergometer positioned so that the crank case was at the same height as the shoulders of the test person.

During the test chair experiments, the distance between the wheel hubs at the anterior and posterior positions was 35 cm. As for the high position, the height of the wheels was adjusted so that the distance between the test person's shoulder joint and the height of the rim wheel was related to the shoulder width of the test person. The distance between the two rim wheels was unchanged during all experiments.

During the wheel-chair work, the rim wheels were loaded with 0.5 kp and 1.0 kp, respectively.

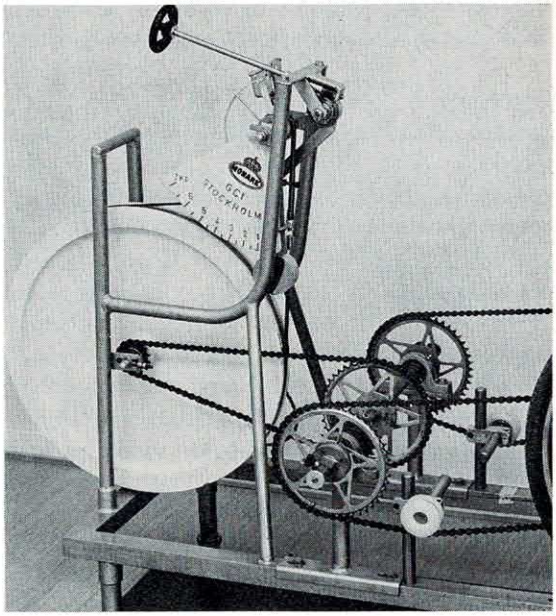

Fig. 3. The driving wheels are connected to a fly-wheel of the type used in von Döbeln's bicycle ergometer.

The test persons had to do 20–30 revolutions/min which gives an average speed of 2.5–3 km/hour. The work load was about 65 kpm/min or 110 kpm/min, respectively (10 and 18 Watt, respectively). On the arm ergometer, they did 50 revolutions/min. The work load was such that the work amounted to about 150 kpm/min and 300 kpm/min, respectively (25 and 50 Watt, respectively).

Each work step was carried out for 6 min.

RESULTS

Table 1 shows the means and standard deviations for the results from the different exercise tests.

At the lowest work load in each type of exercise (Work load I = 65 kpm/min), the mechanical efficiency was significantly higher with the posterior, high wheels than with the anterior high wheels (8.1% as compared with 6.8%). The mechanical efficiency in cranking the arm ergometer was more than twice that for wheel-chair driving. Oxygen uptake and heart rate did not differ significantly between the different positions in wheel-chair driving. It tended to be slightly lower at the chosen work load (150 kpm/min) cranking, but the oxygen pulse that is the amount of oxygen

Table I. *Physiological data on 20 healthy test persons driving a wheel chair and cranking an arm ergometer*

Test situation	Workload (kpm/min)	O_2-uptake STPD (l/min)	Ventilation BTPS (l/min)	RQ	Heart rate (stroke/min)	O_2-pulse (ml/stroke)	Mechanical efficiency (%)
Wheel chair							
Wheel in anterior position, high level	66.1±1.0	0.67±0.015	22.0±1.0	0.98±0.02	127±3.6	5.3±0.2	6.8±0.2
Wheel in anterior position, low level	64.6±1.2	0.67±0.020	20.6±1.0	0.94±0.02	123±3.1	5.5±0.2	6.8±0.2
Wheel in posterior position, high level	67.5±0.8	0.61±0.013	18.6±0.7	0.94±0.02	123±3.8	5.0±0.2	8.1±0.4
Wheel chair							
Wheel in anterior position, high level	109.1±1.8	0.87±0.021	27.4±1.6	0.95±0.01	143±3.9	6.1±0.2	7.9±0.2
Wheel in anterior position, low level	107.1±2.1	0.83±0.021	24.9±1.3	0.91±0.02	137±3.5	6.1±0.2	8.2±0.2
Wheel in posterior position, high level	110.8±1.7	0.80±0.019	25.6±0.9	0.97±0.02	145±3.9	5.6±0.2	8.9±0.2
Arm ergometer	150	0.62±0.018	19.2±0.8	0.95±0.01	116±3.4	5.4±0.2	17.7±0.6
	300	1.03±0.018	32.6±1.0	1.01±0.01	157±3.4	6.6±0.1	17.5±0.4

transported by each heart beat did not differ significantly between the four procedures.

At the higer work load (Work load II = 110 kpm/min), the mechanical efficiency was also higher with the wheels in the posterior position than in both anterior positions (8.9% compared with 8.2% and 7.9%). In all three procedures in wheel-chair driving the mechanical efficiency was higher at work load II than at work load I. At work load II, the mechanical efficiency at cranking was also more than twice the efficiency at wheel-chair driving. There was no significant difference in the mechanical efficiency for cranking between work loads I and II. The oxygen pulse did not differ significantly between the wheel-chair driving procedures. It was significantly higher when cranking at 300 kpm/min, where the oxygen uptake also was somewhat larger than at the work loads chosen for wheel-chair driving.

The heart rate in relation to the oxygen uptake is fairly similar in driving a wheel-chair with the wheel in the anterior position and cranking an arm ergometer. Wheel-chair driving with the wheels in the posterior position gave higher heart rate in relation to oxygen uptake, although the oxygen pulse did not appear to be significantly different.

The ventilation in relation to the oxygen uptake was similar for wheel-chair driving and cranking the arm ergometer although the ventilation was somewhat lower in relation to the oxygen uptake at wheel-chair driving with low wheels in the anterior position, resulting in a significantly lower RQ than during the other procedures.

DISCUSSION

The efficiency in driving wheel-chairs

In the present study, the mechanical efficiency in driving wheel-chairs was about 8% (7.9–8.9) when the effective work load was about 15–20 W (110 kpm/min). With a work load of about 10 Watts (65 kpm/min) the efficiency was lower (6.8–8.1%).

The mechanical efficiency in cranking an arm ergometer with an effective work load of about 25 W (150 kpm/min) was 18.6%.

The present study clearly demonstrates that the mechanical efficiency is considerable lower in driving a wheel-chair ergometer than in cranking an arm ergometer. The range for the mechanical efficiency fell close to the values reported for level driving by Voigt, Berendes & Hildebrandt (7) with the wheel-chair on a tread-mill and other experimental set ups. At a speed of 4 km/hour these authors found a mechanical efficiency of 7.7%. The authors also reported about the same difference between cranking and wheel-chair driving as in the present study.

Thus, our conclusions would be that wheel-chair driving in relation to other exercises involving about the same muscle mass consumes a rather high total amount of energy.

It is of interest to correlate the efficiency of driving a wheel-chair with walking. The mechanical efficiency for leg work on a bicycle ergometer is about 23% for young females (9). In normal walking, the efficiency was calculated to about 27% by Grandjean (1). Thus, the results show that driving a wheel-chair is a rather uneconomical way to move.

In our investigation, two different loads were used on the wheel-chair ergometer. At the lower load (work at 65 kpm/min) the mechanical efficiency was about 7% and at the upper load (work at 110 kpm/min) 8%. Voigt et al. have also found a corresponding difference. At an even greater load, they obtained a mechanical efficiency of almost 13–15%. Such a load, however, is very rare in ordinary wheel-chair work.

Heart rate and oxygen uptake in driving a wheel-chair

The heart rate at a wheel-chair load of about 65 kpm/min (10 W) averaged about 125 beats/min and at a load of 110 kpm/min about 140 beats/min. The oxygen pulse was 5.3 and 5.9 beats/ml, respectively. These results agree with the ones found by Voigt et al. (7). These authors also point out that these results indicate that wheel-chair work involves a considerable strain on the cardiovascular system compared with ordinary walking.

In our investigation we have demonstrated a fairly similar relationship between heart rate and oxygen uptake for wheel-chair driving and exercising an arm ergometer. Our investigations show that it is possible to use the relationship between heart rate and oxygen uptake obtained on an arm ergometer to estimate the energy expenditure from heart rate recordings during wheel-chair driving.

Our results are in agreement with the general findings for leg excercises (2). Hildebrandt et al. (3, 4), on the other hand, found that the heart rate response was similar in the two working situations when related to the effective (external) work load. This would mean that the heart rate in relation to the oxygen uptake was lower in wheel-chair driving than in cranking.

The influence of the position of the rim wheels on the mechanical efficiency and on the circulation

Three different wheel positions were used in the investigation: one with posterior position and two with the wheels in the anterior position at varying heights. The mechanical efficiency was 8.1% with posterior wheels and 6.8% with anterior wheels at a load of 65 kpm/min. The same finding was made when the work load was 110 kpm/min. The investigation thus shows that the mechanical efficiency is somewhat higher when the wheels are in the posterior position.

From the metabolic point of view, it seems that placing the wheels in a posterior position is somewhat better than the anterior position. Our observation is also in accordance with the findings of Hildebrandt et al. (3).

From the circulatory point of view, however, our study may indicate a less favourable response with the wheels in the posterior position. We found a somewhat higher heart rate in relation to the O_2-uptake with the wheels in the posterior than in the anterior position. The lowest heart rate in relation to the O_2-uptake was found when the wheels were in anterior, low position.

It must be remembered, however, that in answering the question of the placement of the wheels, other factors than the metabolic and circulatoric ones must be taken into consideration. Such factors are e.g. the maneuvreability of the wheel-chair, the possibility to move into and out of the chair, degree and type of possible paralyses, especially in the arm and shoulder region. The use of the wheel-chair, e.g. transportation, work chair, rest chair, also effects the choice.

Our physiological observations—as well as those of Voight & Bahn (8) and Hildebrandt et al. (4) have been obtained in laboratory situations where the driving of the wheel-chair was going on with a constant speed over a considerable period of time. This has been the only way to get a measurable response but there are several differences compared with normal wheel-chair driving, including that the normal driving is of a more interval type, and often involves several accelerative phases.

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