A physiological comparison of forward vs reverse wheelchair ergometry

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ABSTRACT

LINDEN, A. L., G. J. HOLLAND, S. F. LOY, and W. J. VINCENT. A physiological comparison of forward vs reverse wheelchair ergometry. *Med. Sci. Sports Exerc.* Vol. 25, No. 11, pp. 1265–1268, 1993. The purpose of this study was to compare metabolic and cardiopulmonary responses for forward wheelchair ergometry (FOR) and reverse wheelchair ergometry (REV) at equal power outputs (PO) levels. Moderately active able-bodied (N = 21) subjects exercised at 3-min stages at PO levels of 15, 20, 25, and 30 W for each mode of ergometry. Oxygen uptake ($\dot{V}O_2$), pulmonary ventilation ($\dot{V}_E$), respiratory exchange ratio (RER), heart rate (HR), percent net mechanical efficiency (ME), revolutions per minute (RPM) and strikes per minute (SPM) were determined at each PO level. With the exception of RER, all the physiological responses ($\dot{V}O_2$, $\dot{V}_E$, and HR) were higher for FOR exercise ($P < 0.05$) than REV exercise. ME increased with PO and was higher ($P < 0.05$) for REV than FOR at each PO level. SPM values for the REV were lower ($P < 0.01$) by almost half of that for the FOR exercise, although RPM remained constant between modes during all four stages. In general, these data suggest that reverse wheelchair ergometry is physiologically more efficient than conventional wheelchair ergometry and should be studied further as an alternative method for wheelchair ambulation.

POWER OUTPUT, MECHANICAL EFFICIENCY, STRIKES PER MINUTE, REVERSE PROPULSION

Conventional, hand-rim wheelchair propulsion has been investigated since the late 1960s. It has been well established that this mode of ambulation leads to considerable physiological demand; high cardiorespiratory responses are seen at relatively low power output (1,9,12,17). In addition, daily-use wheelchairs have a relatively low mechanical efficiency in the 7–8% range (1,7,11). Several researchers have recently examined alternate modes of wheelchair propulsion using arm cranks (8,14,16), lever systems (18), and asynchronous push-rim methods (10). Their results demonstrate unequivocally that these unique mechanical designs are physiologically more efficient than conventional daily-use wheelchairs. As a result, several commercial companies have begun to manufacture these designs as alternate modes of locomotion for the population with wheelchair dependency. Apparently, there has been no previous research conducted attempting to utilize a reverse propulsion system, employing a pulling motion on the push-rims rather than the conventional pushing method.

The purpose of this study was to compare metabolic and cardiopulmonary responses of forward wheelchair ergometry (FOR) and reverse wheelchair ergometry (REV) techniques. FOR simulated conventional wheelchair propulsion, whereas REV simulated a wheelchair being propelled backward. It was hypothesized that REV, which simulates a rowing type motion, would be physiologically more efficient than the conventional propulsion system, due to the larger muscle mass involved.

METHODS

Subjects. Twenty-one moderately active, able-bodied male volunteers, (mean ± SD) 22.1 ± 3.2 yr; weight, 71.7 ± 6.2 kg, participated in both the forward and reverse propulsion exercise. Each subject signed an institution-approved statement of informed consent that discussed the purpose of the study, required test procedures, any known risks, and their right to terminate participation at anytime.

Instrumentation. To compare forward with reverse wheelchair ergometry at the same power output (PO), a wheelchair ergometer was designed and constructed (see Fig. 1). An adjustable-height stool (Fig. 1A) was affixed between two Cateye CS1000 cyclosimulators (Cateye Co., Chicago, IL) that were mounted on a platform. Standard, uncambered, Everest & Jennings (Camarillo, CA) push-rim and tires were then fastened to the ergometer's workload unit (Fig. 1B). The distance between the wheels was set at 17 inches. The two cyclosimulators utilized a four-bit micro computer electronic unit that simultaneously displayed the PO levels (watts) and simulated percent grade for each wheel (Fig. 1C). An electronic revolution counter (Mini Mag, Northridge, CA) was used to allow precise monitoring of revolutions per minute (RPM), while strikes on the hand-rim (SPM) were counted by the technician for each minute of exercise.

Physiological variables. Oxygen uptake ($\dot{V}O_2$, l·

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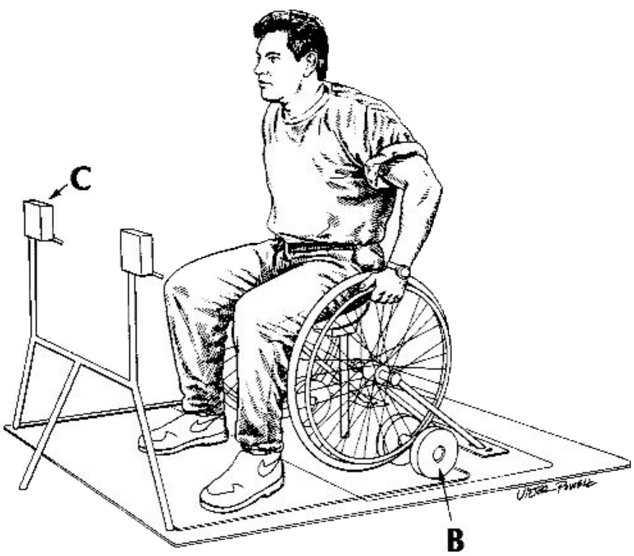

Figure 1—Wheelchair ergometer: (A) adjustable-height stool; (B) workload unit; (C) computer control unit.

$\min^{-1}$ STPD), respiratory exchange ratio (RER), and pulmonary ventilation ($\dot{V}E$, $l \cdot \min^{-1}$ BTPS) were determined by indirect calorimetry. Subjects breathed via a Collins two-way breathing valve (Collins, Braintree, MA) and expired gas samples were collected and analyzed with a Quinton Q-Plex I metabolic cart (Quinton, Seattle, WA). Percent net mechanical efficiency (ME) was determined using Gaesser and Brooks computation (4) of

$$\% \text{ ME} = [\text{W}/(\text{E} - \text{e})] \times 100,$$

where W is the caloric equivalent of external work performed, E is the gross caloric output, and e is the resting caloric output. Glaser et al. (7) utilized the same computation for application in the laboratory study of wheelchair ergometry. Heart rate (HR) was monitored and recorded via electrocardiogram.

Protocol. Prior to testing, all subjects participated in an orientation session. During this meeting, the seat height was adjusted proportionate to an elbow-joint angle of 120°, while hand placement was set at top dead center (TDC) of the push-rim. This angle was measured, utilizing an orthopedic goniometer (Country Technology Inc., Gays Mills, WI). Woude et al. (19) indicated that such an angle optimizes wheelchair mechanical efficiency. Subjects next practiced techniques for both modes of wheelchair ergometry. Instruction of FOR ergometry was given according to Davis et al. (3). Hand contact with the push-rim occurred at approximately −15° of TDC and continued to approximately 120°. At this point the push-rims were released and hands returned to the starting position. REV utilized a modified rowing technique. To initiate the REV stroke, the subjects were instructed to lean forward and make hand contact with the push-rim at the furthermost point (at approximately 160° of TDC). From this point, the rowing stroke produced a strong extension of the spinal erectors and shoulder joint until an upright position was obtained. Hand contact was maintained with the push-rim until approximately −45°, at which point, wrist flexion generated an additional propulsion force before release from the push-rims. Verbal feedback was provided by the investigator until an acceptable proficiency level was achieved.

Before testing, subjects sat quietly for 4 min while resting physiological data were collected. Subjects were randomly assigned to complete either a FOR or REV exercise test. The alternate test was administered within 1 wk. A continuous four-stage test was used with unilateral PO levels of 15, 20, 25, and 30 W, respectively, as provided in the manufacturer's specifications for the Cateye ergometer (20). The left and right cyclosimulator ergometer displays of PO were placed directly in front of the exercising subject for convenient monitoring. This ensured constant and simultaneous PO with the two ergometers during the four stages of the exercise protocol. Both FOR and REV utilized the same stage protocols in the present study to ensure identical conditions for both modes. Each exercise stage was 3 min in duration. Subjects sustained a volitional strikes per minute rate (SPM) that they felt optimal to maintain the PO level during each stage.

Statistical analysis. A within-within MANOVA was used to compare $\dot{V}O_2$, HR, $\dot{V}E$, RER, RPM, SPM, and %ME between both modes of ergometry using statistical software (BMDP, Los Angeles, CA). Statistical significance was accepted at the $P < 0.05$ level with a Tukey's *post-hoc* test of honestly significant differences used to interpret F values. When sphericity was violated with a repeated measures factor, the Greenhouse-Geisser and Huynh-Feldt adjustments for P values were used. An intraclass correlation was used to calculate the reliability coefficient of the testing apparatus for both FOR and REV using all 21 subjects.

RESULTS

MANOVA results are presented in Figures 2 and 3. Figure 2 presents the subject's $\dot{V}O_2$, HR, and $\dot{V}E$ data for the FOR and REV exercise at each PO level. All three variables increased linearly with PO. For these factors, FOR elicited significantly greater responses than REV exercise at each PO level ($P < 0.05$ or better).

Figure 3 represents the ME, SPM and RPM values for FOR and REV exercise at each PO level. REV exercise showed a significantly higher % net mechanical efficiency at all PO levels than the FOR exercise ($P <$ 0.05 or better). ME increased from 4.3% at 15 W to 5.6% at 30 W for FOR exercise, and from 5% at 15 W to 6.3% at 30 W for REV exercise. SPM was signifi-

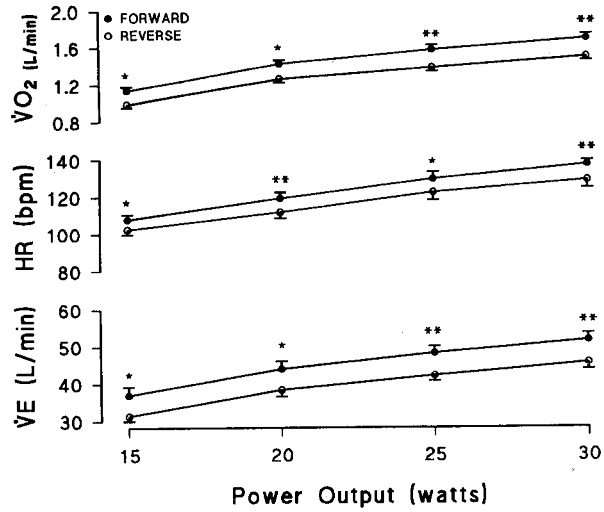

Figure 2—Comparison of oxygen uptake ($\dot{V}O_2$, $l \cdot min^{-1}$), heart rate (HR, beats·min^{-1}), and pulmonary ventilation ($\dot{V}E$, $l \cdot min^{-1}$) between forward and reverse wheelchair ergometry at equal Power Output levels. * $P < 0.05$. ** $P < 0.01$. Values represent mean ± SE.

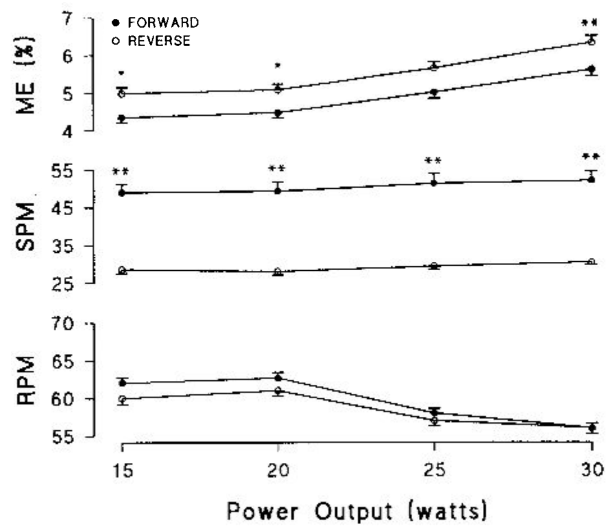

Figure 3—Comparison of percent net mechanical efficiency (ME), revolutions per minute (RPM), and strikes per minute (SPM) between forward and reverse wheelchair ergometry at equal Power Output levels. * $P < 0.05$. ** $P < 0.01$. Values represent mean ± SE.

cantly higher ($P < 0.01$) at all PO levels for the FOR than the REV exercise. In fact, there was a 44% difference between the two propulsion methods. Both exercise modes showed an almost linear decline in RPM for each PO level with a nonsignificant difference or interaction between them. RER showed no significant differences between the two modes of ergometry at any PO, and essentially remained constant throughout exercise. The results of intraclass correlation to determine the reliability coefficient of the testing apparatus was $R = 0.58$ for FOR and $R = 0.51$ for REV, however, after factoring out the mean $\dot{V}O_2$ value changes from stage to stage, then $R2 = 0.92$ and $R2 = 0.97$ for FOR and REV exercise, respectively.

DISCUSSION

During actual daily-use wheelchair operation, PO is influenced by many factors such as body mass, wheelchair mass, bearing friction, as well as the nature and grade of the ground surface (15). To determine whether a reverse propulsion system could improve wheelchair efficiency, physiological responses to FOR and REV exercise were compared at equal PO levels. This comparison of PO levels ranging from 15–30 W, approximates that which may be commonly encountered during actual daily-use wheelchair operation (5,6).

The lower $\dot{V}O_2$, $\dot{V}E$, and HR responses for REV exercise at given submaximal PO levels could be related to more efficient propulsion biomechanics. The reverse propulsion technique requires primary involvement of the large back muscles (shoulder extensors, spinal erectors etc.), as well as different limb and trunk movements. In contrast, FOR propulsion relies predominately on the relatively small muscle groups of the chest and anterior shoulder (3,15). The nature of REV propulsion permits an application of force to the hand-rims over a longer distance, thereby enabling the individual to strike at the rims less frequently. This is evidenced by the significantly lower SPM for the REV, while maintaining the same RPM as the FOR mode (Fig. 3). In contrast, force application during the FOR exercise occurs in shorter "punching" motions, compelling the subject to strike at the hand-rims more times per minute in order to maintain a given PO level (2,13). Sanderson and Sommer (13), using high-speed photography techniques, reported that the push-phase during forward wheelchair propulsion ranged from 34.7–43.7% of cycle time in three world-class male athletes with paraplegia working at 60% $\dot{V}O_{2max}$. This indicated that the remaining 60% of the total cycle time was utilized for recovery and preparation for the following push-phase. Cooper (2), utilizing an analog tachometer, found the percentage of time spent by wheelchair racers in the propulsion-phase to be approximately 33% while the remaining 67% was used for recovery/preparation.

The present study's ME data for the FOR exercise (5.6% ± 0.18 at 30 W) were similar to reported findings of other investigators. Brattgard et al. (1) found ME values of 7–8% for able-bodied females operating a wheelchair ergometer at 18 W. Glaser et al. (7) reported values that ranged from 7.8–9.8% at 25 kpm, for able-bodied males. The significantly higher ($P < 0.05$ or better) ME found in the REV mode of the present study, implies a lower loss of liberated aerobic energy dissipated as heat, and a larger amount functioning to generate external work.

Our present data indicate that for given PO levels, REV exercise elicits lower metabolic and physiologic responses than FOR exercise. Significantly lower ($P < 0.05$ or better) $\dot{V}O_2$, HR, and $\dot{V}E$ values matched with significantly higher ($P < 0.05$ or better) ME values imply that reverse propulsion systems may enable wheelchair users to more efficiently participate in daily activities and could potentially reduce health risks associated with the high physiological demand of conventional wheelchair operation.

Our data indicate that prototype wheelchairs should be developed that allow further study of reverse propulsion under actual locomotive conditions and with disabled wheelchair users. The statistically different results established for REV in the present study may still be possible to achieve using a mechanically efficient gearing device that utilizes a differential or chain and sprocket system.

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