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CLINICAL REPORT

Energy Cost and Locomotive Economy of Handbike and Rowcycle Propulsion by Persons with Spinal Cord Injury

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Abstract—Seven subjects with chronic paralysis due to spinal cord injury completed a series of experiments to 1) determine and compare the metabolic cost of propelling the Handbike and Rowcycle, and 2) evaluate the potential of these upper body–powered devices for improving the cardiorespiratory fitness of persons with lower limb disabilities. Mean intrasubject differences between the Handbike and Rowcycle rides for heart rate, minute ventilation, oxygen uptake, and net locomotive energy cost were small and did not reach statistical significance for any of the ride conditions. Lower net locomotive energy cost (greater economy) during a 5.5 $mi \cdot hr^{-1}$ ride condition predicted vehicle preference in all cases (P=0.008). The range of values for percent peak oxygen uptake suggests that all but one of the subjects were able to utilize either vehicle at an intensity sufficient for improving and maintaining cardiorespiratory fitness without undue fatigue.

Key words: *exertion, oxygen consumption, spinal cord injury, upper body aerobic exercise.*

INTRODUCTION

Exercise training and regular physical activity may improve the health and quality of life of persons with spinal cord injury (SCI) by slowing or reversing physiological degeneration, favorably altering cardiovascular disease and diabetes risk factors, improving psychological status and independence, and allowing the performance of daily activities with less fatigue (1–3). Recently, efforts have been intensified to develop and market exercise devices for persons with lower limb disabilities (4,5). To be useful for the population with lower limb disabilities, the inexperienced operator must be able to use a device without undue fatigue. Excessive metabolic stress is likely to discourage the use of the equipment for exercise that is of adequate intensity and duration to improve and maintain cardiorespiratory fitness (3). In addition, the more skilled and/or fit individual should be able to operate the device at an intensity that is sufficient to promote cardiorespiratory fitness and satisfy recreational objectives.

The present investigation was designed to: 1) determine and compare the metabolic cost, to novice riders, of propelling two upper body–powered vehicles, the Handbike and the Rowcycle, which are suitable for use by persons with lower limb paralysis due to SCI, and 2) evaluate the potential of these devices for improving the cardiorespiratory fitness of these individuals.

METHODS

The Handbike and Rowcycle

The Handbike (**Figure 1a**) is an upper body–powered vehicle which was developed at the Department of Veterans Affairs Rehabilitation Research and Development Center, Palo Alto, CA. It is an extension of an earlier model known

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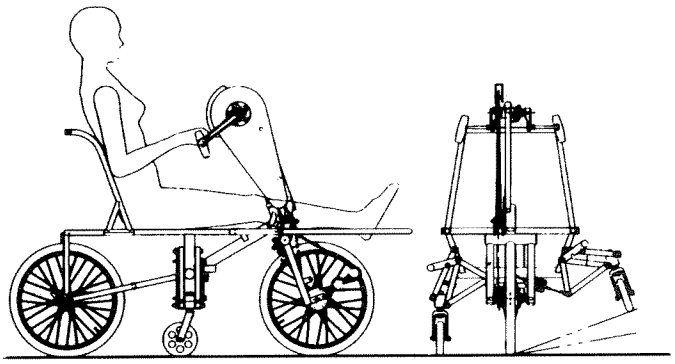

Figure 1a.
The Handbike.

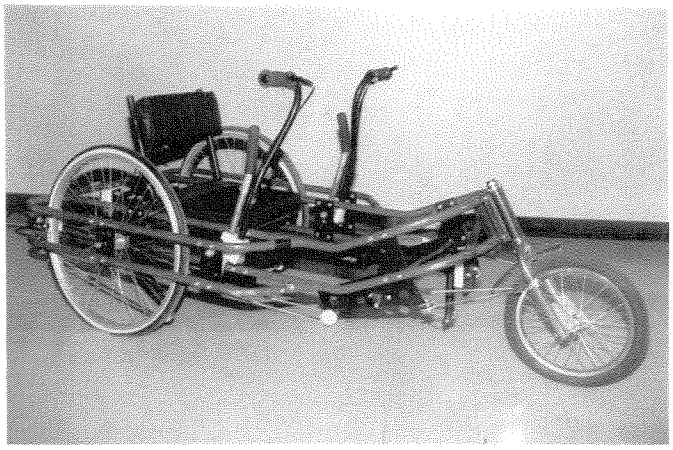

Figure 1b.
The Rowcycle.

as the Para-bike (6–8). The present investigation was conducted as part of a Department of Veterans Affairs Technology Transfer Service evaluation of the Handbike.

The Handbike is powered by a synchronous arm-cranking motion. The moveable crank tower is connected to the front fork which allows steering movements without interruption of cranking. Adjustable side wheels may be kept in contact with the riding surface or lifted so that the vehicle can be balanced on two wheels while riding. In the lifted position, the side wheels will touch the ground at a level that will prevent the rider from tipping over during a sharp turn or after stopping. The gearing system consists of a five-speed Sturmey-Archer hub and a two-speed derailleur which shifts the drivechain from one size hub sprocket to another. The result is 10 possible gearing combinations. Although the inventor suggests the possibility that there is some overlap between gears in the larger and smaller sprockets, he does not specify gear- or drive-ratios (7). The Handbike has an 85 cm wheel base, is 63.5 cm wide with the side wheels in the down position, and weighs 21 kg. It is commercially available from New Dimensions Design, Elmira, OR.

The Rowcycle (**Figure 1b**) used for this study was purchased from Rowcycle Company, Fresno, CA (5,9). It is a three-wheeled vehicle powered by a rowing motion (synchronous or asynchronous). This vehicle was chosen for comparison because it is propelled using an upper body motion that is biomechanically different from that used when riding the Handbike. Steering is accomplished by tilting to the left or right in the seat. The Rowcycle has a three-speed, adjustable leverage transmission which operates by altering the row-handle fulcrum. Gearing, powering, and braking are independent for each side of the Rowcycle. The Rowcycle is 183 cm in length, has a width of 90 cm, and weighs 30 kg.

Subjects

Seven apparently healthy individuals with SCI, six male and one female, participated in this study. Characteristics of the participants are shown in **Table 1**. The study procedures were approved by the Human Subjects Subcommittee of Edward Hines Jr., Department of Veterans Affairs Hospital (Hines VAH). Informed consent was obtained from all subjects as well as a statement from each subject's personal physician giving approval for participation in the study. All subjects were required to have had a physical examination in the 12 months prior to the study and to fill out a Medical History Questionnaire. The Medical History Questionnaire was used in the initial screening of volunteers and to identify contraindications to exercise testing. Data collection was carried out in the Rehabilitation Research and Development (Rehab R&D) Center's Physical Performance Research Laboratory and on the Hines VAH grounds.

Wheelchair Graded Exercise Tests

All subjects were given a maximal wheelchair graded exercise test using the Wheelchair Aerobic Fitness Trainer (WAFT), a wheelchair ergometer developed at the Hines VAH Rehab R&D Center (10–12). A progressive exercise protocol was utilized in which the initial workload was set at 6 watts and increased by ~7 watts every 3 minutes until volitional exhaustion, or until the subject was unable to maintain the workload (12). Testing procedures conformed

Table 1.
Peak values during maximal effort wheelchair ergometry.

Subject	Sex	Age yr	Level of Injury[a]	Body Wt. kg	$\dot{V}O_2$ $L \cdot min^{-1}$	HR $b \cdot min^{-1}$	$\dot{V}_E$ $L \cdot min^{-1}$
1	M	36	T_{12}-L_1[c]	81.0	1.76	200	108.8
2	M	34	T_{5-6}[c]	68.0	1.35	196	65.2
3	M	25	C_{6-7}[inc]	94.8	1.40	120	55.8
4	M	32	T_{5-6}[c]	70.3	1.60	176	56.3
5	M	40	T_{6-7}[c]	59.0	1.11	173	64.7
6	M	29	T_{10-11}[inc]	72.6	2.09	192	93.4
7	F	53	T_7[inc]	48.5	0.80	150	33.3

[a]C = cervical; T = thoracic; L = lumbar; [c] = complete injury, [inc] = imcomplete injury

to guidelines established by the American College of Sports Medicine (13).

Heart rate (HR) was derived from a standard electrocardiogram (ECG). A Q3000B Stress Test Monitor (Quinton Instrument Company, Seattle, WA) was used for visual monitoring and recording of the ECG. Blood pressures were measured by auscultation at rest and in recovery, as well as during short pauses (<30 seconds) between stages. Expired gases were collected and analyzed by an open circuit method using the Horizon Advanced Exercise, Metabolic Measurement Cart (MMC), SensorMedics Corporation, Yorba Linda, CA. Samples of expired gases were analyzed for concentrations of carbon dioxide using a nondispersive infrared technique and concentrations of oxygen using a polarographic sensor cell. Prior to and after each test, analyzer calibration was checked using reference gases and room air.

Gas collection was begun in the last minute of a 15-minute rest period preceding the exercise tests and continued throughout the test and at least 2 minutes into recovery. Ratings of perceived exertion (RPE) were obtained by using Borg's 15-point graded category scale (13). Ratings were taken during the last 30 seconds of each 3-minute stage and the final 30 seconds of the peak workload.

Onset of blood lactate accumulation by gas exchange ($OBLA_{ge}$) was derived from MMC Horizon computer plots. Analysis of the plotted data from the maximal wheelchair graded exercise test was based upon criteria proposed by Wasserman and McIlroy (14). Data points were plotted at 15-second intervals. Two investigators (KCM and WEL) conducted independent analysis of the plots. These analyses were compared and, when they differed, the factors that influenced the determination of the $OBLA_{ge}$ were discussed by the investigators, and a single value decided upon.

Handbike and Rowcycle Training and Practice

Subjects were randomly assigned an order for Handbike and Rowcycle training and testing. Each subject was then given a supervised training and practice period, lasting approximately 60 minutes, on the first of the two vehicles. Before data collection was started, each subject demonstrated the ability to safely stop, steer, execute 90° and 180° turns, and propel the vehicle at different speeds. When the subject indicated that he or she was ready and the investigators were satisfied with the subject's skill level, data collection procedures were initiated. These same steps were repeated on a different day using the other experimental vehicle, or on the same day following a rest period of at least 90 minutes.

Data Collection for Handbike and Rowcycle Field Tests

Subjects performed two rides each on the Handbike and Rowcycle; one at 5.5 $mi \cdot hr^{-1}$ and the other at a freely chosen speed (FCS). In addition, if the subject felt he or she could tolerate it, a third ride was performed on each device at 120 percent of the FCS. Assignment to initial testing device (Handbike or Rowcycle) and ride condition (5.5 $mi \cdot hr^{-1}$ vs. FCS) were made by randomization. The rides were 5–7 minutes in length. A 140-inch drive ratio was used for both vehicles during data collection rides. All rides were performed in the Hines VAH parking lot on a 0.3 mile (0.48 km), curved course which required two gradual 180° turns during the period of expired gas collection.

Ride speed was monitored by an outrider riding next to each subject on a bicycle equipped with a Cateye Cyclocomputer (Performance Bicycle Shop, Chapel Hill, NC). Instructions to increase or decrease speed were given as necessary. For the FCS condition, the subject chose a

speed during the first 1 to 2 minutes and was asked to maintain that speed during the remainder of the ride. Mean ride speed was calculated by dividing the total distance traveled (recorded from the Cateye Cyclocomputer) by the total time elapsed during the ride. Heart rate was monitored using a CIC Wireless Heartwatch (Performance Bicycle Shop) with a telemetry display mounted on subjects' headgear. The Heartwatches used in the study were checked for accuracy prior to testing using an ECG readout from the Quinton 3000 ECG. The outrider reported elapsed ride time, speed, and heart rate into a portable cassette tape recorder during each ride. Total ride time and distance were recorded from the cyclocomputer at the end of each ride.

Expired gases were collected using an open circuit method during the final 45 to 90 seconds of each ride. Subjects were equipped with a rubber mouthpiece, Hans Rudolph two-way valve, and nose clip. Expired gases flowed through a 7-ft hose connected to a three-way directional stopcock. During the collection period, the stopcock was adjusted so that the expired gases were collected in a 100 L neoprene meteorological balloon that was suspended inside a 35 gal plastic container. During testing, the plastic container was carried on the front of another bicycle being ridden by an investigator as shown in **Figure 2.** Gas samples were analyzed within 15 minutes after collection using the Horizon Advanced Exercise MMC operated in the manual mode.

During the last 15 seconds of the final minute of each test ride, the outrider asked the subject to choose an RPE (13). The subject then glanced at a copy of the RPE scale which was tied to his or her leg. The rating was reported at the end of each ride.

After a subject had been tested on both devices, he or she was asked to fill out a four-part questionnaire with questions regarding transferring and seating, vehicle operation, overall impressions, and vehicle preference.

Gross energy cost (GEC) for each riding condition and resting energy expenditure were calculated using respiratory exchange ratio and oxygen uptake ($\dot{V}O_2$) (15). Resting energy expenditure was calculated using data collected during the final 1 to 2 minutes of a 15-minute rest period preceding the wheelchair graded exercise test.

Net locomotive energy cost (NLEC), or net kcal per unit of body weight per unit of distance traveled, was calculated as proposed by Glaser et al. (3,16), for all experimental conditions:

$$NLEC = (GEC - E)(Wt - D)^{-1} \quad [1]$$

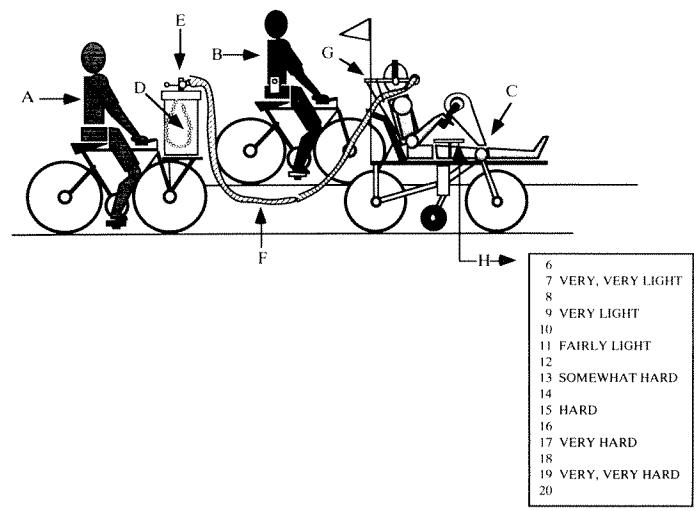

Figure 2.
Illustration of the field testing method employed for data collection during Handbike and Rowcycle propulsion: (A) investigator riding bicycle with gas collection bag; (B) outrider/pacer wearing tape recorder for heart rate, speed, time, distance, and rating of perceived exertion storage; (C) subject riding vehicle (Handbike pictured); (D) 100 L neoprene meteorological balloon suspended inside a 35 gal plastic container; (E) three-way directional stopcock; (F) 7 ft large bore hose; (G) Heartwatch display, Hans-Rudolph non-rebreathing valve, head support for valve, and suspension support for hose; (H) rating of perceived exertion scale attached to subject's leg.

where GEC is the gross energy cost in kcal, E is the resting energy expenditure in kcal, Wt is the subject's weight in kg, and D is the distance traveled in km (16). The units of NLEC are $kcal \cdot kg^{-1} \cdot km^{-1}$. As stated by Glaser and colleagues, "Since gross energy cost is expressed in kcal per unit of time, it provides little information as to the metabolic cost for an individual to travel a given distance. NLEC, however, provides an index to express the relative energy cost (corrected for resting metabolism and body weight) per km of distance traveled. Therefore, to facilitate comparison, we propose that this index be used to express the efficiency [economy] of various locomotive tasks" (16).

Statistical Analysis

The physiologic responses of subjects during Handbike and Rowcycle propulsion were compared using two-way analysis of variance for repeated measures. Dependent variables included ride speed, HR, $\dot{V}O_2$, minute ventilation ($\dot{V}_E$), and NLEC and independent variables were ride condition (5.5 $mi \cdot h^{-1}$, FCS and 120 percent FCS) and vehicle (Handbike vs. Rowcycle).

Where appropriate, paired *t*-tests were used for *post hoc* comparisons without correction for multiple comparisons. Least squares linear regression was also employed to examine the relationships between ride speed, $\dot{V}O_2$, and NLEC. A binomial probability formula was used to determine whether a statistically significant relationship existed between vehicle preference and NLEC at the 5.5 $mi \cdot h^{-1}$ ride condition (17) and single sample *t*-tests were performed on the mean slopes relating ride speed to NLEC for each vehicle. Analyses were performed on a Macintosh LC personal computer using the StatView 4.0 Statistical Analysis Package (Abacus Concepts, Calabasas, CA). An alpha level of 0.05 was used to denote statistical significance.

RESULTS

Physiologic Responses

Mean values for the measured or calculated parameters are presented in **Tables 2–4.** Within subject differences between the Handbike and Rowcycle for speed, HR, $\dot{V}_E$, $\dot{V}O_2$, and NLEC did not reach statistical significance for any of the three ride conditions. Ride speed was significantly different between each of the three conditions for both the Handbike and Rowcycle ($P<0.05$ for all comparisons). NLEC did not differ significantly between ride conditions for either vehicle. In order to examine whether a relationship existed between ride speed

Table 2.
Mean individual values for speed and physiologic variables during Handbike and Rowcycle rides in the 5.5 $mi \cdot hr^{-1}$ condition.

	Speed ($mi \cdot hr^{-1}$)		$\dot{V}O_2$ ($L \cdot min^{-1}$)		$\dot{V}_E$ ($L \cdot min^{-1}$)		HR ($b \cdot min^{-1}$)		NLEC ($kcal \cdot kg^{-1} \cdot km^{-1}$)	
Subject	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**
1	5.9	5.9	0.782	0.832	22.88	24.19	128	113	0.248	0.269
2	5.9	5.8	0.816	0.659	26.84	27.08	132	137	0.246	0.267
3	5.9	5.6	0.802	0.712	39.38	40.19	94	97	0.206	0.188
4	5.6	5.8	0.496	0.486	22.14	19.38	116	99	0.139	0.124
5	5.6	5.2	0.616	0.563	24.64	22.99	155	134	0.290	0.263
6	5.6	5.5	0.571	0.694	16.63	21.47	93	128	0.122	0.177
7	5.9	5.0	0.701	0.450	26.23	21.40	116	113	0.545	0.383
Mean	5.8	5.5	0.683	0.628	25.53	25.24	119	117	0.257	0.239
SD	0.2	0.3	0.125	0.136	6.98	7.03	22	16	0.141	0.084

$\dot{V}O_2$ = oxygen uptake, $\dot{V}_E$ = minute ventillation, HB = Handbike, RC = Rowcycle, HR = heart rate, NLEC = net locomotive energy cost

Table 3.
Mean individual values for speed and physiologic variables during Handbike and Rowcycle rides in the freely chosen speed condition.

	Speed ($mi \cdot hr^{-1}$)		$\dot{V}O_2$ ($L \cdot min^{-1}$)		$\dot{V}_E$ ($L \cdot min^{-1}$)		HR ($b \cdot min^{-1}$)		NLEC ($kcal \cdot kg^{-1} \cdot km^{-1}$)	
Subject	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**
2	6.4	7.1	0.648	0.693	30.80	30.11	163	148	0.226	0.230
3	6.0	6.2	0.773	0.899	53.24	51.37	128	113	0.195	0.240
4	7.0	7.0	0.679	0.760	36.97	34.71	137	113	0.194	0.235
5	6.7	7.4	1.104	0.732	44.86	32.54	159	153	0.509	0.278
6	6.6	9.8	0.987	1.706	33.56	108.70	121	184	0.300	0.464
7	5.9	6.0	0.703	0.479	29.06	27.39	125	122	0.533	0.359
Mean	6.4	7.3	0.816	0.881	38.08	47.47	134	136	0.326	0.301
SD	0.4	1.4	0.186	0.424	9.29	31.16	25	32	0.156	0.093

$\dot{V}O_2$ = oxygen uptake, $\dot{V}_E$ = minute ventillation, HB = Handbike, RC = Rowcycle, HR = heart rate, NLEC = net locomotive energy cost

Table 4.
Mean individual values for speed and physiologic variables during Handbike and Rowcycle rides in the 120% freely chosen speed condition.

	Speed ($mi \cdot hr^{-1}$)		$\dot{V}O_2$ ($L \cdot min^{-1}$)		$\dot{V}_E$ ($L \cdot min^{-1}$)		HR ($b \cdot min^{-1}$)		NLEC ($kcal \cdot kg^{-1} \cdot km^{-1}$)	
Subject	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**	**HB**	**RC**
2	9.0	9.0	0.954	1.020	53.27	57.71	189	183	0.289	0.310
3	•	6.4	•	0.959	•	72.04	•	112	•	0.255
4	9.4	9.1	0.822	1.069	48.27	59.17	151	152	0.198	0.297
5	7.8	8.7	1.369	0.975	57.84	45.51	166	158	0.572	0.340
6	9.4	11.5	1.375	1.725	43.43	112.87	143	186	0.344	0.386
Mean	8.9	8.9	1.130	1.150	51.20	69.46	162	158	0.351	0.318
SD	0.8	1.8	0.290	0.320	7.02	26.02	20	30	0.159	0.049

$\dot{V}O_2$ = oxygen uptake, $\dot{V}_E$ = minute ventillation, HB = Handbike, RC = Rowcycle, HR = heart rate, NLEC = net locomotive energy cost

and NLEC, the slope of the regression line of NLEC ($kcal \cdot kg^{-1} \cdot km^{-1}$) on ride speed ($mi \cdot h^{-1}$) was calculated for each subject for Handbike and Rowcycle rides. A tendency was noted for a slight increase in NLEC with increasing speed (meanβ=0.042±0.099 $kcal \cdot kg^{-1} \cdot km^{-1}$ for the Handbike and 0.031 ±0.036 $kcal \cdot kg^{-1} \cdot km^{-1}$ for the Rowcycle), but this was not statistically different from zero for either vehicle.

Target Training Intensities for Oxygen Uptake

One objective of this study was to evaluate the utility of these devices for exercise training to improve cardiorespiratory fitness. The American College of Sports Medicine has published guidelines for prescribing exercise intensity for this purpose (13). They suggest that the training-sensitive range is from 40–85 percent of $\dot{V}O_{2peak}$. The mean percent of $\dot{V}O_{2peak}$ was within this range for all ride conditions with both vehicles. For the 5.5 $mi \cdot h^{-1}$ condition, percent $\dot{V}O_{2peak}$ for the Handbike and Rowcycle were 52.0 ±20.4 percent and 45.4±9.7 percent, respectively. The corresponding values were 63.5±24.2 percent and 62.2±12.1 percent for the FCS condition and 78.0±31.6 percent and 76.4±9 percent in the 120 percent of FCS condition. Furthermore, of the six persons who completed at least two rides on each vehicle, all six were within the training-sensitive range on at least one ride with the Rowcycle and five of the six were within the training-sensitive range on at least one ride with the Handbike. Percent $\dot{V}O_{2peak}$ was above the training-sensitive range for both the 5.5 $mi \cdot h^{-1}$ and FCS conditions on the Handbike for one individual (88 percent for both rides by subject no. 7).

$OBLA_{ge}$ During Wheelchair Ergometry and Its Relationship To Oxygen Uptake and RPE During Handbike and Rowcycle Rides

Average $OBLA_{ge}$ during the maximal effort wheelchair ergometry tests occurred 57.0±5.0 percent of $\dot{V}O_{2peak}$ and RPEs of 12 to 13. ($OBLA_{ge}$ could not be determined for one subject.) The $OBLA_{ge}$ during maximal effort wheelchair ergometry may or may not be similar to that measured during Handbike or Rowcycle propulsion. Recognizing that there are limitations to the usefulness of any interpretations made from these data, we felt that it was worth considering from a qualitative perspective. The number of subjects exceeding $OBLA_{ge}$ from their wheelchair tests within each condition was one of six for the Handbike and zero of six for the Rowcycle in the 5.5 $mi \cdot h^{-1}$ condition, two of five for the Handbike and three of five for the Rowcycle at FCS, and three of four for the Handbike and four of four for the Rowcycle in the 120 percent FCS condition.

Vehicle Preference and Relationship to NLEC

In response to a questionnaire, four of the seven subjects reported that they preferred the Handbike, while three preferred the Rowcycle. A binomial probability formula was applied to determine whether there was a statistically significant relationship between vehicle preference and NLEC under the 5.5 $mi \cdot h^{-1}$ condition (i.e., whether the vehicle which elicited the lower NLEC was consistently preferred). This ride condition was chosen because it was the only one for which speed was held constant between subjects. Lower NLEC predicted vehicle preference in all seven cases, which was highly significant (p=0.008).

Relationship Between Oxygen Uptake and Speed of Rowcycle and Handbike Propulsion

Nonsignificant correlations ($p>0.05$) were found between ride speed during Handbike propulsion—all conditions combined—and oxygen uptake in $L \cdot min^{-1}$ ($r=0.65$) and $mL \cdot kg \cdot min^{-1}$ ($r=0.51$) (**Figure 3**). Stronger and statistically significant relationships ($p<0.01$) were found for Rowcycle propulsion, $r=0.88$ and $r=0.93$ for speed versus oxygen uptake in $L \cdot min^{-1}$ and $mL \cdot min^{-1} \cdot kg^{-1}$, respectively (**Figure 4**).

Comparison With the Medrano Study

A similar energy cost study was performed with the Rowcycle by Medrano (18). Oxygen consumption was measured in 10 subjects with lower limb disability while propelling the Rowcycle at 4, 6, and 8 $mi \cdot hr^{-1}$. Gear(s) and/or drive ratio(s) utilized were not specified. Raw data were provided for the 8 $mi \cdot hr^{-1}$. Analysis of our data and the raw data of Medrano showed that the regression lines relating speed and oxygen uptake (in $mL \cdot kg \cdot min^{-1}$) were nearly identical, and did not differ significantly in slope or intercept (data not shown).

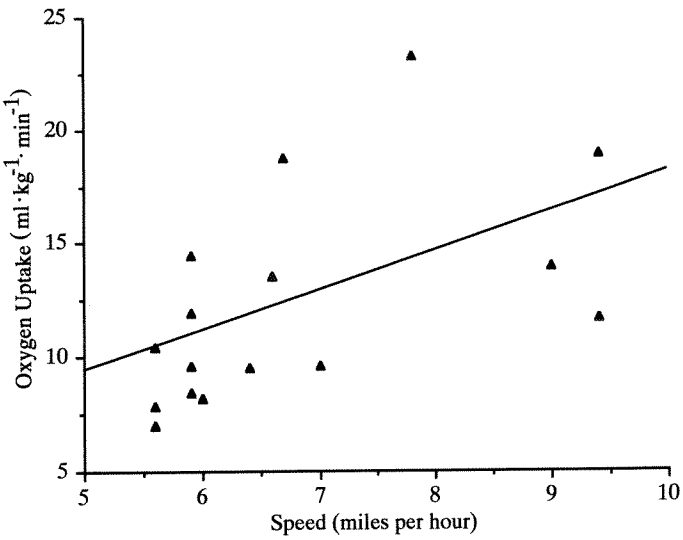

Figure 3.
Oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$) vs. Handbike speed ($mi \cdot hr^{-1}$), $r=0.51$, $P>0.05$, oxygen uptake = 0.79+1.73 (speed).

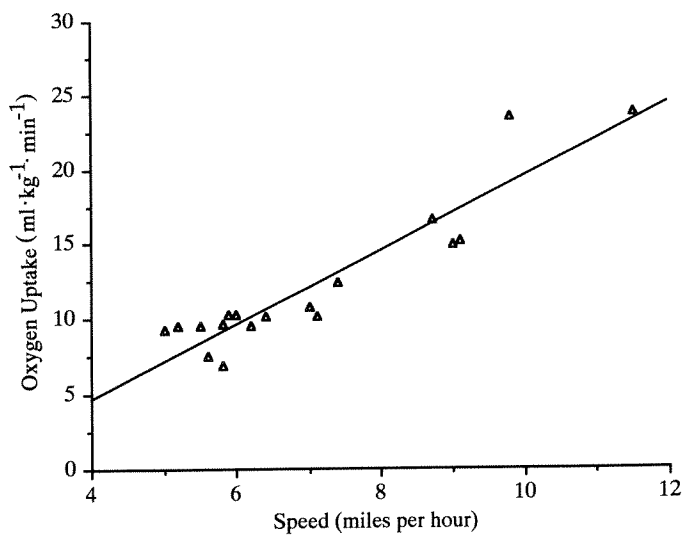

Figure 4.
Oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$) vs. Rowcycle speed ($mi \cdot hr^{-1}$), $r=0.93$, $P<0.01$, oxygen uptake = -5.17+2.46 (speed).

DISCUSSION

Physiological Responses

Factors which influence the magnitude of physiological responses to wheelchair locomotion, as summarized by Glaser et al. (16), include: the fitness level of the user, characteristics of the wheelchair used, velocity of locomotion, and architectural conditions (floor or ground surface, grade, etc.). These same determinants also apply to propulsion of other upper body–powered vehicles. The present investigation assessed the physiological responses to propelling the Handbike and Rowcycle, which utilize different methods of propulsion (synchronous arm-cranking vs. rowing), at similar velocities and drive ratios. All of the subjects were persons with chronic SCI who were inexperienced Handbike and Rowcycle riders. Tests were done out-of-doors to simulate, as closely as possible, environmental conditions encountered during normal use of these vehicles. Within subject differences in HR, $\dot{V}O_2$, $\dot{V}_E$, or NLEC taken during propulsion of the Handbike and Rowcycle under the three experimental conditions (5.5 $mi \cdot hr^{-1}$, FCS, and 120 percent of FCS) were small and not statistically significant.

Comparisons between the Handbike and Rowcycle were limited to riding conditions likely to be encountered by the novice rider. This strategy was employed because early experiences would be expected to exert the greatest influence on the likelihood that an individual would continue to use either vehicle for fitness training and/or recreation. The Handbike and Rowcycle were each tested in only one drive ratio. The 140-inch gear was chosen be-

cause it was common to both the Handbike and Rowcycle. The Handbike was tested only with the side wheels in the down position, which would be used by the novice rider. The time necessary to develop the requisite skill to ride the Handbike on two wheels, as well as concerns for rider safety during expired gas collection, prevented testing of subjects with the side wheels raised.

Potential For Aerobic Conditioning Using The Handbike and Rowcycle

The ACSM recommends a training intensity of 40 to 85 percent $\dot{V}O_{2peak}$ for aerobic conditioning (13). One objective of the present investigation was to evaluate the potential for aerobic conditioning through regular use of the Handbike and Rowcycle by the inexperienced rider with SCI. Of the six subjects who completed rides in at least two conditions, all were within the training-sensitive range (40-85 percent $\dot{V}O_{2peak}$) for at least one ride on the Rowcycle. Five of six subjects were within this range during at least one Handbike ride. One subject was slightly above the training range on both the 5.5 $mi \cdot hr^{-1}$ and FCS Handbike rides (88 percent $\dot{V}O_{2peak}$ for both). Therefore, it appears that most riders with paraplegia should be able to utilize either vehicle for exercise conditioning. The current recommendations of the ACSM for apparently healthy adults (13) were used as a guide in this investigation, but a study by Hooker and Wells (19) suggests that the ACSM guidelines may not be appropriate for improving the fitness of persons with SCI. Further investigation is needed to clarify the optimal training intensity range for aerobic conditioning in this group.

$OBLA_{ge}$ was determined as an additional point of comparison. During the 5.5 $mi \cdot hr^{-1}$ condition, all but one subject was below $OBLA_{ge}$ for the Handbike and none were above $OBLA_{ge}$ during Rowcycle propulsion in this condition. In contrast, all subjects were above $OBLA_{ge}$ for the Rowcycle ride at the 120 percent FCS condition and all but one rider was above $OBLA_{ge}$ during the corresponding Handbike rides. This further suggests that both vehicles may be used for exercise of an intensity covering a wide enough range to effectively train the cardiorespiratory system of persons of varying degrees of physical fitness.

Vehicle Preference

Analysis of the data indicates that locomotive economy, as indicated by NLEC at 5.5 $mi \cdot hr^{-1}$, was significantly related to the subjects' vehicle preference ($p=0.008$). The vehicle associated with the lower NLEC predicted subjects' vehicle preference in all seven cases, even though no overall trend was observed for preference of one vehicle over the other (four preferred the Rowcycle and three the Handbike). Therefore, locomotive economy appears to be an important determinant of vehicle preference. This finding has clinical implications because patient compliance with a prescription for a mobility device, whether for activities of daily living, recreation, sports, or aerobic conditioning, will be significantly impacted by the perception of the physical and psychological stress experienced when using the device.

Glaser et al. (16) compared the energy cost and cardiopulmonary responses to wheelchair locomotion on tile and carpet in 9 wheelchair-dependent men. Mean NLEC for wheelchair propulsion at 3.0 $km \cdot hr^{-1}$ (1.34 $mi \cdot hr^{-1}$ was 0.46 ± 0.03 and 0.80 ± 0.06 $kcal \cdot kg^{-1} \cdot km^{-1}$ for tile and carpet, respectively. Mean NLEC values were considerably lower for the Handbike and Rowcycle (0.24–0.35 $kcal \cdot kg^{-1} \cdot km^{-1}$), indicating that there was greater relative locomotive economy associated with propelling the Handbike and Rowcycle on a paved surface.

Relationship Between Speed and $\dot{V}O_2$ For The Handbike and Rowcycle

The relationship between speed and $\dot{V}O_2$ was stronger for the Rowcycle than for the Handbike. One possible explanation for this may be that riding the Handbike requires greater motor skill (balance, coordination) than riding the Rowcycle, resulting in a more variable speed-$\dot{V}O_2$ relationship. Since all of the riders were inexperienced, it must be remembered that differences in skill requirements between the two vehicles may not affect rider performance in the same way following a more extended period of practice and skill development.

Comparison of the data from the present study with that from Medrano (18) shows that the two studies yielded similar results with regard to the energy cost of propelling the Rowcycle. Combining the data from the two studies results in a strong correlation between speed and $\dot{V}O_2$ in $mL \cdot min^{-1}$ ($r=0.94$, $p<0.001$). The resulting regression equation, derived from gas analysis of 27 Rowcycle rides was:

$$\dot{V}O_2 = 2.46\ (\text{speed}) - 5.09 \qquad [2]$$

where $\dot{V}O_2$ is in $mL \cdot min^{-1} \cdot kg^{-1}$ and speed of propulsion is in $mi \cdot hr^{-1}$. This may be useful for exercise prescription and/or field testing of persons with lower limb disabilities to predict oxygen uptake from a known speed.

Handbike and Rowcycle Use In An Individual With a High Level Spinal Lesion

One of the research subjects found it very difficult to ride the Handbike, but rode the Rowcycle with relative ease. This individual had an incomplete spinal cord lesion at the C_{6-7} level. The motor neurons which innervate the elbow flexor muscles, biceps brachii, and brachialis, exit the spinal cord in the C_{5-6} region, whereas the motor neurons for the elbow extensors, triceps brachii, exit in the C_{7-8} region (20). The rowing action of Rowcycle propulsion relies heavily on the elbow flexors. Propulsion of the Handbike utilizes both the elbow flexors and extensors, and therefore, probably overtaxed this subject's proportionally weaker extensor muscles.

CONCLUSION

Regardless of experimental condition, mean within-subject differences in speed, HR, $\dot{V}O_2$, $\dot{V}_E$, or NLEC between the Handbike and Rowcycle were small and not statistically significant. Both vehicles appear to have potential for use in aerobic conditioning programs which are designed for persons restricted to upper body exercise. Locomotive economy, as indicated by NLEC, was significantly related to vehicle preference. It was concluded that locomotive economy may be an important component in determining an individual's preference for one upper body–powered vehicle over another. This relationship should be explored further for possible applications in design and testing of mobility devices.

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