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Original Article

Submaximal physical strain and peak performance in handcycling *versus* handrim wheelchair propulsion

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Study design: Experimental study in subjects with paraplegia and nondisabled subjects.
Objective: To compare submaximal physical strain and peak performance in handcycling and handrim wheelchair propulsion in wheelchair-dependent and nondisabled control subjects
Setting: Amsterdam, The Netherlands.
Methods: Nine male subjects with paraplegia and 10 nondisabled male subjects performed two exercise tests on a motor-driven treadmill using a handrim wheelchair and attach-unit handcycle system. The exercise protocol consisted of two 4-min submaximal exercise bouts at 25 and 35 W, followed by 1-min exercise bouts with increasing power output until exhaustion.
Results: Analysis of variance for repeated measures showed a significantly lower oxygen uptake (VO_2), ventilation (Ve), heart rate (HR), rate of perceived exertion and a higher gross efficiency for handcycling at 35 W in both subject groups, while no significant differences were found at 25 W. Peak power output and peak VO_2, Ve and HR were significantly higher during handcycling in both groups. The differences between handcycling and wheelchair propulsion were the same in subjects with paraplegia and the nondisabled subjects.
Conclusions: Handcycling induces significantly less strain at a moderate submaximal level of 35 W, and shows noticeably higher maximal exercise responses than wheelchair propulsion, which is consistent in subjects with paraplegia and nondisabled controls. These results demonstrate that handcycling is beneficial for mobility in daily life of wheelchair users.

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Keywords: handcycling; gross mechanical efficiency; heart rate; oxygen uptake; paraplegia; nondisabled subjects; power output

Introduction

Over the past years, handcycling has become increasingly popular among wheelchair users in the Netherlands for sport and recreational purposes. This increased popularity may be explained by the ability of the handcyclist to perform outdoors over longer distances, for a longer duration and at relatively higher speeds compared to wheelchair propulsion, without experiencing excessive fatigue or discomfort. Already in the 1980s research on alternative propelling wheeling modes revealed that wheelchairs with armcrank or lever propulsion systems were more efficient and showed a lower energy cost during submaximal exercise than the conventional handrim wheelchair.[1–7] The gross efficiency of handrim wheelchair propulsion was found to be as low as 2–10%,[8] while values for armcrank exercise were around 15%.[9] Based on these findings, several authors recommended armcrank systems as an alternative and less straining propelling mode for wheelchair ambulation.[1–4]

However, until recently, armcrank-based wheelchairs (ie handcycles) were not widely available and therefore rarely used.[9] Currently, two modern types of handcycles are being used in the Netherlands: the solid frame handcycle, which is mainly utilized in sports, and the attach-unit handcycle, which can be attached to a daily-use handrim wheelchair to create a three-wheeled handcycle. The attach-unit handcycle generally has a variable gear system and is popular for recreational purposes and for daily outdoor use, such as transportation to work.

The majority of studies on armcrank systems were performed on stationary armcrank ergometers, while only few studies investigated the physiological responses

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and efficiency of ambulatory armcrank wheelchairs (handcycles).[3,4,10,11] Armcranking on an ergometer however differs from actual handcycling with respect to steering requirements because the steering and propulsion mechanism are both connected to the front wheel. In addition, most modern handcycles are equipped with synchronous (parallel) cranks, while the majority of former armcrank studies, as well as the older handcycle studies, were performed with asynchronous cranks.

Already in 1986, Woude *et al*[4] found significantly lower values for submaximal physical strain for a fixed armcrank tricycle compared to handrim wheelchair propulsion on a motor-driven treadmill. In addition, three field studies using fixed frame[3,11] or attach-unit handcycles[10] confirmed these findings, showing a reduced physical strain and an increased endurance time and average speed in comparison to handrim propulsion. However, in these studies, only asynchronous armcrank systems were investigated and most studies used rather old-fashioned fixed-frame handcycles, which can hardly be compared to the modern lightweight attach-unit handcycle.

Maximal performance of wheelchair users has also extensively been investigated using armcrank ergometry. As expected from the higher efficiencies in submaximal armcrank exercise, comparison with handrim wheelchair propulsion shows consistently higher values for power output in armcrank exercise,[2,6,7,12,13] but most authors reported no significant differences with respect to peak oxygen uptake.[2,5–7,12,14] Again, it is unknown whether results of armcrank ergometer exercise can be generalized towards handcycling. To our knowledge, no studies have been performed in which maximal performance of handcycling was compared to handrim wheelchair propulsion.

The purpose of the current study was to investigate the differences in submaximal physical strain and peak performance in handcycling and handrim wheelchair propulsion, and to compare these results between subjects with paraplegia and non-disabled controls.

Methods

Subjects

Nine men with paraplegia (PP) and 10 non-disabled men (ND) participated in this study after signing an informed consent. PP were significantly older (36.3 ± 7.8 years) than ND (24.2 ± 2.4 years, $P < 0.001$). There were no differences in length (PP: 1.79 ± 0.10 m; ND: 1.83 ± 0.04 m, $P = 0.244$) and body mass (PP: 74.3 ± 10.5 kg; ND: 76.4 ± 8.5 kg; $P = 0.641$) between groups. Table 1 shows the injury and training characteristics of the subjects with paraplegia. PP were experienced in both handcycle use and in handrim wheelchair propulsion. ND had no experience in both propulsion systems. In addition to their handcycling practice, PP reported the following sport activities: wheelchair basketball ($n = 3$), wheelchair tennis ($n = 3$), fitness ($n = 2$), wheeling ($n = 1$), skiing ($n = 1$), swimming ($n = 1$) and archery ($n = 1$).

Handcycles and wheelchairs

PP performed the tests in their own rigid-frame wheelchairs and attach-unit handcycles. In Figure 1 a typical example of an attach-unit handcycle system is given. The characteristics of the handcycles and wheelchairs are listed in Table 2. All handcycles were equipped with a synchronous crank system and a 7 or 21 gear system. The handcycles differed with respect to wheel diameter (ranging from 16 to 26 inch) and crank type. Five handcycles were provided with U-shape cranks (‘Bullhorn’) and four handcycles had a normal T-shape crank.

The ND performed the handcycle test in a commercially available attach-unit handcycle system (Tracker, Double Performance, Gouda, The Netherlands), which was attached to the wheelchair (RGK, Double Performance) as a ‘third wheel’. The handcycle was provided with seven gears and a synchronous crank system with a T-shape crank. Wheel size of the attach unit was 16 inch. The handrim wheelchair exercise test was performed in the same wheelchair, without the attach unit, and

Table 1 Individual lesion characteristics and training status of the subjects with paraplegia

Subject	*Lesion level*	*Time since injury (years)*	*Duration of handcycle use (years)*	*Handcycle training (h/week)*	*Total training (h/week)*
1	Th7*	5	4	3	4
2	Th12/L1*	7	3	7	14
3	L3	7	6	7	11
4	Th6	9	4	5.5	15.5
5	Th11	7	6	2	4
6	Th12*	31	3	1	3
7	Th11	1	0.5	3	6.5
8	Polio	41	16	6	6
9	Th6/Th7*	12	1	0	3.5
	Mean ± SD	13.3 ± 13.5	4.8 ± 4.6	3.8 ± 2.6	7.5 ± 4.8

*Motor incomplete lesion

with a normal axle position. For some nondisabled subjects, it was necessary to make some adjustments in seating position by changing seat or back rest cushioning.

Design

To compare submaximal physiological responses and maximal performance between handcycling and wheelchair propulsion in both groups, all subjects performed two exercise tests on a motor-driven treadmill ($1.25\,\mathrm{m} \times 3.\ 0\,\mathrm{m}$, Enraf Nonius, Delft, The Netherlands), with 1 week between tests. One test was performed using the handcycle system, and the other test was performed using the handrim wheelchair. The order of the tests was counter balanced. Prior to testing, subjects were asked to refrain from smoking, coffee and alcohol consumption for at least 2 h before testing. The study was approved by the Medical Ethical Committee of the University Hospital of the Vrije Universiteit Amsterdam.

Protocol

The exercise test consisted of two 4-min submaximal exercise bouts at 25 and 35 W, followed by a continuous maximal exercise test in which power output was increased each minute by 10 W. There was a rest period of 3 min after the 25 and 35 W exercise bouts. In order to become accustomed to propelling the handcycle and wheelchair on the treadmill, a 5-min warming-up period preceded the test. In addition, the nondisabled subjects performed a short familiarization session (on a linoleum floor) in both the handcycle and handrim wheelchair beforehand.

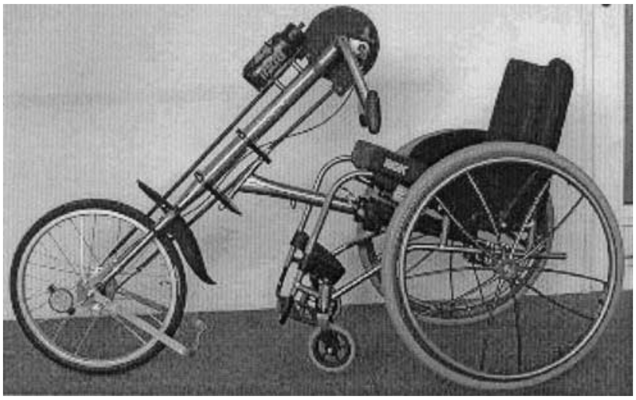

Figure 1 Example of a handcycle with attach unit

In the handrim wheelchair test, velocity of the belt was adjusted according to the preference of the subjects, but within the range of 3–5 km/h. Cycle frequency during handcycling was also adjusted to the preferred frequency of the subjects within the range of 50–70 rpm.

Measurements and apparatus

External power output (PO in W) was calculated from total external resistance (= rolling resistance (Froll) plus extra resistance (Fadd) that was applied to the back of the handcycle or wheelchair by means of a pulley system) and belt velocity (V in m/s) according to

$$\mathrm{PO\ (W)} = [\mathrm{Froll\ (N)} + \mathrm{Fadd\ (N)}] \cdot V\ \mathrm{(m/s)}$$

Froll was determined in two separate drag tests in both the handcycle and handrim wheelchair, as described by Woude *et al.*[4] In this test, rolling resistance (Froll in N) is measured with a force transducer that is connected horizontally with a rope to the front of the wheelchair or handcycle, while the subject is seated passively in the wheelchair or handcycle, and belt velocity is set at testing velocity. To set PO at 25 or 35 W, and to increase the external resistance with 10 W each minute, an extra weight (Fadd in N) was added through the pulley system that was attached to the back of the wheelchair or handcycle.

Oxygen uptake (VO_2, l/min), carbon dioxide output (VCO_2, l/min) and ventilation (Ve, l/min) were continuously measured using a computerized gas analysing system (Oxycon Alpha, Jaeger, Bunnik, The Netherlands). Heart rate (HR, beats/min) was measured with a heart rate monitor (Polar Sporttester, Polar Electro Inc.,

Table 2 Characteristics of the wheelchairs and handcycles of the subjects with paraplegia

Subject	*Wheelchair*	*Handcycle*	*Wheel diameter wheelchair/ handcycle (inch)*	*Rear wheel wheelchair*	*Gears*	*Crank type*
1	RGK[1]	Tracker (DP)	24/16	M	7	T
2	Kuschall[2]	Speedy B26 (OB)	24/26	A	21	T
3	RGK	Tracker (DP)	24/20	M	7	U
4	Topend[3]	Tracker (DP)	24/24	A	7	U
5	Kuschall	Sharky 2 (OB)	24/24	A	21	T
6	Kuschall	Speedy B26 (OB)	24/26	A	21	T
7	Kuschall	Tracker 24 (OB)	25/24	A	7	U
8	RGK	Tracker sport (DP)	24/20	A	7	U
9	RGK	Tracker (DP)	24/20	A	7	U

T: T-crank; U: U-crank; M: massif; A: air; DP: Double Performance, Gouda, The Netherlands; OB: Otto Bock, Duderstadt, Germany; 1: RGK, Staffordshire, England; 2: Kuschall, Invacare AG, Eden, The Netherlands; 3: TopEnd. Invacare AG, Eden, The Netherlands

Kempele, Finland), using a 5 s interval. Respiratory exchange ratio (RER) was calculated as the ratio between VCO_2 and VO_2. Gross mechanical efficiency (GE) was defined as

$$GE = (PO/En)100(\%)$$

where energy expenditure (En) was obtained from VO_2 and associated RER, by using the standard conversion table for the energy equivalent of oxygen.[15] Mean submaximal values for VO_2, Ve, HR and GE were calculated over the last minute of the two 4-min submaximal exercise bouts. Peak VO_2 and Ve were defined as the highest value over 30 s, and peak HR as the highest value measured over 5 s. Peak power output was the power output of the last exercise bout, maintained for at least 30 s. Rate of perceived exertion (RPE) was asked for directly after the submaximal exercise bouts, using the revised 10-point Borg scale. To determine cycle frequency of handcycling and wheelchair propulsion, 2D video recordings (50 Hz, Panasonic, Japan) were made during the whole test.

Statistics

Differences in subject characteristics between groups were tested using an independent Student's *t*-test. An ANOVA for repeated measures with a 2 × 2 × 2 design (handcycle versus wheelchair, 25 versus 35 W, between subject factor: PP versus ND) was applied to determine the effect of propelling mode, power output and subject group on the submaximal exercise responses. To determine the effect of propelling mode and subject group on peak performance, an ANOVA for repeated measures with a 2 × 2 design (handcycle versus wheelchair, between subject factor: PP versus ND) was used. Level of significance was set at $P<0.05$ for all statistical testing.

Results

Protocol

The resulting mean values for preferred velocity, freely chosen cycle frequency and rolling resistance of the wheelchair and handcycle test are shown in Table 3. Velocity of the wheelchair test was significantly higher in PP. Velocity of the handcycle test, cycle frequency and rolling resistance showed no differences between groups.

Submaximal exercise

The results for the physiological responses and RPE for the two propulsion modes, two subjects groups and the two levels of power output are shown in Figure 2. The results of the ANOVA analysis are shown in Table 4.

HR data were lost in one subject (of ND) due to technical problems. Three subjects in ND and one in PP had a RER that exceeded 1.0 in the 35 W condition in the handrim wheelchair. Nevertheless, we included these results in the analysis to avoid losing subjects or conditions. Mean values for RER in wheelchair propulsion were 0.94 ± 0.04 and 0.91 ± 0.05 at 25 W, and 1.00 ± 0.07 and 0.94 ± 0.05 at 35 W, for ND and PP, respectively. RER values in handcycling were 0.96 ± 0.08 and 0.93 ± 0.08 at 25 W, and 0.95 ± 0.05 and 0.95 ± 0.07 at 35 W, in ND and PP, respectively.

There was a significant main effect of propelling mode on all parameters except HR, showing a lower VO_2, Ve and RPE during handcycling (see Figure 2 and Table 4). GE was significantly higher in handcycling compared to wheelchair propulsion (at 35 W: 12.2 versus 10.2% for PP, and 9.8 versus 8.2% for ND).

However, there was also a significant interaction effect between propelling mode and power output for all physiological parameters, indicating that the differences in physiological responses between handcycling and wheelchair propulsion are larger at the 35 W compared to 25 W condition. A separate analysis at each power output condition showed that GE, VO_2, Ve and HR were significantly different at 35 W ($P<0.001$), but not at 25 W. The mean *difference* in GE between handcycling and wheelchair propulsion was 0.7 and 0.1% at 25 W, compared to 1.7 and 1.0% at 35 W, for PP and ND, respectively. In contrast to the physiological responses, RPE showed no significant interaction effect for propelling mode and power output, which means that the *difference* in subjective strain between handcycling and wheelchair propulsion was the same at the two power output conditions.

With the exception of HR, there was a significant main effect of group, showing lower physiological responses and RPE, and a higher GE, in PP compared to ND. However, there was no interaction effect between propelling mode, power output and group. This implies that the combined effect of propelling mode and power output was similar in PP and ND.

Table 3 Velocity, cycle frequency and rolling resistance (Froll) (mean ± SD) of the handcycle and wheelchair test for subjects with paraplegia (PP) and nondisabled subjects (ND)

	Velocity Wheelchair (km/h)	*Velocity Handcycle (km/h)*	*Cycle frequency Wheelchair (cycle/min)*	*Cycle frequency Handcycle (cycle/min)*	*Froll Wheelchair (N)*	*Froll Handcycle (N)*
PP (*n* = 9)	4.5 ± 0.53	6.1 ± 0.73	57.1 ± 6.98	64.3 ± 6.16	10.9 ± 3.9	11.6 ± 4.9
ND (*n* = 10)	3.9 ± 0.53	6.4 ± 0.39	53.8 ± 11.23	64.4 ± 3.81	8.9 ± 1.0	8.8 ± 2.1
P-value	0.020	0.226	0.454	0.950	0.168	0.138

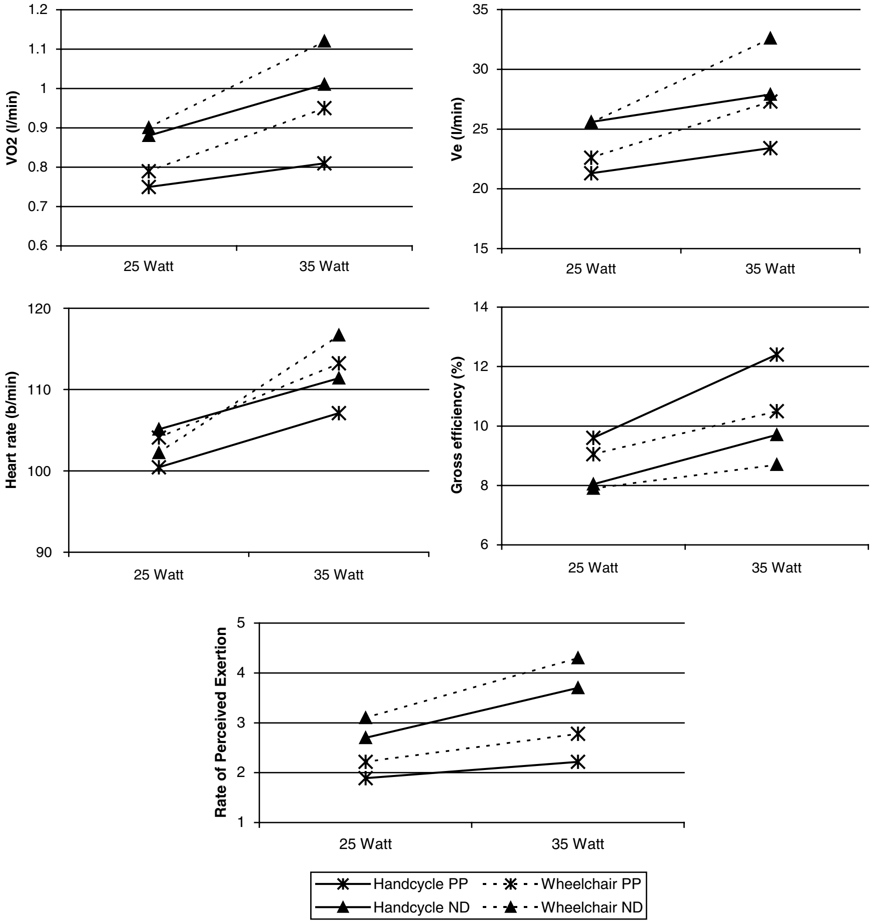

Figure 2 Submaximal oxygen uptake (VO_2), ventilation (Ve), heart rate, gross efficiency and rate of perceived exertion in subjects with paraplegia (PP) and nondisabled subjects (ND)

Table 4 Submaximal results of ANOVA for repeated measures for factors propelling mode (handcycle versus wheelchair), power output (25 versus 35 W) and group (between subject factor, ND versus PP) and the relevant interaction effects

	Mode		*Power output*		*Group*		*Mode × power output*		*Mode × group*		*Mode × power output × group*	
	F-value	*P-value*	*F-value*	*P-value*	*F-value*	*P-value*	*F-value*	*P-value*	*F-value*	*P-value*	*F-value*	*P-value*
GE	18.94	0.000	217.92	0.000	13.24	0.002	11.50	0.003	2.65	0.122	0.08	0.780
VO_2	11.80	0.003	117.47	0.000	18.57	0.000	10.77	0.004	0.01	0.934	0.61	0.446
Ve	9.82	0.006	56.02	0.000	9.33	0.007	11.42	0.004	0.01	0.909	1.63	0.218
HR	2.28	0.150	71.96	0.000	0.14	0.717	12.13	0.003	0.86	0.367	3.50	0.080
RPE	6.13	0.024	46.60	0.000	15.20	0.001	2.01	0.175	0.021	0.886	0.006	0.941

Peak exercise responses

The results of the maximal exercise tests are shown in Table 5. HRpeak recordings were lost in two subjects of the ND group. There was a significant main effect of propelling mode on POpeak, VO_2peak and HRpeak, showing higher values in handcycling. Propelling mode had no effect on RER and Vepeak (just below the level of significance: $P = 0.05$). There was no significant main effect of group, which indicates that peak values were not significantly different between PP and ND. No interaction effect was found for propelling mode and group for any of the parameters. This finding denotes that *differences* in the peak values between the handcycle and handrim wheelchair test were the same for ND and PP.

Discussion

The results of this study showed that submaximal physiological responses are lower, and gross efficiency

Table 5 Mean (±SD) values for peak power output (POpeak), peak oxygen uptake (VO_2peak), peak heart rate (HRpeak), ventilation (Vepeak) and RER (mean±SD), and results of ANOVA for repeated measures for factors propelling mode (wheelchair versus handcycle), group (PP versus ND) and the interaction effect

	PO_{peak} *(W)*	VO_{2peak} *(l/min)*	Ve_{peak} *(l/min)*	HR_{peak} *(beats/min)*	*RER*
PP	$n=9$	$n=9$	$n=9$	$n=9$	$n=9$
Handcycle	117.2±31.9	1.88±0.44	82.8±24.1	188.0±6.5	1.30±0.06
Wheelchair	92.8±16.4	1.79±0.28	80.3+24.6	182.4±8.6	1.31±0.08
ND	$n=10$	$n=10$	$n=10$	$n=8$	$n=10$
Handcycle	111.0±19.0	2.20±0.29	97.2±23.7	184.3±12.7	1.28±0.06
Wheelchair	79.0±13.5	2.01±0.36	80.9±19.9	178.4±16.7	1.27±0.07
Propelling mode					
F-value	38.98	6.86	4.44	8.51	0.00
P-value	0.000	0.018	0.050	0.011	0.988
Group					
F-value	1.35	3.26	0.60	0.55	2.21
P-value	0.261	0.089	0.448	0.469	0.156
Propelling mode × group					
F-value	0.70	0.92	2.41	0.007	0.40
P-value	0.415	0.351	0.139	0.936	0.538

is higher, in handcycling compared to handrim wheelchair propulsion. This effect appeared to be dependent on the level of power output. Peak power output and peak oxygen uptake showed higher values in handcycling than in wheelchair propulsion. Although subjects with paraplegia showed a higher efficiency and lower physiological responses than nondisabled controls, the effect of propelling mode on submaximal and peak responses was the same in both groups.

Submaximal exercise

Former studies comparing submaximal armcrank exercise with wheelchair propulsion also found lower physiological responses in armcrank exercise on an ergometer[1,6,13] or an armcrank-driven wheelchair.[4] Also the results of experimentally less controlled field studies, comparing oxygen uptake between handcycles and handrim wheelchairs, revealed favourable results for the handcycle.[3,10,11]

Values for gross efficiency are in agreement with former studies in handcycling,[4] but are lower than values observed in armcrank exercise.[16,17] Also the difference in efficiency between handcycling and wheelchair propulsion (1.7 and 1.0% at 35 W in the PP and ND group, respectively) was comparable to former findings in handcycling,[4] but were smaller than reported before in armcrank exercise.[16,17] Apparently, the type of armcrank system (handcycle versus ergometer) that was used to perform the test affects the gross efficiency. This is not surprising since energy losses due to increased friction of the front wheel and steering requirements in handcycling are expected to lower the efficiency. However, the gross efficiency of handcycling may also be underestimated slightly by the method that was applied to measure the power output (see discussion below).

Most of the former studies compared the propelling modes at the same absolute power output, as is the case in the present study. Sawka *et al*[1] compared armcrank and handrim wheelchair exercise at a predetermined submaximal VO_2 and reported a lower cardiac output and rate pressure product (heart rate times systolic blood pressure) in armcrank exercise. Also more recently, two studies reported a higher gross efficiency for armcrank compared to wheelchair ergometry at a percentage of the mode-specific VO_2peak.[16,17] These results emphasize that armcrank exercise is inherently less stressful to the cardiovascular system than handrim wheelchair propulsion.

Several possible explanations have been proposed to explain the higher efficiency in armcrank exercise compared to handrim propulsion. These explanations are mostly based on the more complex and discontinuous character of the arm movement in handrim propulsion.[1,9,13,16] The low efficiency of the handrim system has been attributed to the relative small muscle mass and higher static force component involved in handrim propulsion, and extra energy loss due to acceleration and deceleration of the arms in the recovery phase.[1,9,13,16] Although some authors suggested that the higher efficiency of asynchronous limb movements may also explain the higher efficiency of armcranking,[1] recent studies declined this by showing no differences in efficiency between asynchronous and synchronous armcrank exercise.[18] In contrast to the alternating continuous movement in armcrank exercise, force application in handrim propulsion is intermittent, resulting in a smaller period of force application, and a greater isometric muscle work for trunk stabilization and gripping of the rims. Armcrank exercise is a less complex dynamic movement using agonists and antagonists in an alternating order, which increases dynamic muscle activity and benefits the circulation of the arms. In addition, the ineffective manner of force application in handrim propulsion,[19] caused by the mechanical constraint of the handrim, may also explain the lower efficiency of the handrim system.

Apart from the physiological advantages, armcrank propulsion may also be more beneficial to the musculoskeletal system of the arms. The unfavourable deviations of the wrist joint that occur in handrim propulsion are suggested to play a role in the high incidence of injuries of the musculo-skeletal system of the arms in wheelchair users. Whether handcycling reduces the risk for such injuries remains to be investigated.

Maximal exercise

The higher maximal power output in handcycling is in accordance with other studies comparing peak armcrank exercise with wheelchair ergometry in wheelchair-dependent[2,12,7,13] and nondisabled men[16] and women.[6] To our knowledge, peak power output during handcycling was not investigated yet. Peak power output was 24 (26%) and 32 W (40%) higher in the handcycle test compared to the handrim wheelchair test, for subjects with paraplegia and nondisabled controls, respectively. The higher maximal power output can in part be attributed to the higher efficiency of handcycling.

More surprisingly, VO_2peak was in the present study also higher in handcycling than in handrim wheelchair propulsion. The question whether the mode of exercise has an effect on the maximal cardio-respiratory responses of exercise testing in disabled persons has been addressed in several previous studies. In contrast to the results of the present study, most authors reported no differences in maximal oxygen uptake between armcrank and wheelchair exercise.[2,5–7,12,14] Gass and Camp[20] reported even a lower VO_2peak in armcrank exercise compared to wheelchair ergometry. In agreement with our report, Hintzy *et al*[16] reported higher values for VO_2peak in armcrank ergometry, and Wicks *et al*[12] found higher values for armcrank exercise in women only. The higher VO_2peak in handcycling may be related to the more dynamic character of the handcycle movement, which may increase circulation and postpone local muscular fatigue in the arms, enabling the subject to maintain a higher exercise level. From a practical point of view, the higher VO_2peak during handcycling shows that subjects were able to maintain higher exercise levels and that exercise testing should be mode specific.

Protocol

Rolling resistance of the wheelchair and handcycle was determined in a drag test that was developed by Woude *et al*.[4] Although this test has proven to be valid for estimating rolling resistance in wheelchair propulsion, the additional internal resistance of the chain and gear system of the handcycle is not taken into account in this test. It is therefore expected that power output, which is calculated as the product of the total resistance (= rolling resistance plus additional resistance applied by the pulley system) and belt velocity, may be slightly underestimated for the handcycle. For the results of the present study, this implies that the differences in energy expenditure and efficiency between handcycling and handrim wheelchair propulsion may be even greater than reported here. Nevertheless, the magnitude of internal resistance of different handcycle systems remains to be investigated. All subjects with paraplegia used their own handcycle and wheelchair to perform the tests. Although this has introduced variation as a result of differences in handcycle systems and wheelchairs, we preferred this set-up because the subjects with paraplegia were trained on and accustomed to their own wheelchair or handcycle. The nondisabled subjects performed the tests in a standard handcycle and wheelchair since these subjects were equally inexperienced on both systems.

It was preferred to test subjects in the handrim wheelchair at a convenient (preferred) velocity rather than keeping conditions constant because subject groups differed in wheelchair experience and training. Testing all subjects at the same velocity could have introduced coordinative problems in the inexperienced (ND) group, whereas a lower velocity could have led to unreal velocities for the trained (PP) group. The fact that cycle frequency of the handrim wheelchair was the same for both subject groups while the (self-chosen) velocity was higher for subjects with paraplegia, indicates that they were higher skilled on the wheelchair task, and supports the choice for self-chosen velocity.

Group effect

The lower submaximal VO_2 and higher gross efficiency of subjects with paraplegia can be explained by differences in experience of both handcycling and wheelchair propulsion, and by physiological differences caused by the impairment. Although both effects cannot be distinguished in this study, it is expected that the lower submaximal responses and higher gross efficiency in subjects with paraplegia are the result of more experience (skills) and a better training status of the arm muscles.

Although absolute submaximal responses differed between subjects with paraplegia and nondisabled subjects, the lack of differences between both groups with respect to the (combined) effect of propulsion system and power output is relevant for the interpretation of previous studies in nondisabled subjects. The choice for nondisabled subjects is usually based on methodological considerations: to create a homogenous group of subjects with respect to skills, training status and physiological responses. However, generalization towards wheelchair users with different impairments remains the subject of debate. The results of this study show that the effect of propelling mode and power output applies to both groups.

Three nondisabled subjects and one subject with paraplegia showed RER values that exceeded 1.0 during wheelchair propulsion at 35 W. Apparently, this condition was too hard to meet the criteria for submaximal exercise. However, including these values in the analysis may have led to a small overestimation of the gross efficiency for wheelchair propulsion, and accordingly to an underestimation of the *differences* between handcycling and wheelchair propulsion.

In contrast to the other parameters, the heart rate values were not different between the groups. This may result from the usually higher heart rate in paraplegics, compared to controls. The lack of muscle pump in the legs decreases the venous return to the heart, which causes the heart rate to increase in order to maintain the cardiac output.[21] The higher heart rate for subjects with paraplegia apparently compensated the differences between the groups.

Practical implications

The higher physical strain of handrim wheelchair propulsion may limit mobility of wheelchair users, especially when propelling over longer distances and when it concerns persons with low physical abilities, such as individuals with tetraplegia or older individuals. The present findings indicate that at a moderate power output of 35 W, handcycling is more efficient and less straining than handrim wheelchair propulsion, and is therefore preferred for ambulation over longer distances. The lower energy cost of handcycling may postpone fatigue and enables the handcyclist to propel at a higher velocity or maintain exercise over longer distances than in the handrim wheelchair. Handcycling is therefore expected to be also useful in rehabilitation or sports for improving physical fitness of wheelchair users, and in particular for those with low physical abilities.

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