ORIGINAL ARTICLE

Power-Assisted Wheels Ease Energy Costs and Perceptual Responses to Wheelchair Propulsion in Persons With Shoulder Pain and Spinal Cord Injury

Mark S. Nash, PhD, Daan Koppens, MD, Mirjam van Haaren, MD, Andrew L. Sherman, MD, James P. Lippiatt, John E. Lewis, PhD

ABSTRACT. Nash MS, Koppens D, van Haaren M, Sherman AL, Lippiatt JP, Lewis JE. Power-assisted wheels ease energy costs and perceptual responses to wheelchair propulsion in persons with shoulder pain and spinal cord injury. Arch Phys Med Rehabil 2008;89:2080-5.

Objective: Test effects of pushrim-activated power-assisted wheelchairs (PAPAWs) on the energetics and perceptual responses to steady-state and intensity-graded wheelchair propulsion in persons with paraplegia and tetraplegia having chronic shoulder pain.

Design: Test, retest with a control condition.

Setting: Academic medical center.

Participants: Subjects (N=18) aged 19 to 70 years with chronic, motor-complete paraplegia and tetraplegia having confirmed shoulder pain.

Interventions: Study participants underwent testing on 4 randomized nonconsecutive days during either 6 minutes of steady-state or 12 minutes of intensity-graded wheelchair propulsion on stationary rollers. Participants used their own manual wheelchair and either their customary wheels or power-assist wheels attached with an axle bracket.

Main Outcome Measures: Oxygen consumption ($\dot{V}O_2$, L/min), distance (m), energy cost (L/m), and ratings of perceived exertion (RPE; Borg Categorical 6–20 Scale) were measured during propulsion.

Results: Significant main effects of testing were observed for $\dot{V}O_2$, heart rate, and RPE in both subject groups. Distances propelled were significantly increased in both groups across both tests and in each of their 2-minute exercise stages.

Conclusions: Use of PAPAWs by persons with paraplegia and tetraplegia having shoulder pain significantly lowers energy cost responses and perceived exertion compared with manual wheelchair propulsion while significantly increasing the distanced propelled.

Key Words: Exertion; Pain; Shoulder; Spinal cord injuries; Rehabilitation; Wheelchairs.

PAIN ACCOMPANIED BY diminishing function of the upper limbs is a familiar medical problem faced by persons with SCIs.[1,2] Upper-limb pain after SCI is the most widespread symptom of physical dysfunction[3-5] and the shoulder is the most common site,[3,6-9] with complaints of pain ranging from 35%[10] to 73%[5] of persons with chronic SCI. Onset of pain from muscle and joint overuse occurs earlier in those with SCI than persons without disability, and worsens with time and advancing age.[3,11] Although a sole cause for shoulder pain has not been identified, many studies attribute pain to deterioration and injury resulting from insufficient shoulder strength, range, and muscle endurance.[8,9,11-13]

Several essential daily activities are known to precipitate pain in persons with SCI, including wheelchair propulsion on level surfaces and inclines, and weight bearing sustained during body transfers.[2,8,14,15] Wheelchair propulsion and depression transfers cause the most pain, and increase the intensity of existing pain to a greater extent than other daily activities.[16] Up to half of persons with SCI experience intensified shoulder pain during these activities,[14] which are critical for health maintenance. The onset of pain from wheelchair propulsion is especially troubling because the wheelchair is the device most widely relied on for sustaining mobility and personal independence.

A straightforward solution for pain arising from manual propulsion of wheelchairs might be to abandon their use in favor of powered chairs. Although use of electric powered wheelchairs might spare the shoulder complex and arm from incipient pain and dysfunction, they are expensive, require special vans and lifts, and afford little flexibility for persons who are capable of manually propelling their chair and might occasionally wish to. To address these limitations a series of power-assisted wheels that can be mounted on an existing manual wheelchair have been brought to the marketplace. These devices, referred to as PAPAWs,[17,18] offer a power-assist to the user during arm-driven propulsion. The benefit of these devices has been reported by several investigators,[17-20] although the populations undergoing study are generally healthy, may incorporate study participants with varied disability diagnoses, and are sometimes tested using a wheelchair with which they are fundamentally unfamiliar. Pain is typically an exclusion criterion for study participation.

The purpose of the current study was to examine the energy cost and perceptual effort of persons with tetraplegia and

List of Abbreviations

PAPAW	pushrim-activated power-assisted wheelchairs
RPE	ratings of perceived exertion
SCI	spinal cord injury
$\dot{V}O_2$	oxygen consumption
WUSPI	Wheelchair Users Shoulder Pain Index

From the Departments of Neurological Surgery (Nash), Rehabilitation Medicine (Nash, Sherman), Psychiatry and Behavioral Sciences (Lewis), and the Miami Project to Cure Paralysis (Nash), Miller School of Medicine, University of Miami, Miami, FL; Department of Physical Therapy, Jackson Memorial Rehabilitation Center, Miami, FL (Lippiatt); and Department of Physiology, Radboud University Nijmegen Medical Centre, Nijmegen, The Netherlands (Koppens, van Haaren).

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Reprint requests to Mark S. Nash, PhD, The Miami Project to Cure Paralysis, University of Miami Miller School of Medicine, Lois Pope Life Center, 1095 NW 14th Terrace, R-48, Miami, FL, 33136, e-mail: *msnash@miami.edu*.

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paraplegia during steady-state and intensity-graded wheelchair locomotion. To examine the patient population that would best benefit from power assistance, and control for critical elements of wheelchair characteristics, testing was conducted in study participants with motor-complete SCI having confirmed shoulder pain, and when using their customary manual wheelchair adapted for use with PAPAWs.

METHODS

Subjects

Study participants in this randomized, controlled study were 18 men aged 19 to 70 years (mean ± SD, 39.1±12.3y) with motor-complete (American Spinal Injury Association score A/B) tetraplegia (n=6) and paraplegia (n=12) at the C5-L1 spinal levels. Participants were injured for 1 to 21 years (9.2±7.4y) and used a manual wheelchair as their primary means of mobility. All participants were in good health, community-dwelling, and recreationally active, and reportedly free from infection and illness at the times of testing. All consented to participate after review and approval of the study by the institutional medical sciences committee for the protection of human subjects.

Testing For Shoulder Pain

Because the study sought to examine wheelchair locomotion in persons with existing shoulder pain, participants self-administered the WUSPI.[12] The WUSPI is a 15-item self-report instrument that measures shoulder pain during transfers, wheelchair mobility, self care, and general activities. It is a valid and reliable measure of shoulder pain causing limitation of function for people who use wheelchairs for locomotion. The WUSPI was scored using a visual analog scale according to the methods of Curtis et al,[12] with possible scores ranging from 0 to 10 for each of the 15 items. Individual item scores were summed to achieve a total index score ranging from 0 to 150. The WUSPI items include: transfers (bed-wheelchair, car-wheelchair, tub/shower-wheelchair, load wheelchair in car); wheelchair mobility (>10-min duration, ramp/uneven); self care (lift object from overhead, put on pants, put on T-shirt, put on button-down shirt, wash back); and general activities (work/school activities, driving, household chores, sleeping).

Practice Session and Testing Protocols

We performed testing in an indoor, room-temperature environment using either the participants' customary wheelchair or the same chair retrofitted with PAPAWs (E-Motion[a]). To execute the modification, all ordinary wheelchairs had a bracket adapter affixed to the frame that interfaced with the axle shaft of both manual and power-assist wheels. This fixed a common axle position for use under both testing conditions while maintaining uniformity in other seating dimensions, configurations, and cushions. Study participants whose customary wheels had rubber-coated hand rims used PAPAWs with a rubber molding placed tightly over the metal rim. Testing was conducted at the default setting for indoor propulsion (stage 1). Sensitivity was set at the midpoint of the operating range. Starting, degree of assistance, and after-running parameters were set at number 1 for participants with paraplegia (respectively, 0.4s, 12Nm torque, 0.8s) and number 8 (respectively, 0.9s, 24Nm torque, 0.8s) for those with tetraplegia. This provided the minimum recommended assistance and after-running.

Testing was performed on a stationary platform with rollers on which the wheelchairs were mounted and secured (fig 1). Each study participant underwent 5 testing sessions. The first session was used to familiarize each subject with the exercise platform and PAPAWs. Thirty minutes were allowed for subjects to practice unresisted steady-state wheelchair propulsion with their customary chair, after which the PAPAWs were mounted and the same time was allowed to experience the novelty of the PAPAWs testing condition.

Fig 1. A study participant prepared for metabolic monitoring with the wheelchair secured on stationary rollers and a PAPAW mounted on the wheelchair.

The 4 testing sessions were randomized in order and performed on nonconsecutive days within a 2-week period. Two sessions consisted of unresisted, steady-state wheelchair locomotion for 6 minutes at the greatest attainable speed. The remaining 2 sessions consisted of graded wheelchair locomotion for 12 minutes at greatest attainable speed. Resistance was applied to the rollers in 1kg increments every 2 minutes using a calibrated force meter. The 2 conditions were tested using customary wheels and PAPAWs. Participants were instructed to "go as far and fast as possible," but received no additional guidance or verbal encouragement during testing.

Data Collection

Before testing, we prepared participants for metabolic analysis by placing a pliable mask over the nose and mouth. Expired air was analyzed for $\dot{V}O_2$ by the open-circuit method (Vmax229[b]) and expressed in L/min. Distance propelled was measured by a cyclometer interfaced with the wheelchair rollers and expressed in meters. RPE were obtained every 2 minutes using the Borg Categorical 6-20 Scale. The energy cost of locomotion was computed as the ratio of absolute $\dot{V}O_2$ to the distance traveled during the same time interval. Data for all dependent measures were collected at baseline and 2-minute intervals thereafter.

Data Analysis

We analyzed data using SPSS for Windows.[c] Frequency and descriptive statistics were calculated to check all relevant characteristics of the data. A repeated-measures model analysis of variance was used to examine main effects for group (tetraplegia vs paraplegia), wheel (customary vs PAPAWs), and time. Significant interaction effects were further examined using simple effects tests. To control type I and family-wise error rates, a Holm-modified Bonferroni correction method[21] was applied to each family of contrasts (group, wheel, time, wheel ×

time interaction, and group × time interaction) for each of the 4 dependent variables (oxygen uptake, distance propelled, energy cost, and perceived exertion). All *P* values were ordered from lowest to highest and then assessed against the corrected *P* values, which were .013, .017, .025, and .050, respectively.

RESULTS

WUSPI scores obtained before testing were 10.4±13.9 based on a range from 0 to 42. Pain ratings were nearly equal between groups, with average WUSPI ratings of 10.2 and 10.8 for participants with paraplegia and tetraplegia, respectively. When queried, the single subject reporting a WUSPI score of 0 acknowledged shoulder pain sufficient to avoid all activities specified on the WUSPI instrument. This clarification justified inclusion of the subject's data in the analysis.

Six-Minute Steady-State Test Sessions

Data for steady-state propulsion trials are shown in table 1.

Oxygen Uptake

For $\dot{V}O_2$, significant effects were found for group ($F_{1,32}=17.2$, *P*<.001), time ($F_{3,96}=37.6$, *P*<.001), and the group × time interaction ($F_{3,96}=11.2$, *P*<.001). Further analysis of these interaction effects indicated significant increases at each time point between time 0 and 6 for the persons with paraplegia, but not for those with tetraplegia.

Distance Propelled

For distance, significant effects were found for group ($F_{1,32}=50.3$, *P*<.001), wheel ($F_{1,32}=27.3$, *P*<.001), time ($F_{3,96}=247.5$, *P*<.001), the group × time interaction ($F_{3,96}=27$, *P*<.001), and the wheel × time interaction ($F_{3,96}=14.7$, *P*<.001) with the persons with paraplegia traveling significantly farther than the persons with tetraplegia, and the PAPAWs traveling farther than the customary wheels. Additional analyses of the interaction effects indicated that the magnitude of change was greater in the persons with paraplegia and when the subjects used the PAPAWs.

Energy Cost

A significant effect for wheel was found for energy cost ($F_{1,32}=9.7$, *P*<.01) with the customary wheels requiring a greater energy cost than the PAPAWs.

Perceived Exertion

For RPE, time was the only significant effect that was observed ($F_{3,96}=52.3$, *P*<.001), with the score getting significantly higher at each stage across all subjects. Table 2 shows data collected during the 6-minute steady-state trial.

Twelve-Minute Test Sessions

Data for resistive propulsion trials are shown in table 2.

Oxygen Uptake

For $\dot{V}O_2$, significant effects were found for group ($F_{1,32}=14.8$, *P*=.001), time ($F_{6,192}=18.0$, *P*<.001), and the group × time interaction ($F_{6,192}=7.5$, *P*<.001). Further analysis of these interaction effects indicated significant increases at each time point between time 0 and 12 for the persons with paraplegia, but not for those with tetraplegia.

Distance Propelled

For distance, significant effects were found for group ($F_{1,32}=59.6$, *P*<.001), wheel ($F_{1,32}=66.9$, *P*<.001), time ($F_{6,192}=216.5$, *P*<.001), the group × time interaction ($F_{6,192}=22.3$, *P*<.001), and the wheel × time interaction ($F_{6,192}=25.8$, *P*<.001) with the persons with paraplegia traveling significantly farther than the persons with tetraplegia and the PAPAWs traveling farther than the regular wheels. Additional analyses of the interaction effects indicated that the magnitude of change was greater in the persons with paraplegia and when the subjects used the PAPAWs.

Table 1: Comparison of Responses to Unresisted, Steady-State Wheelchair Locomotion Under Customary and Power-Assisted (PAPAW) Conditions

Minute	Wheel	$\dot{V}O_2$*‡ (L/min)	Energy Cost† (L/m)	Distance$^{*\dagger\ddagger\S\|}$ (m)	RPE‡
Paraplegia (n=12)					
Rest	Customary	0.275±0.16			6.0±0
	PAPAW	0.228±0.13			6.0±0
2	Customary	0.796±0.39	8.19±4.24	165.8±36.8	9±3.3
	PAPAW	0.554±0.25	3.86±1.37	246.7±24.6	7.8±2.1
4	Customary	0.817±0.40	9.69±4.95	163.3±40.1	10.1±3.5
	PAPAW	0.616±0.24	4.82±1.76	248.3±19.9	8.7±2.6
6	Customary	0.789±0.46	9.27±4.65	165.7±52.4	11.3±4.0
	PAPAW	0.672±0.30	4.93±1.91	260.8±26.4	10.2±3.9
Tetraplegia (n=6)					
Rest	Customary	0.152±0.05			6.0±0
	PAPAW	0.150±0.04			6.0±0
2	Customary	0.310±0.10	17.87±19.38	70.5±56.5	10.0±3.2
	PAPAW	0.272±0.07	5.18±4.27	141.7±68.0	9.7±3.1
4	Customary	0.286±0.09	15.39±11.97	70.1±58.6	12.0±3.3
	PAPAW	0.278±0.09	6.47±5.23	131.7±68.2	10.8±3.9
6	Customary	0.299±0.09	14.58±13.63	74.8±58.5	13.7±4.0
	PAPAW	0.277±0.11	5.49±3.98	141.7±65.5	11.5±4.5

NOTE. Values are mean ± SD. Significant analysis of variance effects: *group; †wheel; ‡time; §group × time interaction; $^{\|}$wheel × time interaction.
Abbreviation: L/m, locomotion.

Table 2: Comparison of Responses to Resistance-Graded Wheelchair Locomotion Under Manual and Power-Assisted Conditions

Minute	Wheel	$\dot{V}O_2$*‡§ (L/min)	Energy Cost† (L/m)	Distance*†‡§‖ (m)	RPE†‡‖
Paraplegia (n=12)					
Rest	Customary	0.235±0.08			6.0±0
	PAPAW	0.208±0.08			6.0±0
2	Customary	0.612±0.32	8.34±2.40	134.2±30.3	8.5±1.8
	PAPAW	0.512±0.20	4.74±3.94	218.3±44.3	7.1±1.1
4	Customary	0.627±0.36	9.42±3.71	133.3±27.7	10.2±2.7
	PAPAW	0.505±0.21	4.68±2.90	227.5±44.3	8.4±2.7
6	Customary	0.643±0.33	9.48±3.41	136.7±31.1	11.1±2.7
	PAPAW	0.521±0.24	4.73±3.22	231.7±28.9	9.7±2.2
8	Customary	0.627±0.32	8.89±3.48	141.7±36.1	11.8±3.0
	PAPAW	0.556±0.26	5.00±3.78	235.0±33.2	10.0±2.3
10	Customary	0.644±0.35	9.22±3.68	139.2±34.8	12.5±3.3
	PAPAW	0.534±0.26	4.91±3.67	234.2±31.2	10.8±2.7
12	Customary	0.688±0.35	9.25±3.81	140.0±36.7	13.3±3.2
	PAPAW	0.634±033	5.32±3.08	230.8±28.4	11.3±3.0
Tetraplegia (n=6)					
Rest	Customary	0.181±0.05			6.0±0
	PAPAW	0.182±0.06			6.0±0
2	Customary	0.218±0.05	7.96±1.66	48.3±34.3	9.7±2.7
	PAPAW	0.218±0.09	4.27±3.41	128.3±58.1	8.2±1.9
4	Customary	0.281±0.09	18.03±18.54	48.3±28.3	10.8±1.9
	PAPAW	0.290±0.12	5.10±4.01	140.0±63.2	9.0±2.7
6	Customary	0.314±0.14	17.83±15.66	50.0±30.3	12.3±1.9
	PAPAW	0.263±0.10	4.82±3.06	131.7±59.8	10.3±3.4
8	Customary	0.286±0.11	13.57±9.07	43.3±38.3	13.5±2.5
	PAPAW	0.251±0.09	4.50±2.31	147.9±46.5	11.3±3.5
10	Customary	0.287±0.14	20.85±19.23	43.3±28.0	14.2±2.9
	PAPAW	0.237±0.06	4.47±2.66	149.4±42.8	12.0±3.8
12	Customary	0.292±0.04	8.94±4.74	45.0±28.8	15.3±3.4
	PAPAW	0.245±0.10	4.01±1.85	159.6±35.2	12.5±4.5

NOTE. Values are mean ± SD. Significant analysis of variance effects: *group; †wheel; ‡time; §group × time interaction; ‖wheel × time interaction.
Abbreviation: L/m, locomotion.

Energy Cost

A significant effect was found for the wheel ($F_{1,32}=20.4$, $P<.001$) with the customary wheels requiring a higher energy cost than the PAPAWs.

Perceived Exertion

For RPE, time ($F_{6,192}=89.6$, $P<.001$), and the wheel × time interaction ($F_{6,192}=2.2$, $P<.05$) were significantly different with the score rated significantly higher at each stage across all subjects, and the overall score for PAPAWs being lower than the customary wheels. Further analysis of the interaction effects indicated a significant increase in RPE between time 0 and 12 for both customary wheels and PAPAWs, with the magnitude of change being greater in the customary wheels at time 2, 4, and 12. See table 2 for a description of the data during the 12-minute sessions.

DISCUSSION

The key finding of this study is that persons with chronic paraplegia and tetraplegia, and pain in their shoulders, propel their wheelchairs farther, at lower energy cost, and with a reduced perception of exertion, when using PAPAWs. These findings are consistent with previous studies examining metabolic advantages conferred by use of PAPAWs,[20,22] and they apply to people with SCI having established shoulder joint pain. Because previous studies reporting that wheelchair propulsion is easier when using a power assist have studied persons without physical disability or functional limitation, Cooper et al[22] have suggested that testing of PAPAWs should include subjects with impaired upper-extremity functions. Because upper-limb pain worsens the impairment imposed by SCI, Cooper's study was the first to test the advantages of the study device in a population that would benefit most from their use. The design of this study also allowed participants to use their customary wheelchair and cushion for both test conditions. In several studies subjects were tested when propelling an unfamiliar, mechanically-instrumented wheelchair.[17-19] Such testing afforded the advantage of data collection on the biomechanics of propulsion not undertaken by our study, but it had the disadvantage of subtly changing the wheelchair configuration to one with which test subjects might have been less familiar.[17-19]

The benefits provided by power assist to wheelchair propulsion have been noted by a number of investigators using various outcome assessments. Several studies have noted reduced oxygen consumption and heart rate at several speeds when compared with manual wheelchair propulsion.[20,22] Algood et al[17] reported subjective ratings of PAPAWs use that were lower than those reported during propulsion of the customary chair. Ease of propulsion as assessed by reports on a visual analog scale was accompanied by lower heart rate responses during the use of

PAPAWs. It is reasonable to expect that decreased range reported during PAPAWs use is partly responsible for this lower perception of effort.[19]

Results obtained from subjects with SCI and shoulder pain confirm benefits of power assistance during wheelchair propulsion. During steady state work for people with paraplegia, the observed energy cost of locomotion during PAPAWs use was roughly half that observed during propulsion of the customary wheelchair. The distance covered at this energy cost averaged 80% greater and did so at a perceived exertion reduced by about 11%. Benefits for those tested with paraplegia were comparable for distance covered and greater for reduction of energy cost and perceived exertion. Under graded exercise conditions, the energy cost regardless of workload was roughly half that of conventional locomotion during PAPAWs use, while moving at a velocity that was 65% greater, but perceived as 15% less. As observed during steady-state test conditions, the energy savings for those with tetraplegia were greater than for those with paraplegia, and at higher work intensities expended about 75% less energy during PAPAWs use, while propelling 3-4 times farther and at a 15% reduction in perceived exertion. Interestingly, self-selected locomotion velocities for both test groups were remarkably consistent across time while at steady state, and equally consistent in the graded test regardless of imposed resistance. Because stroke repetitions are a key factor in the development of upper-limb pain for those with SCI, it is reasonable to assert that use of the PAPAWs might reduce, or at least counterbalance, wheelchair-associated upper-limb pain. Nonetheless, evidence for this belief requires direct assessment.

Study Limitations

The study findings are limited by lack of data collection for stroke rate or range. Notwithstanding these limitations, distances propelled were remarkably consistent across time and resistance. Propulsion was conducted on wheelchair rollers, which has the benefit of standardizing testing conditions but the disadvantage of not reflecting the biomechanics or energy costs of propulsion over terrain. Further, propulsion velocities when using their customary wheels were somewhat faster than those reported in persons with paraplegia when pushing over a tile surface, and slightly faster than 55 m/min reported in those with C-6 tetraplegia.[23] Although we find a significant benefit of PAPAWs when tested at the described propulsion velocities and resistance levels, confirmation of other potential benefits must await direct testing under the unique conditions of use. For example, use of the wheels has been reported to benefit elderly persons who must traverse challenging terrain.[18] Conversely, a decision to adopt the wheels for habitual or occasional use must also incorporate an appreciation of their added weight, which we measured at 12kg (26.5lb) each (including drive wheel and battery). The wheels also add about 2.5cm to the thickness of typical wheelchair wheels. These factors may be especially limiting in persons with shoulder pain who manually lift a wheelchair into a vehicle, or for those encountering architectural restrictions such as narrow doorways.

CONCLUSIONS

The use of PAPAWs by persons with tetraplegia and paraplegia spares the energy of wheelchair propulsion, while increasing locomotion velocity. Propulsion in both study groups was accompanied by a reduced perception of effort despite the greater distances navigated.

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Suppliers

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