Physiologic Comparison of Forward and Reverse Wheelchair Propulsion

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ABSTRACT. Salvi FJ, Hoffman MD, Sabharwal S, Clifford PS. Physiologic comparison of forward and reverse wheelchair propulsion. Arch Phys Med Rehabil 1998;79:36-40.

Objectives: Conventional wheelchair propulsion is physiologically demanding because of the small muscle mass that is used and the low mechanical efficiency of the movement. Previous research has suggested that a reverse wheeling technique might be more economical than conventional forward wheeling. The present study sought to compare the physiologic demands of forward and reverse wheeling techniques.

Design: A repeated measures design was used to compare the dependent variables between forward and reverse wheeling techniques in the same subjects.

Setting: Human exercise research laboratory.

Participants: Ten able-bodied men.

Intervention: Subjects completed graded, discontinuous exercise tests on a wheelchair ergometer, using both forward and reverse wheeling techniques.

Main Outcome Measures: Oxygen uptake ($\dot{V}O_2$), ventilation ($\dot{V}_E$), and heart rate were measured during the last 30 seconds of each 3-minute exercise stage. Blood lactate concentration ([La]) and rating of perceived exertion (RPE) were determined immediately after each stage.

Results: Repeated measures analysis of variance demonstrated that $\dot{V}O_2$, $\dot{V}_E$, heart rate, [La], and RPE were all significantly greater ($p < .05$) with reverse wheeling compared with forward wheeling. $\dot{V}O_2$ values with reverse wheeling averaged 9% higher than forward wheeling at identical power outputs.

Conclusions: Reverse wheelchair propulsion is physiologically more demanding than conventional forward wheelchair propulsion and does not appear to offer potential for improving the economy of wheelchair propulsion.

IN THE UNITED STATES, wheelchairs are used to increase mobility by more than 1.4 million individuals with physical impairments.[1] Conventional wheelchair propulsion is performed primarily with the muscles of the arms and anterior upper body.[2] In contrast, walking utilizes a much larger muscle mass. Activities using a larger muscle mass allow a larger peak oxygen uptake and power output.[3] Conventional wheelchair propulsion is also limited by a low mechanical efficiency (external work rate/rate of energy expenditure) of approximately 7%, compared with values of more than 20% for other forms of locomotion, such as walking and cycling.[4-10] The inefficiency of wheelchair propulsion has been attributed to the position of the arms, synchronicity of the arm movements, a large component of static work, and inherent histochemical characteristics of the upper body musculature.[7]

Many individuals who use wheelchairs have additional functional limitations from neuromuscular disorders, diminished muscular and cardiorespiratory fitness, and overuse syndromes.[7,11-14] Improving the mechanical efficiency of wheelchair propulsion would reduce the energy expenditure associated with this form of locomotion, and allow greater independence for many disabled individuals.

Unfortunately, relatively little attention has been directed to the physiologic and ergonomic design of daily-use wheelchairs. Previous research has found that the efficiency of wheelchair locomotion can be improved with systems utilizing arm cranks, levers, smaller handrims, or asynchronous force application to the handrims.[15-21] The improved efficiency for some of these propulsion systems may result from the use of greater muscle mass, greater continuity of movement of the arms, and a smaller component of static work. An asynchronous movement pattern may also take advantage of inherent neural pathways for reciprocal innervation of contralateral muscle groups.[16] Unfortunately, the wheelchairs with these nonconventional propulsion systems have not gained popularity for reasons that include esthetics, increased difficulty with transfers, and decreased portability and maneuverability. Although smaller handrims result in a higher drive ratio, they increase the difficulties in turning and overcoming obstacles such as curbs and inclines.[15,16]

A wheelchair propulsion system that might avoid some of these problems would use a more conventional wheelchair with a mechanism to translate reverse handrim propulsion into forward wheelchair movement. Recent research by Linden and associates[22] suggested that a reverse wheeling technique might be more economical than conventional forward wheeling. The authors hypothesized that the use of an increased muscle mass, including the back extensor musculature, during reverse propulsion might account for the difference. In that study, however, the ergometer consisted of a stool between two wheelchair rims and tires connected to separate wheel ergometers that displayed, but did not record, power output. Thus, the ergometer seat was different than a standard wheelchair, and power output was not precisely known. The purpose of our investigation was to compare the physiologic demands of forward and reverse wheeling techniques using a standard wheelchair on a wheelchair ergometer that allowed an accurate measurement of power output.

METHODS

Ten able-bodied men who were clinically free of cardiac, metabolic, and upper body musculoskeletal disorders participated in the study. Able-bodied individuals were purposely selected as study subjects to avoid a bias favoring forward propulsion that would be present among experienced wheelchair users.

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Submitted for publication March 31, 1997. Accepted in revised form July 14, 1997.

Supported in part by the VA Rehabilitation Research and Development Service, Technology Transfer Section.

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit upon the authors or upon any organization with which the authors are associated.

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0003-9993/98/7901-4442$3.00/0

The subjects had a mean (±SD) age of 35 ± 6yrs, height of 179 ± 6cm, and mass of 74.2 ± 6.1kg. Each subject signed an informed consent meeting the guidelines of our Institutional Review Board before participating in the study.

The same standard wheelchair[a] was used by all subjects. This wheelchair had a seat height of 48cm and the wheel axis was positioned directly below the seat back. The diameter of the wheelchair rims was 54cm, and the rims were wrapped with elastic tubing to improve grip. The wheels were hard rubber and the arm rests were removed. The wheelchair was positioned on a wheelchair ergometer.[b] The rear wheels were centered on the ergometer rollers and the front wheels were secured to the ergometer. Work load was altered through wheeling speed and computer-controlled electronic particle brakes acting on the rollers. A monitor displayed both numerical and graphic feedback to the user about the desired and actual wheeling speed. A graded discontinuous protocol with six 3-minute stages separated by 3-minute rest periods was used for each exercise test. Through combinations of increasing roller resistance and wheeling speed, target power outputs for the six stages were 2.5, 6.0, 12.5, 18.5, 25.0, and 30.0 watts. Across these power outputs, wheeling speed ranged from 27 to 94m/min. Mean wheeling speed and power output during the last minute of each stage was measured. When subjects were unable to stay within 10% of their target wheeling speed and power output for each stage, the test was repeated on a separate day. Only one test required repeating.

Ventilation ($\dot{V}_E$) and oxygen uptake ($\dot{V}O_2$) were measured by open circuit spirometry. Expired air was collected in 30-liter meteorological balloons during the last 30 seconds of each exercise stage. Oxygen and carbon dioxide concentrations were measured with calibrated electronic oxygen[c] and carbon dioxide[d] analyzers. Expired volumes were determined with a calibrated dry gas meter[e] and corrected for the volume removed for analysis of oxygen and carbon dioxide concentrations. Heart rates were measured with a telemetry system[f] and values were averaged over the last 30 seconds of each exercise stage. The number of times that the hand contacted the handrim to propel the wheel was also counted in the last minute of each exercise stage to determine strike rate. Immediately upon completion of each exercise stage, blood was collected in a heparinized capillary tube utilizing an automated lancet puncture of a fingertip. Whole blood lactate concentration ([La]) was then immediately measured on an automated lactate analyzer.[g] A rating of perceived exertion (RPE) was also requested immediately upon completion of each exercise stage using the 6- to 20-point scale.[23]

Before testing, each subject came to the laboratory for a training session, including instruction about the measurement techniques, and practice using both forward and reverse wheeling techniques. Subjects were allowed to adopt the wheeling pattern that they felt was most comfortable. To avoid residual fatigue and muscle soreness, the practice and test sessions were separated by 2 to 7 days. The order of testing with forward versus reverse wheelchair propulsion was counterbalanced. Tests were scheduled at approximately the same time of day. Each subject was asked to refrain from eating or taking caffeine for three hours before reporting to the laboratory. The mean (±SD) ambient temperature of the laboratory was 23.4 ± 0.9°C during testing.

The symmetry of the braking resistances of the wheelchair ergometer rollers, between left and right wheels and between forward and reverse rolling, was examined through roll-down tests. This was accomplished through multiple measurements of the time required for a bicycle wheel on the rollers to come to a stop from an initial speed of 86m/min. These tests confirmed that the braking resistance settings of the rollers was the same between sides and between forward and reverse rolling.

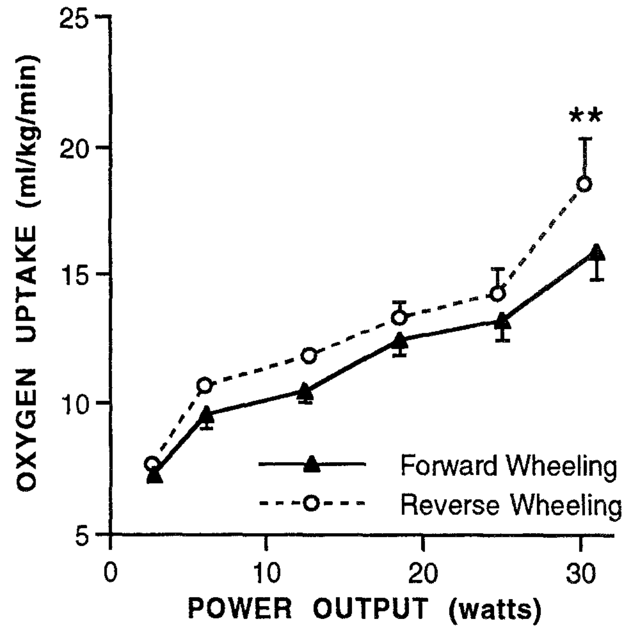

Fig 1. Mean $\dot{V}O_2$ values for the two wheeling techniques. Brackets represent 1 SE. Note that the SE values are sometimes too small to be evident on the graph. (Post hoc analysis revealed differences between wheeling techniques at the $p < .01$ level of significance.)**

Statistical analysis was performed using two-way repeated measures analysis of variance (ANOVA) to compare the dependent variables between forward and reverse wheeling techniques and across work loads. Significant *F* values were followed with a Newman-Keuls post hoc analysis. A probability of .05 was set as the level of statistical significance.

RESULTS

Comparison of power outputs across stages revealed no significant difference between the two wheeling techniques.

A significant main effect difference ($p = .02$) in $\dot{V}O_2$ between forward and reverse wheeling techniques was observed, with $\dot{V}O_2$ values averaging 9% higher with the reverse wheeling technique (fig 1). $\dot{V}_E$ values were also significantly higher ($p = .03$) with reverse wheeling compared with forward wheeling (fig 2). For both $\dot{V}O_2$ and $\dot{V}_E$, post hoc testing revealed significant differences ($p < .01$) between the two wheeling techniques at the highest power output. $\dot{V}O_2$ and $\dot{V}_E$ increased significantly ($p < .01$) with increasing power outputs for both wheeling techniques. A significant interaction effect ($p = .004$) between wheeling technique and power output was present for $\dot{V}_E$ indicating that there was a greater increase in this variable across power outputs for reverse wheeling than forward wheeling.

A main effect difference ($p = .047$) between wheeling techniques was observed for heart rate, with values for reverse wheeling averaging 5beats/min higher than forward wheeling (fig 3). Likewise, [La] values were higher ($p = .006$) for reverse compared with forward wheelchair propulsion (fig 4). RPE values averaged about 1 point higher ($p = .01$) for reverse wheeling compared with forward wheeling (fig 5). For heart rate, [La], and RPE, post hoc testing revealed significant differences ($p < .05$) between the two wheeling techniques at most of the power output levels. Heart rate, [La], and RPE increased significantly ($p < .01$) with increasing power outputs for both wheeling techniques. A significant interaction effect ($p = .005$) between

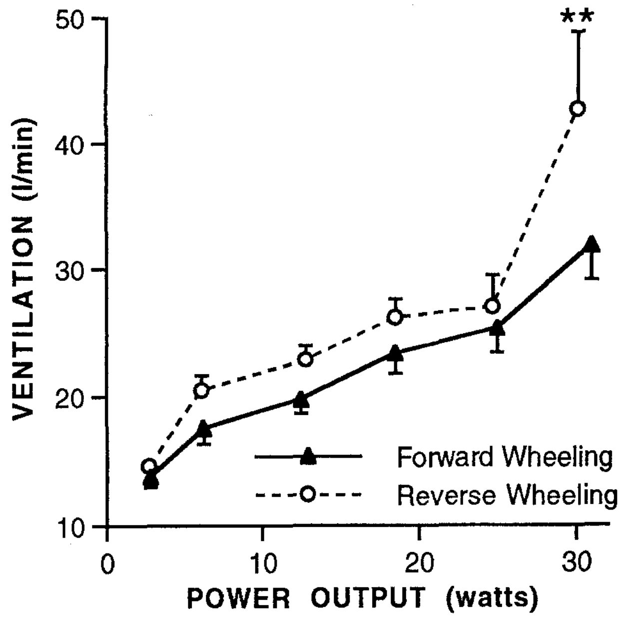

Fig 2. Mean $\dot{V}_E$ rates for the two wheeling techniques. (Symbols are the same as in figure 1.)

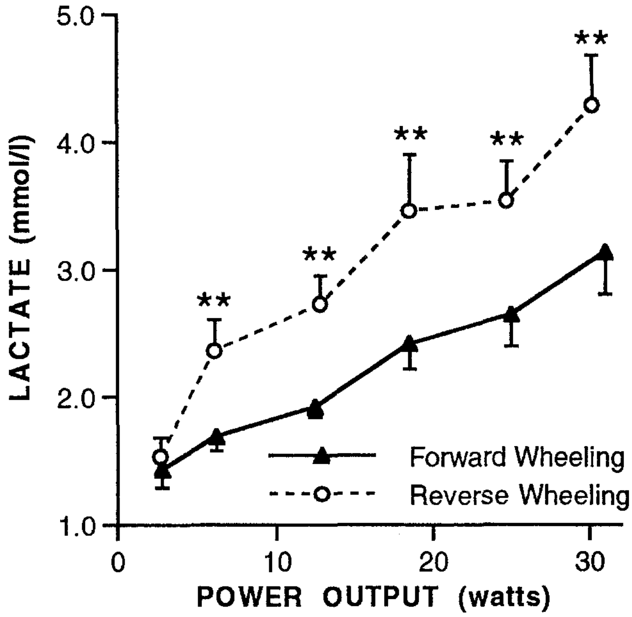

Fig 4. Mean [La] for the two wheeling techniques. (Symbols are the same as in figure 1.)

wheeling technique and power output was present for [La] indicating that there was a greater increase in this variable across power outputs for reverse wheeling than forward wheeling.

Strike rates were significantly higher ($p = .04$) for forward wheeling than reverse wheeling (fig 6). There was a significant main effect increase ($p = .003$) in strike rate with increasing power outputs. A significant ($p = .01$) interaction effect between wheeling technique and power output indicates that there was a greater increase in strike rate across power outputs for forward wheeling than reverse wheeling.

DISCUSSION

Each of the physiologic measurements demonstrates that the reverse wheeling technique is more demanding than the conventional forward wheeling technique. Based on RPE, it appears that reverse wheeling is also subjectively more demanding. Therefore, reverse wheelchair propulsion in a standard wheelchair does not appear to offer potential for reducing the energy demands of wheelchair users.

Linden and colleagues[22] reported reverse wheeling to be approximately 20% more economical than forward wheeling across power outputs of 15 to 30 watts. What might explain

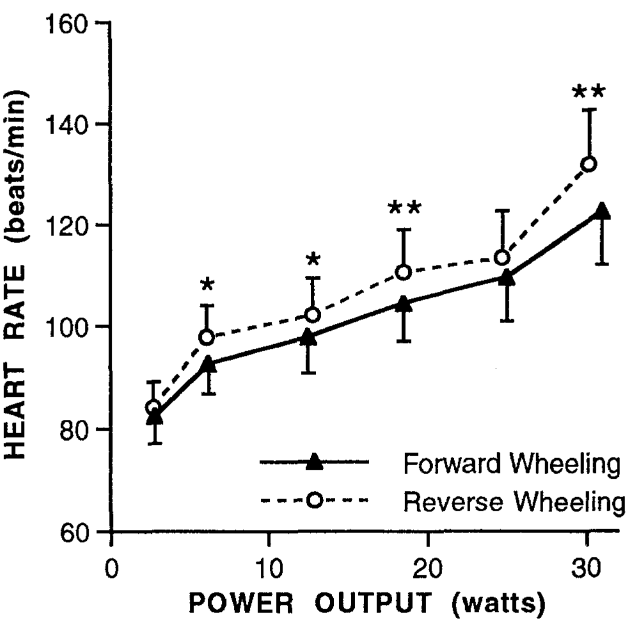

Fig 3. Mean heart rates for the two wheeling techniques. Brackets represent 1 SE. (Post hoc analysis revealed differences between wheeling techniques at the $*p < .05$ and $**p < .01$ levels of significance.)

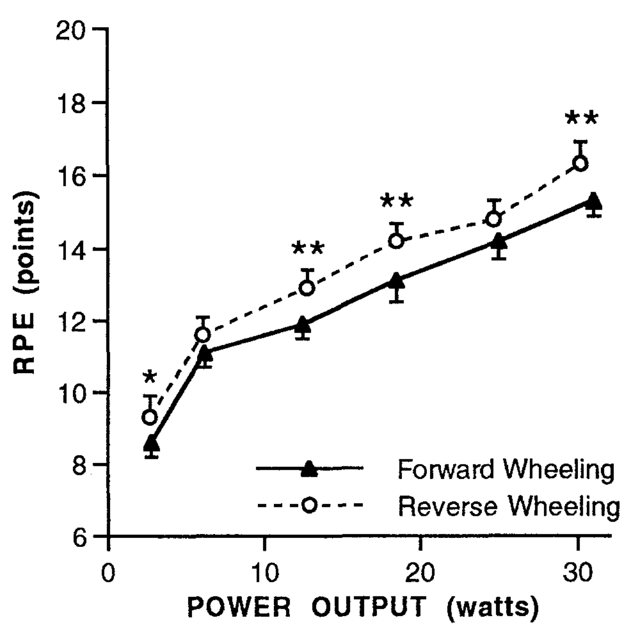

Fig 5. Mean RPE values for the two wheeling techniques. (Symbols are the same as in figure 3.)

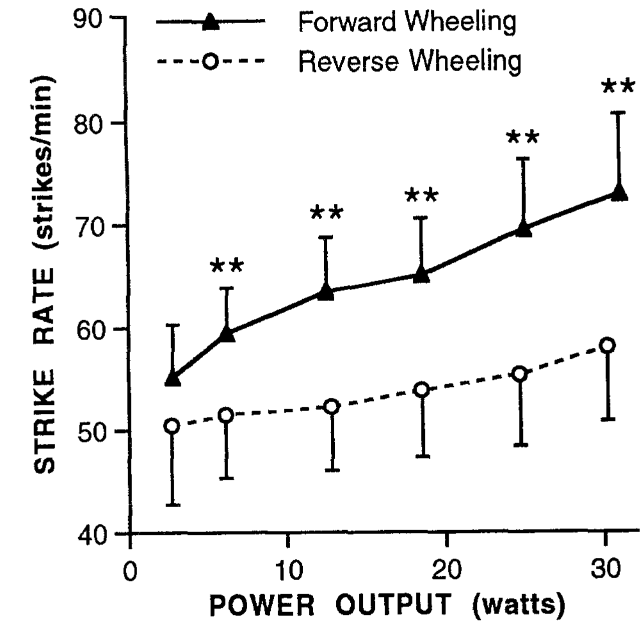

Fig 6. Mean strike rates for the two wheeling techniques. (Symbols are the same as in figure 1.)

the contradiction between our study and Linden's report? One difference between studies was that our subjects selected the wheeling technique that felt optimal, whereas Linden's subjects were instructed to use a specific movement pattern. Compared with observations of our subjects, the reverse wheeling technique used by Linden was described as using a more prominent forward flexion of the trunk to grab the wheel rim at a lower starting point during each stroke. This technique may have allowed for increased use of the relatively large back extensor muscle mass, but it is unknown whether this difference in movement pattern would affect the economy of movement. Related factors that might affect the efficiency of wheelchair propulsion include differences in recovery phase technique and the proportion of the cycle in which propulsive forces are generated.[24,25] The study by Linden also used a stool placed between two independent wheel ergometers. The absence of a seat back might have provided an extended range for the reverse propulsion handrim pull, again increasing the contribution of the back extensors. Absence of a seat back might also have had a negative impact on the forward wheeling technique. The reaction to a forward handrim push includes forces transmitted through the shoulders and torso in a backwards direction. To keep the trunk from extending beyond a neutral seated position, additional energy must be spent stabilizing the torso. Therefore, when a seat back is present to stabilize the torso, force transmission to the wheelchair handrims should require less energy during forward propulsion. Finally, the position of the wheel axis relative to the seat was not reported by Linden.[22] It is possible that the relative economy of forward and reverse wheeling techniques could be altered by seat height and wheel axis position.[26]

Unfortunately, even if the increased use of back extensor muscles might allow a reverse wheeling technique to be more economical than the conventional forward wheeling technique, its generalizability would still be limited. Spinal cord injured patients, one major subgroup of wheelchair users, frequently have absent or diminished use of these muscles.

We purposely selected as subjects able-bodied individuals who were inexperienced in wheelchair propulsion. We reasoned that experienced wheelchair users would have developed the muscle mass and perfected the movement pattern used in the forward wheeling technique.[27-29] The use of novice wheelchair users avoided a bias favoring the conventional forward propulsion technique that would be present among experienced wheelchair users.

Given the relatively low efficiency of wheelchair propulsion, improving the economy of this mode of transportation remains a desirable goal. Although under the conditions of the present study, the reverse wheeling technique was demonstrated to be more physiologically demanding than the conventional forward wheeling technique, the possible benefits of reverse wheeling have not been fully examined. It is possible that there are wheelchair users (ie, those with good back extensors or some quadriplegic individuals who might be able to pull on a handrim better than they can push) who could benefit from the use of a reverse wheeling technique. Design changes that include alteration in the position of the wheel axis relative to the seat might also allow for improved economy of a reverse wheeling technique. Finally, reverse wheeling might reduce the morbidity from overuse syndromes that develop from conventional forward wheelchair propulsion and might also serve as a tool for increasing the function of what might otherwise be relatively underused muscles.

Acknowledgment: The wheelchair used in the study was provided by Functional Rehab Inc.

References

1. LaPlante MP, Hendershot GE, Moss AJ. Assistive technology devices and home accessibility features: prevalence, payment, need, and trends. Advance Data 1992;217:1-8.
2. Cerquiglini S, Figura F, Marchetti M, Ricci B. Biomechanics of wheel chair propulsion. In: Moreki A, Fidelis K, Kedzior K, Wit A, editors. Biomechanics VII-A. Baltimore (MD): University Park Press; 1981. p. 410-19.
3. Bergh U, Kanstrup I-L, Ekblom B. Maximal oxygen uptake during exercise with various combinations of arm and leg work. J Appl Physiol 1976;41:191-6.
4. Brattgård S-O, Grimby G, Höök O. Energy expenditure and heart rate in driving a wheel-chair ergometer. Scand J Rehabil Med 1970; 2:143-8.
5. Donovan CM, Brooks GA. Muscular efficiency during steady-rate exercise II. Effects of walking speed and work rate. J Appl Physiol Respir Envir Exerc Physiol 1977;43:431-9.
6. Gaesser GA, Brooks GA. Muscular efficiency during steady-rate exercise. Effects of speed and work rate. J Appl Physiol 1975;38: 1132-9.
7. Glaser RM. Exercise and locomotion for the spinal cord injured. Exerc Sport Sci Rev 1985;13:263-303.
8. Glaser RM, Sawka MN, Laubach LL, Suryaprasad AG. Metabolic and cardiopulmonary responses to wheelchair and bicycle ergometry. J Appl Physiol Respir Envir Exerc Physiol 1979;46:1066-70.
9. Hildebrandt G, Voigt E-E, Bahn D, Berendes B, Kroger J. Energy costs of propelling wheelchair at various speeds: cardiac responses and effect on steering accuracy. Arch Phys Med Rehabil 1970;51: 131-6.
10. Stoboy H, Rich BW, Lee M. Workload and energy expenditure during wheelchair propelling. Paraplegia 1971;8:223-30.
11. Hoffman MD. Cardiorespiratory fitness and training in quadriplegics and paraplegics. Sports Med 1986;3:312-30.
12. Nichols PJ, Norman PA, Ennis JR. Wheelchair user's shoulder. Shoulder pain in patients with spinal cord lesions. Scand J Rehabil Med 1979;11:29-32.
13. Rogers MM, Gayle GW, Figoni SF, Kobayashi M, Lieh J, Glaser RM. Biomechanics of wheelchair propulsion during fatigue. Arch Phys Med Rehabil 1994;75:85-93.
14. Subbarao JV, Klopfstein J, Turpin R. Prevalence and impact of wrist and shoulder pain in patients with spinal cord injury. J Spinal Cord Med 1995;18:9-13.
15. Engel P, Hildebrandt G. Wheelchair design-technological and physiological aspects. Proc R Soc Med 1974;67:409-13.

16. Glaser RM, Sawka MN, Young RE, Suryaprasad AG. Applied physiology for wheelchair design. J Appl Physiol Respir Envir Exerc Physiol 1980;48:41-4.
17. Sawka MN, Glaser RM, Wilde SW, von Luhrte TC. Metabolic and circulatory responses to wheelchair and arm crank exercise. J Appl Physiol Respir Envir Exerc Physiol 1980;49:784-8.
18. Smith PA, Glaser RM, Petrofsky JS. Arm crank vs handrim wheelchair propulsion: metabolic and cardiopulmonary responses. Arch Phys Med Rehabil 1983;64:249-54.
19. Van der Woude LH, de Groot G, Hollander AP, van Ingen Schenau GJ, Rozendal RH. Wheelchair ergonomics and physiological testing of prototypes. Ergonomics 1986;29:1561-73.
20. Van der Woude LH, van Kranen E, Ariëns G, Rosendal RH, Veeger HE. Physical strain and mechanical efficiency in hubcrank and handrim wheelchair propulsion. J Med Eng Tech 1995;19:123-31.
21. Van der Woude LH, Veeger HE, de Boer Y, Rosendal RH. Physiological evaluation of a newly designed lever mechanism for wheelchairs. J Med Eng Tech 1993;17:232-40.
22. Linden AL, Holland GJ, Loy SF, Vincent WJ. A physiological comparison of forward vs reverse wheelchair ergometry. Med Sci Sports Exerc 1993;25:1265-8.
23. Borg G. Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med 1970;2:92-8.
24. Sanderson DJ, Sommer HJ III. Kinematic features of wheelchair propulsion. J Biomechanics 1985;18:423-9.
25. Vanlandewijck YC, Spaepen AJ, Lysens RJ. Wheelchair propulsion efficiency: movement pattern adaptations to speed changes. Med Sci Sports Exerc 1994;26:1373-81.
26. Mâsse LC, Lamontagne M, O'Riain MD. Biomechanical analysis of wheelchair propulsion for various seating positions. J Rehabil Res Dev 1992;29:12-28.
27. Brown DD, Knowlton RG, Hamill J, Schneider TL, Hetzler RK. Physiological and biomechanical differences between wheelchair dependent and able-bodied subjects during wheelchair ergometry. Eur J Appl Physiol 1990;60:179-82.
28. Robertson RN, Boninger ML, Cooper RA, Shimada SD. Pushrim forces and joint kinetics during wheelchair propulsion. Arch Phys Med Rehabil 1996;77:856-64.
29. Veeger HEJ, Lute EMC, Roeleveld K, van der Woude LHV. Differences in performance between trained and untrained subjects during a 30-s sprint test in a wheelchair ergometer. Eur J Appl Physiol 1992;64:158-64.

Suppliers

a. Everest and Jennings Vista 18 × 16; Everest and Jennings, 3601 Rider Trail South, Earth City, MO 63045.
b. Department of Veterans Affairs, Rehabilitation Research and Development, Technology Transfer Section, 103 South Gay Street, Baltimore, MD 21203.
c. Beckman OM-11 oxygen analyzer; SensorMedics Corporation, 1630 South State College Boulevard, Anaheim, CA 92806.
d. Beckman LB-2 carbon dioxide analyzer; SensorMedics Corporation, 1630 South State College Boulevard, Anaheim, CA 92806.
e. Rayfield Equipment Ltd., P.O. Box 819 Village Square, Waitsfield, VT 05673.
f. Polar Vantage XL heart rate monitor; Polar USA, Inc., 470 West Avenue, Stamford, CT 06902.
g. Yellow Springs Instruments model 27 lactate analyzer; Yellow Springs Instrument Company, Inc., 1725 Brannum Lane, Yellow Springs, OH 45387.