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ORIGINAL ARTICLE

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

Objective: To compare the metabolic cost (oxygen uptake per unit time [$\dot{V}O_2$ consumption], heart rate, and number of pushes), performance (velocity and distance traveled), and efficiency (oxygen uptake per distance traveled [VO_2 efficiency]) of propulsion using a novel ergonomic hand drive mechanism (EHDM) and a conventional manual wheelchair (CMW).

Design: Repeated-measures crossover design.

Setting: Semicircular track.

Participants: Adult full-time manual wheelchair users with spinal cord injuries (N=12; mean age ± SD, 38.8±12.4y; mean body mass ± SD, 73.7±13.3kg; mean height ± SD, 173.6±11.1cm) who were medically and functionally stable and at least 6 months postinjury.

Intervention: Participants propelled themselves for 3.5 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, $\dot{V}O_2$ consumption, VO_2 efficiency, and heart rate were compared by wheelchair condition for the last 30 seconds of each trial using paired *t* tests ($\alpha=.01$).

Results: The CMW condition resulted in more distance traveled (33.6±10.8m vs 22.4±7.8m; $P=.001$), greater velocity (1.12±0.4m/s vs .75±.30m/s; $P=.001$), and better VO_2 efficiency (.10±.03mL·kg^{-1}·m^{-1} vs .15±.03mL·kg^{-1}·m^{-1}; $P<.001$) than the EHDM condition, respectively. No significant differences were found between the 2 conditions for number of pushes (27.5±5.7 vs 25.7±5.4; $P=.366$), $\dot{V}O_2$ consumption (6.43±1.9mL·kg^{-1}·min^{-1} vs 6.19±1.7mL·kg^{-1}·min^{-1}; $P=.573$), or heart rate (100.5±14.5 beats per minute vs 97.4±20.2 beats per minute; $P=.42$).

Conclusions: The results demonstrate that metabolic costs did not differ significantly; however, performance and efficiency were sacrificed with the EHDM. Modifications to the EHDM (eg, 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.

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In the United States in 2010, the National Spinal Cord Injury Statistical Center estimated that 232,000 to 316,000 individuals had a spinal cord injury, with approximately 12,000 new injuries occurring each year. Most of these individuals depend on 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%−73% of CMW users)[3-5] and have been shown to greatly reduce users' overall quality of life.[6] 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

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independence. Further, numerous secondary health issues, such as increased risk of heart failure, can arise as a result of 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 injuries.[2] In the same way that exercise on an elliptical trainer reduces knee joint reaction forces generated during overground running,[11] the continuous contact of the hand with the grip and more constant force application may reduce wrist joint reaction forces.[9] Further, lever-propelled wheelchair use permits both a more relaxed grip and more neutral orientation of the wrist, reducing the overall muscular force needed.[9]

In general, wheelchair users report greater overall satisfaction with a lever-propelled wheelchair than a CMW; however, 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 and a pivoting handgrip. Ergonomic can be operationally defined as matching an individual's biomechanical properties to the environment 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 ($\dot{V}O_2$ consumption), heart rate, and push frequency, whereas efficiency is typically quantified by oxygen uptake per distance traveled (VO_2 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 costs.[14] Additionally, these researchers found that $\dot{V}O_2$ consumption and heart rate are nonlinearly related to push frequency. Subsequent studies of wheelchair racers and members of the general CMW population have also found a relation between $\dot{V}O_2$ consumption and heart rate.[15-17] As opposed to $\dot{V}O_2$ consumption, VO_2 efficiency has been shown to differentiate between groups of wheelchair users when self-selected speeds are used.[18] Accordingly, a number of researchers have opted to use VO_2 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 $\dot{V}O_2$ consumption, heart rate, push frequency, and VO_2 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 $\dot{V}O_2$ 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 wheelchair.[22] 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 variables.[22] Consequently, the metabolic costs and efficiency of a 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.

List of abbreviations:	
CMW	**conventional manual wheelchair**
EHDM	**ergonomic hand drive mechanism**
$\dot{V}O_2$ consumption	**oxygen uptake per unit time**
VO_2 efficiency	**oxygen uptake per distance traveled**

Methods

Participants

A heterogeneous sample of 12 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 6 months and at least 6 months postinjury before inclusion. The protocol was approved by the institutional review board. All participants signed an informed consent before testing started.

Equipment

The EHDM uses a cam pawl and ratchet mechanism that grabs onto the tire tread for forward propulsion and releases during the recovery phase (fig 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 to 35.5cm in length and handgrip orientation could be rotated 110° in either direction from a vertical orientation (fig 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 99.3m, semicircular track making only