Published in final edited form as:

Arch Phys Med Rehabil. 2014 March ; 95(3): 546–551. doi:10.1016/j.apmr.2013.08.238.

Comparison of Metabolic Cost, Performance, and Efficiency of Propulsion Using an Ergonomic Hand Drive Mechanism and a Conventional Manual Wheelchair

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Abstract

Objectives—To compare the metabolic cost (VO₂ consumption, HR, and number of pushes), performance (velocity and distance travelled), and efficiency (VO₂ efficiency) of propulsion using a novel ergonomic hand drive mechanism (EHDM) and a conventional manual wheelchair (CMW).

Design—Repeated measures crossover design

Setting—Semi-circular track

Participants—Twelve adult full-time manual wheelchair users with spinal cord injuries (38.8±12.4 yrs, 73.7±13.3 kg, 173.6±11.1 cm) who were medically and functionally stable and at least six months post injury.

Interventions—Participants propelled themselves for three and a half minutes at a self-selected pace in a CMW and in the same chair fitted with the EHDM.

Main Outcome Measures—Velocity, distance traveled, number of pushes, VO₂ consumption, VO₂ efficiency, and heart rate were compared by wheelchair condition for the last 30 seconds of each trial using paired t-tests ($\alpha=0.01$).

Results—The CMW condition resulted in more distance traveled (33.6±10.8 m vs. 22.4±7.8 m, $p=0.001$), greater velocity (1.12±0.4 m/s vs. 0.75±0.3 m/s, $p=0.001$), and better VO₂ efficiency (0.10±0.03ml/kg/m vs. 0.15±0.03ml/kg/m, $p<0.001$) than the EHDM condition. No significant differences were found between the two conditions for number of pushes (27.5±5.7 vs. 25.7±5.4, $p=0.366$), VO₂ consumption (6.43±1.9 ml/kg/min vs. 6.19±1.7 ml/kg/min, $p=0.573$), or HR (100.5±14.5 bpm vs. 97.4±20.2 bpm, $p=0.420$).

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Conclusions—The results demonstrate that metabolic costs did not differ significantly although performance and efficiency were sacrificed with the EHDM. Modifications to the EHDM (e.g. addition of gearing) could rectify the performance and efficiency decrements while maintaining similar metabolic costs. Although not an ideal technology, the EHDM can be considered as an alternative mode of mobility by wheelchair users and rehabilitation specialists.

Keywords

Wheelchairs; Ergonomics; Oxygen Consumption; Heart Rate

In the United States in 2010, the National Spinal Cord Injury Statistical Center estimated that 232,000 to 316,000 individuals have a spinal cord injury, with approximately 12,000 new injuries occurring each year. Most of these individuals depend upon a conventional manual wheelchair (CMW) for mobility. However, CMW use is associated with repetitive strain injuries^{1,2}, which are characterized by shoulder and wrist pain (30 to 73% of CMW users)^{3–5} and have been shown to greatly reduce these individuals' overall quality of life⁶. Upper limb pathology can inhibit CMW users' ability to propel themselves or perform activities of daily living, reducing their activity levels and interfering with their general independence. Further, numerous secondary health issues, such as increased risk of heart failure, can arise due to decreased activity levels^{7,8}. As a result, developing healthier and safer modes of wheelchair propulsion is an important area of study.

Lever-propelled wheelchairs have been developed as an alternative to the CMW and are designed to reduce repetitive strain injuries^{2,9,10}. Previous research shows that lever-propelled wheelchair designs shift and reduce shoulder muscular demands, decreasing the risk of incurring rotator cuff injuries². In the same way that exercise on an elliptical trainer reduces knee joint reaction forces generated during overground running¹¹, the continuous contact of the hand with the grip and more constant force application may reduce wrist joint reaction forces⁹. Further, lever-propelled wheelchair use permits both a more relaxed grip and more neutral orientation of the wrist, reducing overall muscular force needed⁹.

In general, wheelchair users report greater overall satisfaction with a lever-propelled wheelchair as compared to a CMW, although previous designs do not consider user anthropometrics^{9,10}. Therefore, a novel ergonomic hand drive mechanism (EHDM) was designed and machined for this study that incorporates an adjustable lever length as well as a pivoting handgrip. Ergonomic can be operationally defined as matching an individual's biomechanical properties to his environment in order to minimize discomfort. Therefore, both the adjustable lever length and pivoting handgrip are ergonomic features designed to allow wheelchair users of different physical capabilities and varying height/arm lengths to comfortably and effectively propel themselves. The effectiveness of the ergonomic design in shifting awkward postures to more neutral shoulder, elbow, and wrist ranges of motion and lessening the risk of developing shoulder impingement syndrome has been shown previously, with implications for reducing pain associated with upper limb pathologies^{12,13}. Despite these benefits, it is not known whether the lever system is efficient or imposes additional metabolic costs onto the user.

The metabolic costs of wheelchair propulsion are typically quantified by oxygen uptake per unit time (VO₂ consumption), heart rate (HR), and push frequency, while efficiency is typically quantified by oxygen uptake per distance travelled (VO₂ efficiency). CMW metabolic cost and efficiency have been studied in depth for wheelchair users. A study of wheelchair racers determined that the self-selected push frequency at any set speed resulted in the lowest metabolic costs¹⁴. Additionally, these researchers found that VO₂ consumption and HR are non-linearly related to push frequency. Subsequent studies of wheelchair racers and members of the general CMW population have also found a relationship between VO₂ consumption and HR^{15–17}. As opposed to VO₂ consumption, VO₂ efficiency has been shown to differentiate between groups of wheelchair users when self-selected speeds are used¹⁸. Accordingly, a number of researchers have opted to use VO₂ efficiency to determine the relative efficiencies of persons with paraplegia and tetraplegia on different floor surfaces and using different CMWs^{19,20}. These studies together substantiate VO₂ consumption, HR, push frequency, and VO₂ efficiency as appropriate variables for the examination of metabolic cost and efficiency of wheelchair propulsion.

Although not as thoroughly explored, a few researchers have examined the metabolic costs and efficiency of using various lever-propelled wheelchair designs. Van der Woude et al.²¹ examined the mechanical advantage and VO₂ consumption of a lever-propelled tricycle with different gearing options, but the results were limited to determining the most efficient gearing for this particular wheelchair. Another study involved a comparison of a newly designed lever mechanism for wheelchairs with a CMW and another lever-propelled wheelchair²². These authors determined that lever-propelled designs are generally more efficient and require less oxygen consumption than a CMW, although not all lever propulsion mechanisms are equal in terms of these variables²². Consequently the metabolic costs and efficiency of one lever-propelled wheelchair design cannot be generalized to other lever-propelled wheelchair designs. Therefore the purpose of this study was to compare the metabolic cost, performance, and efficiency of propulsion using the novel EHDM and a CMW.

METHODS

Participants

A heterogeneous sample of twelve adult, full-time manual wheelchair users, including persons with paraplegia and persons with tetraplegia (Table 1), participated in the study. All participants were medically stable with no change in their medical history for the past six months and at least six months post injury before inclusion. The protocol was approved by the Institutional Review Board. All participants signed an informed consent before testing started.

Equipment

The EHDM utilizes a cam pawl and ratchet mechanism that grabs onto the tire tread for forward propulsion and releases during the recovery phase (Figure 1). The EHDM was attached to the axle of both wheels on a CMW (QuickieGP^a). Modifications were made to the chair to ensure that the EHDM could be rotated around to the back of the chair when not

in use, allowing for uninhibited push rim propulsion in addition to lever propulsion in the same chair with permanent attachment of the EHDM. With this setup, the same chair was used for all testing and maintained all of the same attachments and settings, ensuring that all chair parameters, including weight, remained constant across both chair conditions. In order to make certain that participants' anthropometrics were accommodated and an ergonomic fit was achieved, lever length could be adjusted from 16 cm to 35.5 cm in length and handgrip orientation could be rotated 110 degrees in either direction from a vertical orientation (Figure 2).

Protocol

Prior to testing, participants transferred into the prototype CMW fitted with the EHDM and were allowed to propel themselves using the EHDM and push rims until they were comfortable with the operation of the chair in either mode. Additionally, lever length and handgrip orientation were adjusted to each individual's preference. Participants were then asked to continuously propel themselves around a 99.3 m, semi-circular track making only gradual, rounded right hand turns for 3.5 minutes at a steady, self-selected pace using conventional push rim propulsion as well as in the same chair using the EHDM. The testing order of propulsion styles was randomized for all subjects to prevent a fatigue bias in the results. Additionally, participants were allowed to rest between trials as long as desired to decrease the effects of fatigue. A steady, self-selected pace was used because the aim of the study was to examine metabolic cost, performance, and efficiency and previous research has shown that individuals automatically select their most economical propulsion speed, as noted previously¹⁴. Finally, the same chair was used for both propulsion types in order to: first, eliminate any inadvertent comparison between wheelchair types rather than propulsion styles and second, enable each participant to act as his or her own control.

In order to quantify metabolic cost, performance, and efficiency, VO₂ consumption (ml/kg/min), HR (bpm), distance traveled (m), velocity (m/s), VO₂ efficiency (ml/kg/m), and number of pushes were recorded during both trials. Wireless, portable devices were used to record VO₂ consumption (K4b2 unit^b) and HR (T31 coded transmitter and FT2 training computer^c). The VO₂ unit was calibrated prior to each testing session. Distance was recorded with the use of a distance measuring wheel (Road Runner^d) operated by a researcher following behind the wheelchair. Velocity was then calculated based on the set time and distance traveled for each trial. VO₂ efficiency was calculated by dividing the VO₂ consumption by velocity. Finally, the number of pushes was measured with a click counter (Home and Road Pitch Counter^e) with each push defined as a forward propulsive movement made with the right arm.

Data Reduction and Statistical Analysis

Distance traveled, velocity, VO₂ efficiency, number of pushes, VO₂ consumption, and HR were all recorded for the entire 3.5 minutes of each trial, but only the last 30 seconds were analyzed. Previous studies have shown that a steady state is achieved after three minutes of continuous exertion, and measures of metabolic cost and efficiency can only be reliably analyzed after this three minute point²³. Because a steady pace was utilized, the distance traveled, velocity, and number of pushes recorded during the last 30 seconds were

proportional to the entire 3.5 minutes. Therefore, to maintain consistency in the analysis, only the last 30 seconds of the oxygen consumed, oxygen efficiency, heartrate, distance traveled, velocity, and number of pushes recorded were used for analysis. The final 30 seconds of each variable were compared by propulsion type condition using five paired t-tests (Bonferroni adjusted $\alpha=0.01$ for multiple comparisons).

RESULTS

Participants traveled 11.2 m farther during the final 30 seconds during the CMW condition as compared to the EHDM ($p=0.001$, Table 2). Accordingly, participants traveled 0.37 m/s faster in the CMW to travel the greater distance ($p=0.001$, Table 2). No differences were observed between the EHDM and the CMW in terms of the number of pushes, VO2 consumption, and heart rate (Table 2). Finally, participants were 0.05 ml/kg/m more efficient with the CMW than with the EHDM ($p<0.001$, Table 2).

DISCUSSION

The aim of this study was to compare metabolic costs, performance, and efficiency between the EHDM and a CMW. The prototype EHDM was previously shown to be effective in shifting awkward propulsion postures to more neutral ranges of motion and reducing the risk of developing a pathology of the upper extremity with implications for pain, while allowing individuals to customize the ergonomic fit of the lever system^{12,13}. In order to be an ideal solution, the EHDM should not demand more energy output to achieve neutral orientation.

A performance decrement was observed with the use of the EHDM. Participants travelled farther with the CMW than with the EHDM. Additionally, because participants travelled farther and each trial lasted for a set period of time, CMW velocity was also greater. As a result of trying to create a low-maintenance design, the EHDM was not able to reach the speeds achieved by the CMW. Future modifications to the design could rectify the problem. The addition of gearing to the EHDM, although adding weight to the chair and the need for slightly more maintenance, could enable the EHDM to attain greater speeds.

Importantly, participants did avoid additional metabolic costs with the use of the EHDM. Although a performance decrement was observed, the number of pushes used, VO2 consumption, and HR were not significantly different between the two propulsion styles. This similarity is likely a result of allowing participants to propel themselves at a self-selected speed. Previous research has shown that individuals naturally choose a push frequency that optimizes metabolic cost, as evidenced by HR and VO2 consumption¹⁴. Therefore, because the push frequency was not significantly different between the two propulsion styles, VO2 consumption and HR were not significantly different either. This result further supports the suggestion that the addition of gearing to the EHDM could resolve the performance problem. The gearing could enable the EHDM to achieve higher speeds without additional effort. This assertion is supported by a study by van der Woude et al.²¹ in which different gearings were employed on a lever-propelled wheelchair, with similar VO2 consumption exhibited at several different gearing ratios. If effort is

maintained, push frequency should remain unchanged and therefore similar VO₂ consumption and HR would continue to be observed.

The EHDM was less efficient than the CMW. This result is reinforced when the performance and metabolic costs results are viewed together. Because less distance was travelled at a slower speed with the EHDM utilizing a similar number of pushes, HR, and VO₂ consumption as the CMW, the EHDM resulted in less efficient propulsion. As previously noted, however, the addition of gearing to the EHDM could resolve the performance problem, which would likely address the efficiency problem as well. Additionally, when viewed in relation to VO₂ efficiency reported by other researchers, both the CMW and EHDM in this study were relatively efficient. Beekman et al.²⁰ reported 0.17 ± 0.04 ml/kg/m and 0.16 ± 0.05 ml/kg/m for persons with tetraplegia using a standard and ultralight CMW, respectively, and 0.16 ± 0.02 ml/kg/m and 0.13 ± 0.02 ml/kg/m for persons with paraplegia using the same standard and ultralight wheelchairs. The VO₂ efficiency of the heterogeneous participants in this study using the EHDM (0.15 ± 0.03 ml/kg/m) was only less efficient than that of the persons with paraplegia utilizing the ultralight CMW (0.13 ± 0.02 ml/kg/m) in the Beekman et al. study²⁰.

Similarly, oxygen consumption during the EHDM condition in the current study was less metabolically costly than during CMW use in other studies. Hilbers and White¹⁵ collected VO₂ consumption data (L/min) at four different speeds, the slowest of which matches the CMW velocity found in this study (1.12 m/s). When their average VO₂ consumption is converted to match our VO₂ consumption variable by dividing the oxygen consumed with the average mass of the sample, their oxygen consumption for a CMW (10.95 ml/kg/min) is higher than either our CMW or EHDM results (6.43 ml/kg/min and 6.19 ml/kg/min, respectively). In fact their average VO₂ consumption (9.08 ml/kg/min) for the same velocity in a more efficient sports wheelchair is still higher than our average VO₂ consumption. These results exemplify that although participants suffered a performance decrement with EHDM use, this mode of propulsion is still less metabolically costly as compared to oxygen consumption seen with CMW use in other studies.

Further, the lack of a difference between the two propulsion styles in terms of metabolic cost is a favorable result for the EHDM. With numerous upper limb pathologies associated with CMW use, any propulsion style that might lessen wrist and/or shoulder pain or the likelihood of developing pain while maintaining comparable metabolic costs may be a worthwhile option for some wheelchair users. The performance and efficiency decrements observed here are a negative consequence of EHDM use, but as noted in the walking aid literature, sometimes sacrificing functionality is necessary in favor of the individual's health^{24,25}.

Walking aids are designed to increase stability of movement, enabling individuals to remain both active and mobile who would otherwise have trouble walking. Similarly, lever-propelled wheelchairs are designed to decrease stress on the upper extremities enabling individuals to remain both active and mobile when otherwise these individuals would have trouble utilizing a conventional wheelchair. For individuals using either of these mobility aids, often the only other option is a motorized chair. Although these motorized chairs

improve self-perceived quality of life, they lead to decreases in physical activity levels and concomitant increases in the risk of developing cardiovascular problems²⁶. Previous research has shown that decreased activity levels can reduce quality of life for these groups of people^{6,27}. With mobility aids in general, a less efficient device that allows some mobility is better than the alternative. Although walking with crutches or another type of walking aid can require as much as twice the metabolic energy of able-bodied gait²⁸, individuals have reported both mental and physical benefits from the ability to ambulate as opposed to relying upon motorized mobility²⁷. Similarly, a lever-propelled wheelchair that is less efficient than a conventional wheelchair is a worthwhile option for individuals who have upper extremity joint complications if it enables them to maintain both their activity levels and independence.

Study Limitations

This study is limited by a relatively small and heterogeneous participant group. Although the results cannot be generalized to all wheelchair users, useful preliminary proof-of-concept data have been provided. The small number of participants required that all results be pooled into one group, which may have increased the variability of the results and therefore decreased the significance of the findings. Future studies should incorporate a larger sample size that would allow for the separate analysis of groups of wheelchair users (specific non-spinal cord injuries, persons with paraplegia, persons with tetraplegia, etc.).

Additionally, all subjects used the same chair regardless of height and weight. Because each participant acted as his or her own control, precise fit of the chair to the participant was not imperative, but a more optimal fit should improve the efficiency and therefore the ecological validity of the results. Future studies would utilize multiple wheelchair sizes to achieve a better fit to all study participants.

Finally, although 3.5 minute trials are long enough to reach a steady state of propulsion using each propulsion condition, this amount of time is not long enough to provide a true test of ergonomic comfort. Future work would employ a longitudinal study design in order to explore the effects of prolonged use of the EHDM.

CONCLUSIONS

This study provides evidence that the number of pushes, HR and VO₂ consumption were similar between the two propulsive styles. The EHDM condition, however, resulted in decreased distance, speed, and efficiency as compared to the CMW condition. Although the EHDM is not an ideal technology, it can be considered as an alternative mode of mobility by wheelchair users and rehabilitation specialists.

Acknowledgments

This material has previously been presented at the American College of Sports Medicine Conference in Denver, Colorado in June of 2011.

We certify that no party having a direct interest in the results of the research supporting this article has or will confer a benefit on us or on any organization with which we are associated. We also certify that all financial and material support for this research and work are clearly identified in the title page of the manuscript.

LIST OF ABBREVIATIONS

CMW	conventional manual wheelchair
EHDM	ergonomic hand drive mechanism
VO2 consumption	oxygen uptake per unit time
VO2 efficiency	oxygen uptake per distance travelled
HR	heart rate

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Figure 1.
The EHDM attached to the axle of both wheels on a CMW

Figure 2.
Pivoting Handgrip as Attached to Lever of Adjustable Length

Table 1

Participant Demographics

	Subject	Sex	Age (yrs)	Body Mass (kg)	Height (cm)	Lesion
Persons with Paraplegia	1	M	45	81.8	185.4	T4
	2	M	23	68.2	172.7	T6
	3	M	53	70.5	177.8	T7
	4	F	19	59.1	162.6	T8
	5	M	31	59.5	172.7	T9
	6	F	48	72.7	162.6	T11–T12
Persons with Tetraplegia	7	F	29	59.1	152.4	Unknown lesion
	8	M	25	84.1	185.4	C6
	9	M	52	84.1	180.3	C6
	10	M	49	95.5	190.5	C6–C7
	11	F	46	59.1	170.2	C7–T1
	12	F	45	90.9	170.2	C7–T3
Mean	–	–	38.8	73.7	173.6	–
SD	–	–	12.4	13.3	11.1	–

Table 2

Paired Sample T-Tests comparing the CMW and EHDM

Outcome Variables	CMW	EHDM	T-Test Value	Significance
Distance (m)	33.6±10.8	22.4±7.8	-4.535	p=0.001*
Persons with Paraplegia	37.4±8.6	23.9±7.0		
Persons with Tetraplegia	28.2±12.2	20.5±9.2		
Velocity (m/s)	1.12±0.4	0.75±0.3	-4.535	p=0.001*
Persons with Paraplegia	1.25±0.3	0.80±0.2		
Persons with Tetraplegia	0.94±0.4	0.68±0.3		
Number of Pushes	27.5±5.7	25.7±5.4	-0.942	p=0.366
Persons with Paraplegia	28.0±7.1	26.6±4.0		
Persons with Tetraplegia	26.8±3.6	24.4±7.3		
VO2 Consumption (ml/kg/min)	6.43±1.9	6.19±1.7	-0.581	p=0.573
Persons with Paraplegia	6.82±1.3	6.47±1.8		
Persons with Tetraplegia	5.87±2.7	5.79±1.8		
VO2 Efficiency (ml/kg/m)	0.10±0.03	0.15±0.03	6.449	p<0.001*
Persons with Paraplegia	0.10±0.03	0.14±0.04		
Persons with Tetraplegia	0.11±0.02	0.15±0.03		
Heartrate (bpm)	100.5±14.5	97.4±20.2	-0.851	p=0.420
Persons with Paraplegia	110.4±2.9	110.0±9.0		
Persons with Tetraplegia	100.2±29.6	81.6±19.5		

CMW = Conventional manual wheelchair; EHDM = ergonomic hand drive mechanism; VO2 Consumption = oxygen uptake per time; VO2 Efficiency = oxygen uptake per distance travelled.

NOTE. Values are mean ± SD.

NOTE. Bold values are average values of both groups used in statistical analyses.

* Denotes a significant result at the 0.01 level.