DEVELOPMENT AND TESTING OF A NOVEL HUMAN-POWERED WATERCRAFT FOR PEOPLE WITH LOWER-BODY DISABILITIES

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The purpose of this study was to develop a human-powered watercraft for people with lower-body disabilities and investigate its mechanical efficiency and metabolic cost of locomotion. Metabolic variables and mechanical power output was measured during different trials and the results showed a linear correlation between metabolic power and mechanical power. Energy expenditure when pedalling the watercraft was similar to other physical activities performed by people with lower-body disabilities and could as a result, be an alternative fitness tool for those who seek water activities.

KEY WORDS: spinal cord injury, exercise, energy expenditure, efficiency, energy cost of locomotion.

INTRODUCTION: Spinal cord injury (SCI) may impair sensory, motor, and autonomic function below the level of the injury. As a result, people suffering from SCI often develop secondary impairments such as cardiovascular diseases, pressure ulcers and musculoskeletal pain. These impairments are often the consequence of a sedentary lifestyle in a wheelchair, a device that 80-90% of persons with SCI rely on in everyday life according to Biering-Sørensen (2004). People with SCI are among the most inactive ones in our society, as 50% of people with SCI reported less than 28 min of mild intensity activity *per* day in a study by by Gibbons (2014), which is considered insufficient to maintain or improve physical capacity. Accordingly, additional physical activity is recommended for wheelchair users as physical activity is related to a reduced risk of cardiovascular diseases, obesity, and pressure ulcers, and leads to less pain and fatigue in everyday life (Tawashy, 2009).

A popular form of physical activity for SCI persons is handcycling. Handbikes for handcycling are driven by an arm crank system, similarly to what is known in cycling, but are usually equipped with synchronous hand-pedals, three tires, and a seat. Handbikes are more mechanically efficient than everyday wheelchairs and handcycling is highly recommended to maintain the level of physical fitness and to prevent arteriosclerotic diseases as it is characterized by a relatively high energy consumption at moderate training intensities (Abel, 2006). The closed-chain motion of handcycling enables propulsion force to be applied throughout the whole 360° of crank rotation, which is suggested to cause less musculoskeletal strain compared to everyday wheelchair use, and thereby decrease the risk of overuse injury (Dallmeijer, 2004).

People suffering from SCI also have the option of doing both alpine and cross-country skiing using sit skis, which assist the para-skiers with balancing, turning, and controlling the speed. Equipment also exists that enables SCI people to participate in activities such as basketball, rugby, tennis and throwing events. At present, however, it is difficult for people with high-to-medium level (HML) SCI to navigate with human-powered watercrafts such as rowing boats, canoes, and kayaks, mainly due to the trunk movement impairment that often follows SCI. Accordingly, a new human-powered watercraft that is suitable for people with HML SCI would represent a highly valuable option for them for fitness and leisure activities as well. The aim of this study was to develop such a watercraft and investigate the mechanical efficiency and metabolic cost of locomotion when pedaling the watercraft.

METHODS: The experiments were carried out on nine (eight male and one female) able-bodied subjects (34.2 ± 8.3 years; 75.3 ± 9.5 kg; 1.75 ± 0.07 m). The subjects had no experience in handcycling or injuries of the upper extremities. All subjects gave their written informed consent before testing.

Figure 1: the Handwaterbike

The watercraft, named Handwaterbike, is a catamaran consisting of two carbon hulls, provided by The Open Waterbike Project, to provide buoyancy, while a handbike seat with backrest and footrests is fixed between the two hulls using aluminum pipes. A synchronous arm-crank system in front of the seat is connected via a chain to the transmission system, which drives a flex-shaft and propeller. When pedaling is paused, the propeller folds together, removing potential seaweed from the blades. The main dimensions of the Handwaterbike are: length over all: 4.89 m; length of water line: 4.77 m; weight without subjects: 69.17 kg; maximal beam: 1.08 m; draught (vertical distance between waterline and the bottom of the hull): 0.098 m.

Oxygen consumption ($\dot{V}\mathrm{O2}, \mathrm{L} \cdot \mathrm{min}^{-1}$), carbon dioxide production ($\dot{V}\mathrm{CO}_2, \mathrm{L} \cdot \mathrm{min}^{-1}$), energy expenditure ($\mathrm{Kcal} / \mathrm{min}^{-1}$) and heart rate (HR) were assessed breath-by-breath using a portable metabolic system (K5, COSMED, Italy). Before each test, the system was calibrated according to the manufacturer’s instructions. The Handwaterbike was instrumented with a power-meter crankset (Quarq RIKEN R, SRAM, USA) with a crank length of 170 mm allowing the measurement of pedaling frequency ($\mathrm{rev} \cdot \mathrm{min}^{-1}$) and of external mechanical power ($\dot{W}$) at a sampling rate of 60 Hz. Boat speed was measured every second by means of a GPS (Rider 20, Bryton Inc., Taiwan) fastened to the arm-crank system. A 3D computer-aided design model of the Handwaterbike was created using SolidWorks CAD software in order to measure the frontal surface area of the submerged part. The submerged area was corrected by accounting for the additional volume of water displaced when a subject was on board.

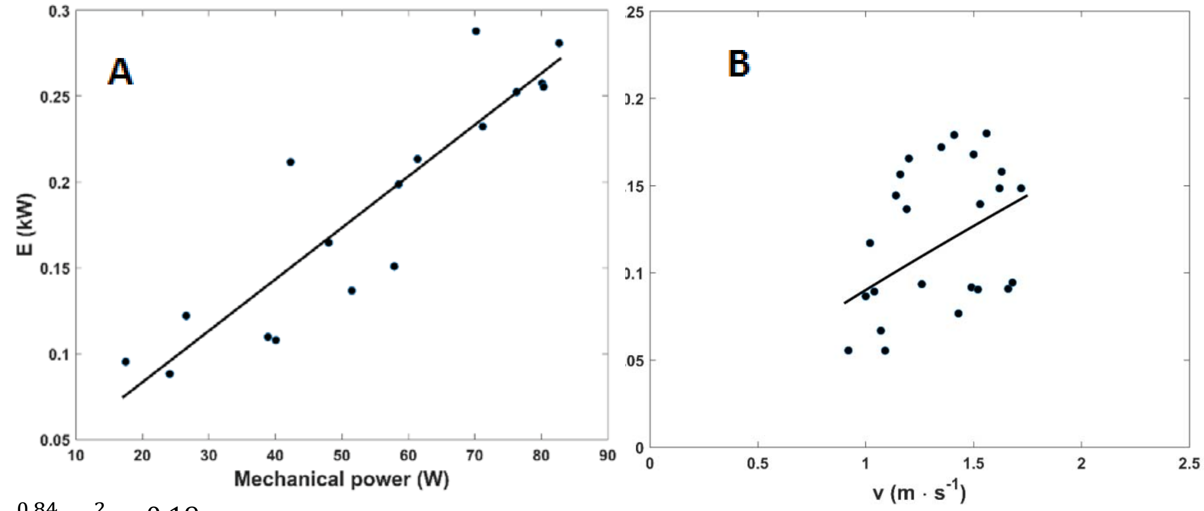
The experiments were performed along the shore of the Garda Lake (Italy) in still water and with wind speed always less than 2 $\mathrm{m} \cdot \mathrm{s}^{-1}$. The subjects were asked to pedal in a linear direction for at least 5 min, to allow steady-state metabolic measurements, at three different speeds: (1) a speed the subject would be able to maintain for approximately 1 hour, (2) a little bit slower than that and (3) a little bit faster than that. In between the trials at different speeds, the subjects rested for 5 minutes. Before the trials, the subjects were asked to sit on a chair for 5 min for measurement of metabolic variables at rest.Only data collected from the last minute of each trial was used for analysis. Mean oxygen consumption and respiratory exchange ratio (RER) was converted into metabolic power using the empirical formula $E = ([4.94 \times \mathrm{RER} + 16.04] \times \dot{V}\mathrm{O2} / 60)$ from Garby and Alstrup (1987). The metabolic power was then divided by the average speed during the corresponding trial to calculate the metabolic cost of locomotion, C.

The net mechanical efficiency η_0, of pedaling with the Handwaterbike was calculated by dividing the external mechanical power output by the metabolic power above rest level.

All data are presented as mean values and standard deviations. Data from the metabolic system were low-pass filtered (2nd order Butterworth).

RESULTS:

In Fig. 2 the metabolic power at steady state, E (kW), during pedaling the Handwaterbike is plotted as a function mechanical power (W). Data were fitted by a linear function: $E = 0.0033 \cdot W - 0.0022$; $r^2 = 0.93$. The metabolic cost of locomotion, C (kJ · m^{-1}), for pedaling the Handwaterbike as a function of speed v (m · s^{-1}) is shown in Fig. 2B and fitted by a power function of the form: $C = 0.0901 \cdot$



$v^{0.84}$; $r^2 = 0.19$.

Figure 2: A): Metabolic power (E) at steady state plotted as a function of the mechanical power (W) while pedaling the Handwaterbike. B): The energy cost needed to cover one unit distance (C) plotted as a function of the speed (v).

Net mechanical efficiency when pedaling the Handwaterbike was 30.49 ± 4.45%. During the trial, where the subjects were asked to pedal at a speed they would be able to maintain for 1 hour, the mean energy expenditure (EE) was 4.11 ± 0.67 kcal/min.

DISCUSSION:

The aim of this study was to investigate the efficiency and metabolic cost of locomotion of a novel human-powered watercraft for people lower body disabilities. The data shows a strong linear correlation between metabolic power and mechanical power. The subjects were able to reach power outputs above 80 W. Armcranking at this power has been shown to be sufficient for maintaining or improving cardiovascular health and fitness, and likely help prevent cardiovascular diseases for people with spinal cord injury (Abel, 2003). The Handwaterbike has a single gear ratio and the testing demonstrated that this was sufficient at power outputs from 20-80 W. Experienced handcyclists however, may be able to produce a significantly higher power output, which could limit the utilization of the Handwaterbike as a training tool for this population, if the cadence becomes too high.

Several studies have demonstrated that additional energy consumption due to physical activity decreases the risk of mortality and morbidity (Blair & Connelly, 1996; Blair & Brodney, 1999). The mean energy expenditure during the trial, where the subjects were asked to pedal at a speed they would be able to maintain for 1 hour, was 4.11 kcal/min. This is similar to activities such as arm cranking at 48 W, shooting baskets, wheeling outside (Collins, 2009) and rugby (Price, 2010). According to Paffenberger (1986), an additional daily energy consumption of 300 kcal minimizes the probability of myocardial infection. This would require approximately 73 min of pedaling the Handwaterbike.

The metabolic cost of locomotion and speed showed a very low correlation. This is likely due to the multiple testing days. Even though the wind speed was lower than 2 $m \cdot s^{-1}$ during all

trials, it is plausible to think that water streams have influenced the boat speed. If the testing would have been performed during the same day or in a pool, the correlation would presumably have been higher.
It should be noted that the subjects in this study were able-bodied, while the Handwaterbike is intended for people with lower-body disabilities. Going forward, it should be investigated if the metabolic cost and mechanical efficiency is different for this population.
The testing showed some ergonomic problems of the Handwaterbike, mainly a lack of seat, footrests and backrest adjustability. The mechanical efficiency proved to be comparable with other boats (Zamparo, 2008), so to optimize the performance, it could be suggested to reduce the drag by reducing the weight of the aluminum frame.

CONCLUSION:
The Handwaterbike is a novel human-powered watercraft designed for people with lower body disabilities. This study showed that pedaling the Handwaterbike could be a promising fitness tool for people with lower body disabilities looking for physical activities on the water. Pedaling the Handwaterbike proved to induce energy expenditure and power outputs that have been proven to maintain or improve cardiovasucular health and fitness, and reduce the risk of cardiovascular diseases. A number of improvements are proposed however, mainly regarding ergonomics and including people with lower-body disabilities as subjects.

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