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ORIGINAL REPORT

METABOLIC COST AND MECHANICAL EFFICIENCY OF A NOVEL HANDLE-BASED DEVICE FOR WHEELCHAIR PROPULSION

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Objective: To investigate differences in metabolic cost and gross mechanical efficiency of a novel handle-based wheelchair propulsion device and to compare its performance with conventional push-rim propulsion.
Design: Double-group comparative study between 2 different propulsion methods.
Participants: Eight paraplegic individuals and 10 non-disabled persons.
Methods: Participants performed the same exercise using a push-rim device and the novel handle-based device on a wheelchair-based test rig. The exercise consisted of a combined submaximal and maximal test. Power output, oxygen uptake, ventilation, respiratory exchange ratio and heart rate were recorded continuously during the tests. Analysis of variance was performed to determine the effects of group, mode and on power output.
Results: Submaximal exercise resulted in a higher efficiency for the novel device and significant main effects of propulsion mode on all investigated parameters, except heart rate. On the respiratory exchange ratio, a significant interaction effect was found for both mode and group. The maximal exercise resulted in a higher peak power output and lower peak heart rate during propulsion using the handle-based device. A significant main effect on mode for mean peak power output, ventilation and heart rate was also observed.
Conclusion: Wheelchair propulsion using the handle-based device resulted in lower physical responses and higher mechanical efficiency, suggesting that this novel design may be well suited for indoor use, thereby offering an attractive alternative to push-rim wheelchairs.

Key words: wheelchair; upper extremity; metabolism; rehabilitation; activities of daily living.

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LAY ABSTRACT

The push-rim is the preferred mode of propulsion for more than 90% of all self-propelled wheelchair users, even though it is the least efficient. Furthermore, push-rim propulsion is highly strenuous for the musculoskeletal system and often leads to severe upper limb injuries. Alternative modes of manual wheelchair propulsion are available (e.g. arm-crank propulsion (handbikes) and lever-propulsion) but most of these are bulky, heavy and mostly suitable for outdoor use. The aim of the current study was to investigate differences in metabolic cost and mechanical efficiency for a novel handle-based and ergonomically optimized device and to compare its performance with conventional push-rim propulsion. Eight paraplegic subjects and 10 non-disabled controls performed exercises at different power resistances. The results show that the performance of the handle-based device is below that of the handbike, but that it out-performs lever-propelled and push-rim wheelchairs, suggesting that this novel design is more suited to indoor use and may therefore be an attractive alternative to push-rims for activities of daily living.

Manual wheelchair propulsion is the most favoured mode of propulsion adopted by a large percentage of wheelchair users: More than 90% of all self-propelled wheelchairs are ambulated via push-rims by using the arms to apply force (1). Push-rim propulsion (PRP) is energetically inefficient, highly strenuous for the musculoskeletal system, and associated with high cardiopulmonary effort (1–6). Furthermore, PRP often leads to severe upper limb injuries, especially at the shoulder and wrist joints (7–9).

Gross mechanical efficiency (GME), defined as the percentage ratio between external power output (PO) and energy expenditure (En) is often used to benchmark mechanical efficiency of manual wheelchair propulsion. Oxygen uptake per unit time (VO_2), heart rate (HR) and propulsion frequency are the parameters typically used to assess the metabolic cost and efficiency of wheelchair propulsion (10, 11). Due to high physical strain during PRP most of the expended energy dissipates, for example in heat loss, the rest contributes to propulsion. Thus, GME is typically measured to be in the range 2–10% and rarely exceeds 10% (1, 12). Despite similar power output conditions, reported values for GME vary widely, which may be explained by individual differences in the physical ability of wheelchair users and by the influence of propulsion speed and surface properties (1, 12).

Alternative modes of manual wheelchair propulsion have been tested, the most common alternatives being lever-propulsion and arm-crank propulsion. Compared with PRP, both of these methods increase the joint range of motion in the upper limb, particularly at the wrist and shoulder joints (1, 5, 11). Lever-propelled devices were mainly designed to reduce repetitive strain injuries (1, 6, 11, 13). In general, GME in lever-propelled devices is reported to be higher compared with PRP, and wheelchair users report greater overall satisfaction with lever-propelled wheelchairs, but previous designs often do not consider user anthropometrics (1, 4, 13). Handbikes are the most popular arm-crank-propelled alternative to PRP for manual wheelchair propulsion, with values for GME reported to range from 8% to 15% (5, 14–17). Due to a higher energetic efficiency and lower strain on the cardiorespiratory system, several investigators have recommended the handbike as an alternative to push-rim wheelchair propulsion for outdoor use (5, 14–16, 18–20). Although the efficiency of alternative devices for wheelchair propulsion is often higher, most of these are limited to outdoor use because they are bulky, heavier, less convenient for transferring, and less manoeuvrable (1, 5, 15).

Our group has developed a novel handle-based propulsion (HBP) mechanism for conventional wheelchairs as a compact indoor alternative to PRP (21). With an ergonomically optimized propulsion movement and the ability to continuously apply propulsive force, HBP offers a continuous cyclic motion at ergonomic joint ranges of motion and has been shown to decrease joint excursions and maximum joint torques during propulsion (21–23). The aim of the current study was to investigate differences in metabolic cost and mechanical efficiency for this novel HBP device compared with the standard PRP. Data were collected from paraplegic subjects, who are long-term wheelchair users, and non-disabled individuals, to further investigate effects on propulsion mode and efficiency and to determine how the results differ for long-term wheelchair users who have trained muscle coordination patterns for PRP and may also have changed relative muscle strengths. Each group used an instrumented wheelchair-based test rig operating at constant speed and different resistance levels. It was hypothesized that, under similar conditions, HPB would be more energetically efficient and less strenuous than conventional PRP, due to continuous force application.

METHODS

Subjects

Eight right-handed paraplegic (PP) subjects were recruited from the spinal cord injury (SCI) rehabilitation centre “Weisser Hof”, in Klosterneuburg, Austria. PP subjects were eligible for the study if they had an SCI level between L1 and T12, no permanent medication and no history of upper-limb injury.

The 10 non-disabled (ND) students (controls), who participated in this study (Table I), were eligible if they were right-handed, had no history of upper limb injury, and no permanent medication. The significantly younger ND group had no experience with PRP, whereas all PP subjects were long-term wheelchair users with a minimum experience of 3 years. The sample size was defined by the maximum number of PP subjects available, rather than based on statistical considerations. All subjects provided informed consent and approval for the study was obtained from the responsible federal state ethics committee Ethikkommission für das Land Niederösterreich (NÖ Ethikkommission), Landhausplatz 1, Haus 15B, 3109 St. Pölten, Austria (GS1-EK-3/149-2018).

Experimental set-up

All subjects were tested using a previously developed test rig (24) (Fig. 1) consisting of a lightweight manual wheelchair (Eurochair Vario,XXL, Meyra Orthopedics, Germany, Kalletal) with 0.42 m seat depth, 0.50 m seat width, and an adjusted seat height of 0.51m. The wheelchair was mounted on a square tube frame to avoid direct contact between the wheels and the floor

Table I. Characteristics of paraplegic (PP) and non-disabled (ND) subjects

Subject (sex)	Age, years	Weight, kg	Height, cm	BMI, kg/m²	SCI level
PP					
1 (f)	54	62	179	19	T11–12
2 (m)	27	80	188	23	T6–7
3 (f)	43	75	160	29	T10–L1
4 (f)	56	63	158	25	T12–L1
5 (m)	52	65	175	21	T12–L2
6 (m)	45	85	192	23	T11–L1
7 (m)	21	62	185	18	T8–9
8 (m)	51	93	173	31	T12–L2
Mean (SD)	44 (12)	73 (11)	176 (12)	24 (5)	
ND					
1 (f)	23	70	165	26	
2 (f)	21	63	170	22	
3 (m)	21	92	185	27	
4 (f)	21	54	162	21	
5 (m)	23	58	181	18	
6 (m)	24	70	169	25	
7 (f)	26	58	175	19	
8 (m)	36	99	181	30	
9 (f)	35	64	176	21	
10 (m)	19	61	187	17	
Mean (SD)	25 (5)	69 (14)	175 (8)	22 (4)	

SD: standard deviation; SCI: spinal cord injury; BMI: body mass index; m: male; f: female.

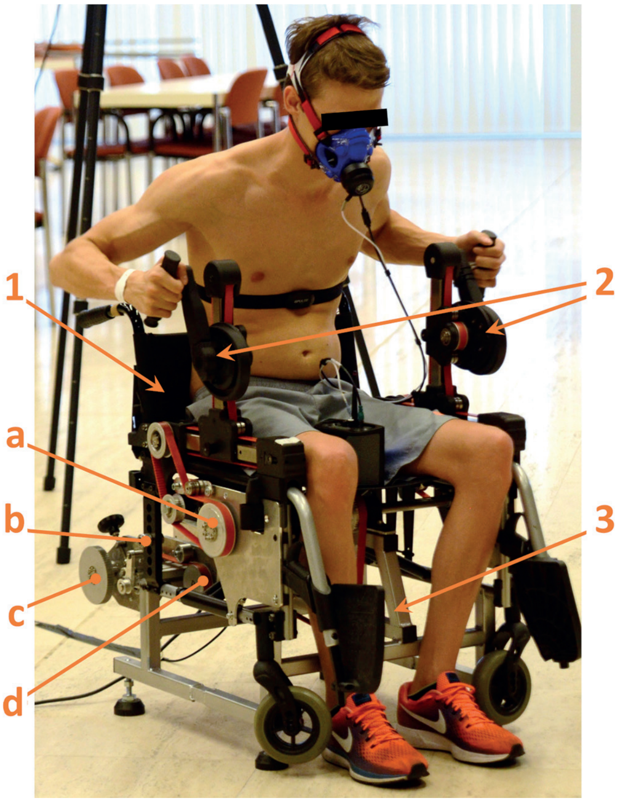

Fig. 1. Wheelchair-based test rig with mounted handle-based propulsion (HBP) devices: 1: wheelchair; 2: HBP devices; 3: mounting frame; a: front attachment pulley; b: back wheel hub; c: rear attachment pulley; d: resistance power unit.

and to facilitate mounting of different hand-driven propulsion devices. A controlled brushless motor combined with gearbox and flywheel mounted under the seat of the wheelchair provided torques that simulated resistances during wheelchair propulsion. Timing belts were used to promote a slip-free power transmission to the wheels and front connection points. For this study, the test rig operated in maximal power mode, where the resistance progressively increased according to a predefined resistance increment and time interval. In all trials, visual feedback allowed the participant to maintain the target speed during propulsion.

Propulsion devices

For PRP, conventional 24-inch (609,6 mm) diameter push-rim wheels were mounted on the test rig whereas for crank propulsion 2 HBP devices (25) were utilized instead of the armrests (Figs 1 and 2). Each HBP device consisted of a rotating crank on which a handle was mounted. During propulsion, a sliding guide changed the length of the crank during each rotation, allowing the handle to follow the optimized propulsion path (22). The gear ratio of the HBP device was fixed at 1.2.

Test protocol

All participants performed the same exercise with both PRP and HBP consecutively on the same day, with a least 10 min rest between exercises. The subjects were instructed to refrain from smoking for at least 2 h before testing, to not consume any caffeinated or alcoholic beverages, and to void their bladder shortly before the measurements. To control the influence of fatigue on the effect of mode, subjects were assigned to alternately start with PRP or HBP, i.e. even-numbered subjects started the exercises with PRP, and odd-numbered subjects with HBP. To ensure familiarization with all equipment, subjects participated in a short preliminary session in which both HBP and PRP were used with low resistance (5 W). The exercise test consisted of 2 parts: a 2-min submaximal exercise test performed at 15 W constant resistance power, followed by a maximal exercise

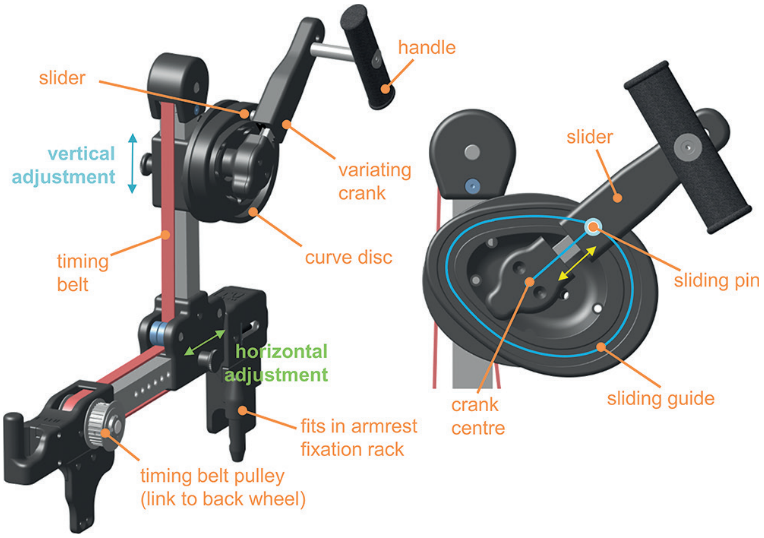

Fig. 2. Handle-based propulsion (HBP) device and its components. The horizontal and vertical positions of the crank centre can be adjusted according to the user's body anthropometry.

test in which the resistance power was increased by 5 W every minute. Both parts were performed consecutively with no break in between. The test was terminated when either 55 W of resistance power was reached or when the subject reached physical exhaustion and could not continue. To simulate a common propulsion speed, subjects were asked to maintain a propulsion speed in the range 1.20–1.65 m/s for both HBP and PRP, similar to the range of speeds used in previous studies (14, 26, 18). Sixteen of the 18 subjects completed all exercises. One female participant was excluded due to problems with balance during testing, while 1 male ND subject was excluded because the required speed range was not achieved during the experiments.

Data collection

Actual resistance power (PO, W) and linear velocity (v, m/s) were measured concurrently during each test. In addition, oxygen uptake (VO_2, mL/min), carbon dioxide output (VCO_2, mL/min) and ventilation (Ve, mL/min) were measured continuously using a wearable metabolic measurement system (Cosmed K5, Cosmed GmbH, Fridolfing, Germany), while heart rate (HR, beats/min) was measured using a mobile chest heart rate monitor (Polar H10 ANT+, Polar Electro Inc., Kempele, Finland). The spirometry system was matched to the subjects with respect to ethnicity (Caucasian) and calibrated with a reference gas after each subject. Linear velocity (v, m/s) and cadence (RPM, 1/min) were obtained from the test rig control and were also measured using cadence sensors (B00JLMS848 ANT+/B00JLMRXCQ ANT+, Garmin Ltd., Schaffhausen, Switzerland) mounted on both HPB cranks and the back wheels.

Data analysis

Respiratory exchange ratio (RER, –) was calculated as the ratio between carbon dioxide output (VCO_2, mL/min) and oxygen uptake (VO_2, mL/min). Metabolic expenditure (En, W) was obtained from VO_2 and RER using the equation reported by Garby et al. (27):

$$En = \left(4.94 \cdot RER + 16.04\right) \cdot \frac{VO2}{60}\left[\mathrm{W}\right] \qquad (1)$$

Gross mechanical efficiency (*GME,* %) was defined as the ratio between the actual resistance power (PO, W) provided by the test rig and energy expenditure (En) of the subject:

$$GME = \frac{PO}{En} \cdot 100\left[\%\right] \qquad (2)$$

Weight-specific oxygen uptake (VO_2/kg, mL/min/kg) was obtained from oxygen uptake (VO_2) and the weight of the subject. Oxygen uptake per unit distance travelled (VO_2 efficiency, mL/kg/m) was found from the measured VO_2/kg and the corresponding mean linear velocity (v).

Mean submaximal values of VO_2, VO_2/kg, VO_2 efficiency, VCO_2, Ve, RER, HR and GME for both HBP and PRP were measured during the last minute of the 2-min (15 W) submaximal exercise. During the maximal power exercise, the subject's mean values of VO_2, VO_2/kg, VO_2 efficiency, VCO_2, Ve, RER, HR and GME were calculated for both propulsion modes at each achieved resistance level to provide a comparison between the 2 propulsion modes. Peak values of VO_2, VO_2/kg, VO_2 efficiency, VCO_2, Ve, RER were found by calculating the highest mean value of each variable measured over a time-interval of 30 s, whereas the peak value of HR was defined as the highest mean value of HR measured over an interval of 10 s. Peak power output was defined as the highest resistance level achieved during the maximal exercise, which was maintained for at least 30 s.

Statistical analysis

All analyses were performed using SPSS (IBM SPSS Statistics 26, SPSS, Inc., Chicago, IL, USA). Mean and peak values were calculated using descriptive statistics. An analysis of variance (ANOVA) with a 2 × 2 design (mode: HBP, PRP; group: ND, PP) was used to determine the effect of propulsion mode and subject group on submaximal exercise responses. An ANOVA with a 2 × 4 × 2 design (mode: HBP, PRP; power output: 15, 20, 25 and 35 W; group: ND, PP) was also used to evaluate the interaction between propulsion mode, power output, and subject group for the resistance levels achieved by all subjects during the maximal exercise tests. The effect of propulsion mode and subject group on peak performance was found using an ANOVA with a 2 × 2 design (mode: HBP, PRP; group: ND, PP). Statistical significance for all tests was set at $p < 0.05$ with no adjustment for multiple comparisons.

RESULTS

Submaximal exercise

There was a significant main effect of propulsion mode on all parameters except HR, indicating lower VO_2, VO_2/kg, Ve, RER and higher GME and VO_2 efficiency during HBP (Table II). Mean values of VO_2 efficiency during HBP were 0.07 mL/kg/m lower for ND and 0.03 mL/kg/m lower for PP. Similarly, mean GME was 1.03% higher for ND and 2.75% higher for PP during HBP compared with PRP. There was a significant main effect of group on all parameters except Ve and HR, indicating that the mean values were significantly different between ND and PP. HR in both subject groups

Table II. Mean (standard deviation) submaximal values measured for handle-based propulsion (HBP) and push-rim propulsion (PRP) at 15W constant resistance for the paraplegic (PP) and non-disabled (ND) groups

	GME, %	VO_2 efficiency, mL/kg/m	VO_2/kg, mL/min/kg	VO_2, mL/min	Ve, L/min	RER –	HR, bpm
ND, *n*	9	9	9	9	9	9	9
HBP	7.59 (1.37)	0.12 (0.02)	9.94 (2.28)	620.04 (106.17)	20.42 (4.24)	0.83 (0.06)	110.00 (17.84)
PRP	6.56 (1.73)	0.19 (0.06)	10.94 (2.82)	738.93 (198.00)	24.74 (7.23)	0.87 (0.06)	108.80 (21.26)
PP, *n*	7	7	7	7	7	7	7
HBP	9.9 1(1.41)	0.08 (0.02)	6.72 (1.71)	486.72 (68.19)	17.35 (2.41)	0.68 (0.05)	96.10 (11.14)
PRP	7.16 (1.22)	0.11 (0.02)	8.89 (1.97)	649.70 (104.18)	23.76 (4.87)	0.84 (0.05)	111.33 (11.59)
Mode							
F-value	13.23	11.38	3.80	8.82	8.60	26.37	1.41
p-value	**0.001**	**0.002**	**0.049**	**0.006**	**0.007**	**<0.001**	0.245
Group							
F-value	7.92	17.68	10.48	5.50	1.22	21.07	0.92
p-value	**0.009**	**<0.001**	**0.003**	**0.026**	0.279	**<0.001**	0.345
Mode × Group							
F-value	2.70	1.52	0.52	0.22	0.33	7.78	1.93
P-value	0.111	0.229	0.478	0.646	0.573	**0.009**	0.176

GME: gross mechanical efficiency; VO_2 efficiency: oxygen uptake per unit distance travelled; VO_2/kg: weight-related oxygen uptake; VO_2: oxygen uptake; Ve: ventilation, RER: respiratory exchange ratio; HR: heart rate; bpm: beats per min. **Bold** values indicate significance ($p<0.05$).

did not show any significant effects. A significant interaction effect was found for mode and group on RER, indicating that the changes in RER during the HBP and PRP tests were different between PP and ND.

Maximal exercise

Maximum power resistance levels were different between PP and ND. Both groups achieved higher power levels for HBP than PRP. Values for GME were

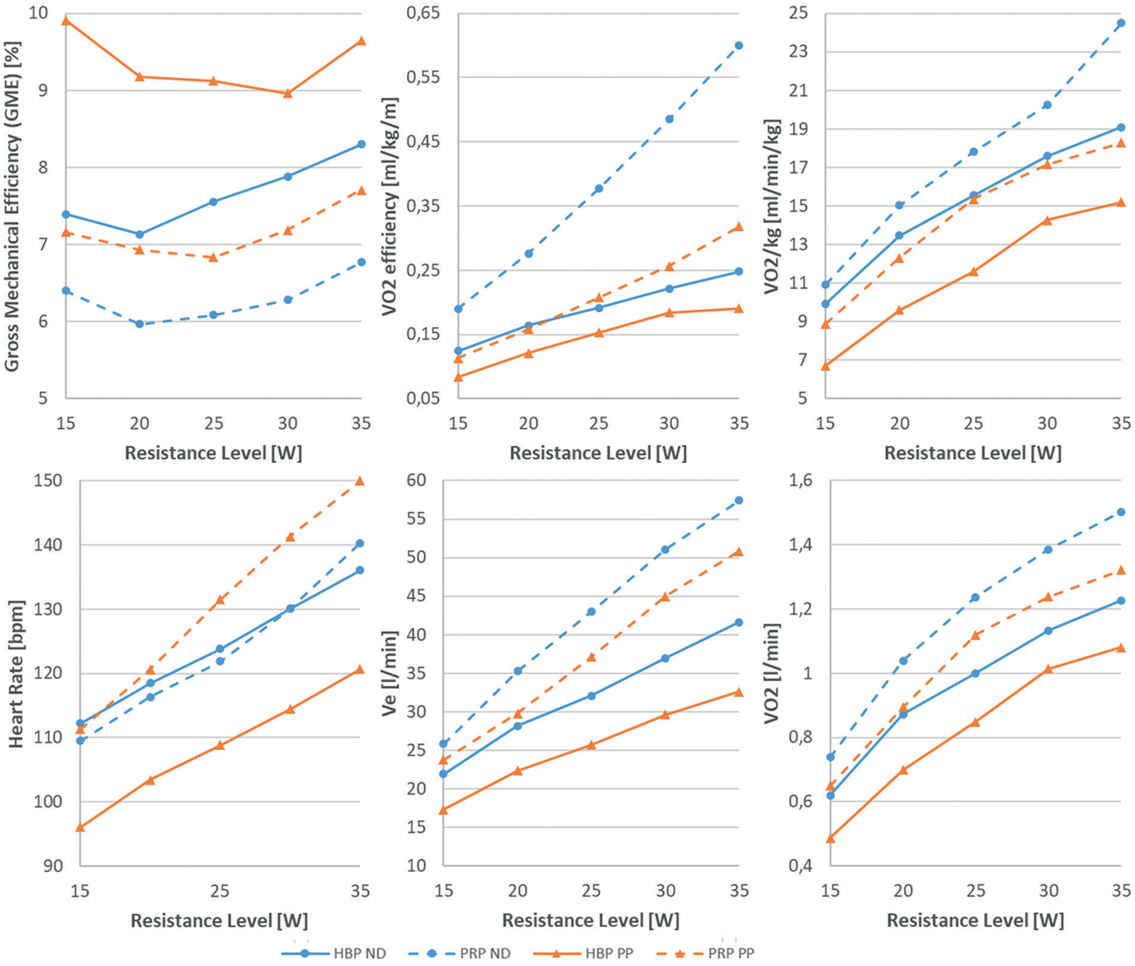

Fig. 3. Dependence of gross mechanical efficiency (GME), oxygen uptake per unit distance travelled (VO_2 efficiency), weight-related oxygen uptake (VO_2/kg), heart rate (HR), ventilation (Ve) and oxygen uptake (VO_2) on resistance level measured for paraplegic (PP) subjects (*orange lines*, *triangle markers*) and non-disabled (ND) subjects (*blue lines*, *circle markers*) during handle-based propulsion (HBP) (*solid line*) and push-rim propulsion (PRP) (*dashed lines*).

Table III. Analysis of variance (ANOVA) results obtained for the maximal exercise tests (15–35 W) for the paraplegic (PP) and non-disabled (ND) subject groups

	Mode		Group		Mode group		Mode PO		Mode group PO	
	F-value	*p*-value	F-value	*p*-value	F-value	*p*-value	F-value	*p*-value	F-value	*p*-value
GME	68.410	**< 0.001**	31.782	**< 0.001**	3.127	0.079	0.049	0.995	0.386	0.818
VO_2 efficiency	37.194	**< 0.001**	26.753	**< 0.001**	9.375	**0.003**	2.584	**0.040**	0.676	0.610
VO_2/kg	24.859	**< 0.001**	39.676	**< 0.001**	0.098	0.755	0.668	0.615	0.400	0.808
VO_2	56.350	**< 0.001**	24.057	**< 0.001**	0.023	0.879	0.641	0.634	0.083	0.988
Ve	53.835	**< 0.001**	10.167	**0.002**	0.049	0.825	1.968	0.103	0.042	0.997
HR	18.579	**< 0.001**	1.955	0.164	12.999	**< 0.001**	0.626	0.645	0.048	0.996
En	62.511	**< 0.001**	30.945	**< 0.001**	0.000	0.995	0.839	0.503	0.098	0.983

GME: gross mechanical efficiency; VO_2 efficiency: oxygen uptake per distance travelled; *VO_2/kg*: weight related oxygen uptake; VO_2: oxygen uptake; Ve: ventilation; HR: heart rate; EN: energy expenditure; PO: power output (resistance level). **Bold** values indicate significance ($p < 0.05$).

higher in HBP than PRP for both the PP and ND groups (Fig. 3). Furthermore, HR increased as resistance level increased. A significant main effect of propulsion mode for all parameters in HBP was evident, indicating higher GME and VO_2 efficiency and lower VO_2/kg, VO_2, Ve, HR and En (Table III). HR was significantly higher for the PP group during PRP, whereas no significant differences were found with respect to propulsion mode for the ND group. Except for HR, there was also a significant main effect of group for all outcome variables, indicating higher GME and VO_2 efficiency and lower physiological responses for the PP group compared with the ND group. A significant interaction effect between propulsion mode and group was found for VO_2 efficiency and HR, suggesting that the differences between HBP and PRP were larger for VO_2 efficiency and smaller for HR in the ND group compared with the PP group. No interaction effects were found between propulsion mode, group, and power output, indicating that the combined effect of power output and propulsion mode was similar for both groups. In both groups, mean RER values were lower for HBP than PRP (Fig. 4). As power resistance increased, RER values were above 1.0 for PRP but remained below 1.0 for HBP, indicating higher physical exhaustion during PRP.

Peak responses

A significant main effect was observed for propulsion mode on $PO_{(peak)}$, $Ve_{(peak)}$ and $HR_{(peak)}$; specifically, power output was higher and Ve and HR were lower for HBP than PRP (Table IV). No main effect was found for propulsion mode on peak oxygen uptake ($VO_2/kg_{(peak)}$, $VO_{2(peak)}$) and $RER_{(peak)}$. There was a significant main effect on group for all parameters except $HR_{(peak)}$. However, no interaction effect was found for propulsion mode and group on any of the outcome variables, as the ND and PP groups showed similar trends in peak values during HBP and PRP.

DISCUSSION

The aim of this study was to measure metabolic cost and mechanical efficiency during wheelchair propulsion using a novel HBP device and to compare these performance indicators against those measured for conventional PRP. The study investigated physiological parameters for both propulsion modes in a combined submaximal

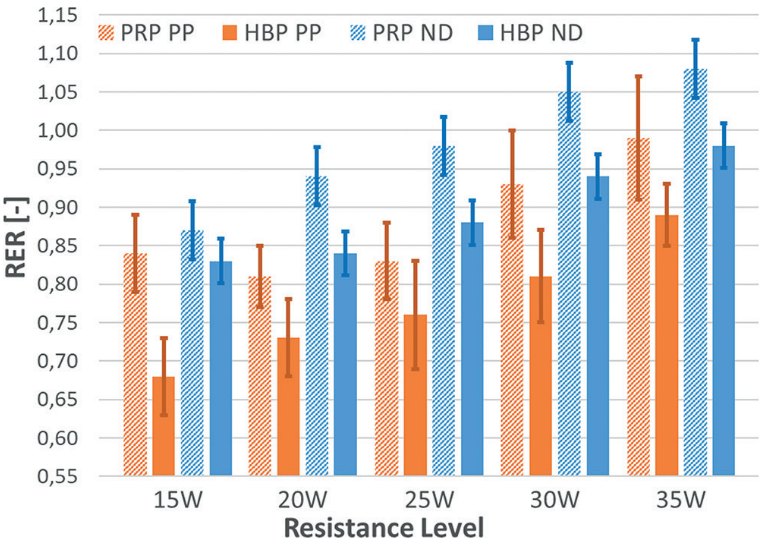

Fig. 4. Mean respiratory exchange ratio (RER) values and standard deviations measured for handle-based propulsion (HBP) (*solid shading*) and push-rim propulsion (PRP) (*diagonal stripes shading*) in paraplegic (PP, *orange*) and non-disabled (ND, *blue*) subjects.

Table IV. Mean values and standard deviations for peak power output ($PO_{(peak)}$), peak weight-related oxygen uptake ($VO_2/kg_{(peak)}$), peak oxygen uptake ($VO_{2(peak)}$), peak ventilation ($Ve_{(peak)}$), peak respiratory exchange ratio ($RER_{(peak)}$) and peak heart rate ($HR_{(peak)}$)

	$PO_{(peak)}$, W	$VO_2/kg_{(peak)}$, mL/min/kg	$VO_{2(peak)}$, mL/min	$Ve_{(peak)}$, L/min	$RER_{(peak)}$ –	$HR_{(peak)}$, bpm
ND, *n*	9	9	9	9	9	9
HBP	55.56 (7.68)	37.86 (30.70)	1,615.42 (236.50)	59.69 (8.59)	1.09 (0.07)	157.67 (23.01)
PRP	46.67 (6.61)	34.41 (8.85)	1,833.95 (541.13)	77.58 (26.71)	1.15 (0.09)	161.89 (21.12)
PP, *n*	7	7	7	7	7	7
HBP	46.43 (4.76)	19.42 (2.01)	1,351.39 (178.50)	43.17 (7.05)	0.99 (0.06)	134.86 (7.13)
	42.86 (4.88)	25.19 (8.13)	1,541.17 (182.56)	57.79 (9.20)	1.04 (0.07)	158.86 (12.31)
Mode						
F-value	7.78	0.03	2.89	8.20	3.87	4.87
p-value	**0.009**	0.856	0.100	**0.008**	0.059	**0.036**
Group						
F-value	8.38	4.90	5.37	10.23	13.81	4.08
p-value	**0.007**	**0.035**	**0.028**	**0.003**	**0.001**	0.053
Mode × Group						
F-value	1.42	0.54	0.01	0.08	0.02	2.39
p-value	0.244	0.468	0.906	0.776	0.888	0.133

Results of the analysis of variance (ANOVA) for propulsion mode (handle-based propulsion (HBP) vs push-rim propulsion (PRP)), group (ND vs PP) and interaction effects are also shown.

PO: power output; bpm: beats per minute. **Bold** values indicate significance ($p < 0.05$).

and maximal exercise test using both PP and non-disabled (ND) subjects. The results of the submaximal test showed that higher GME and VO_2 efficiency were attained with lower physiological responses during HBP compared with PRP. This effect was also observed during the maximal exercise tests with continuously increasing resistance (i.e. increasing power output).

Furthermore, HBP showed higher peak power output and lower peak heart rate compared with PRP. In all tests, subjects showed significantly higher efficiency and lower physiological responses during HBP compared with PRP. Thus, our hypothesis that HPB is more efficient and less strenuous than conventional PRP was supported.

The results for the submaximal and maximal tests showed higher GME and lower physiological responses with the HBP device, which is consistent with findings from previous studies that have focused on comparing submaximal arm-crank exercise with conventional PRP under similar conditions (2, 14, 28, 29). Our measured values of GME and VO_2 efficiency for PRP are also consistent with data reported previously by others (10, 30). The higher GME and VO_2 efficiency achieved by the PP group compared with the ND control group may be due to their familiarity with PRP as well as better upper-limb muscle conditioning resulting from everyday use of the wheelchair. However, the results of the maximal exercise indicate that the effects of propulsion mode and power output apply to both groups. Previous studies on arm-crank devices report higher peak power output compared with conventional PRP (14, 29). Similar findings were observed during the propulsion mode with HBP, where mean peak power output values were 8.3% higher for the PP group and 19.0% higher for the ND group compared with PRP. Regarding peak oxygen uptake, we found significant differences between the subject groups but no significance was found between HBP and PRP, which is consistent with the results of other studies comparing arm-crank devices with PRP (14, 31–34).

Particularly for subjects with paraplegia, mean heart rates at power levels between 15W and 35W as well as $HR_{(peak)}$ were significantly reduced using the HBP device, which is also supported by lower RER values. This suggests a higher endurance capacity of the paraplegic subjects, which is also reflected in higher mean peak power output values achieved in HBP compared with PRP.

However, comparing the differences in HR values between both subject groups, no statistical significance was found: an observation that has also been reported previously and has been attributed to the normally higher HR in paraplegic persons (14).

Thus, independent of subject group, HBP was shown to achieve higher mechanical efficiencies and lower oxygen uptake at both submaximal and maximal workloads compared with PRP.

Although studies reported in the literature on alternative propulsion devices are not easily compared, the data on efficiency presented here, particularly our measurements of GME and VO_2 efficiency, place the HBP below the performance of the handcycle but above lever-propelled and PRP wheelchairs. Moreover, the current findings indicate that propelling a wheelchair with this novel HBP device is more efficient and less strenuous than propelling a wheelchair with a push-rim. In addition, our previous study (23) showed that the HBP device may lower the probability of upper limb injuries by reducing joint loads and ergonomic joint ranges. To adapt to an individual user's wheelchair, the horizontal and vertical adjustment mechanisms shown in Fig. 2 can be eliminated, leading to an even more compact and lightweight design of the crank mechanism that can also be swivelled for transfers.

Therefore, we consider the novel wheelchair drive to be more suitable for indoor use than, for example, handcycles, making it an attractive alternative to push-rims for activities of daily living.

This study has some limitations. The sample size (PP $n=8$; ND $n=10$) was relatively small. Because force application during wheelchair propulsion is highly individualized, especially for PRP, a larger number of test subjects may influence the findings reported here. In addition, the age difference between the 2 groups may have affected the group comparison, as, in general, younger subjects are more likely to have higher cardiorespiratory fitness. However, it is generally difficult to establish groups of able-bodied and paraplegic subjects that are comparable in terms of cardiorespiratory fitness, as it has been well investigated (35) that paraplegic subjects have lower cardiorespiratory fitness in comparison with able-bodied subjects. In any case, only group comparisons may have been influenced by the age difference, the effects of propulsion mode are not affected.

Another improvement that is recommended for further studies is to make the test rig adjustable in the medial-lateral direction to also account for individual differences in body anthropometry in this dimension.

In conclusion, we found that both subject groups demonstrated significantly higher peak power output, higher mechanical efficiency, and lower physiological responses during HBP compared with PRP. The results indicate that propelling the wheelchair with this novel HBP device is less strenuous and more efficient than conventional push-rim propulsion. Overall, the performance of the HBP was below that of the handbike, but exceeded the performances of the lever-propelled and push-rim wheelchairs.

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