Annals of Physical and Rehabilitation Medicine xxx (2018) xxx–xxx

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Original article

Cardiorespiratory demand and rate of perceived exertion during overground walking with a robotic exoskeleton in long-term manual wheelchair users with chronic spinal cord injury: A cross-sectional study

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A R T I C L E I N F O

Article history:
Received 26 July 2017
Accepted 19 December 2017

Keywords:
Spinal cord injuries
Exercise
Rehabilitation
Technology
Physical fitness
Oxygen consumption

A B S T R A C T

Background: Many wheelchair users adopt a sedentary lifestyle, which results in progressive physical deconditioning with increased risk of musculoskeletal, cardiovascular and endocrine/metabolic morbidity and mortality. Engaging in a walking program with an overground robotic exoskeleton may be an effective strategy for mitigating these potential negative health consequences and optimizing fitness in this population. However, additional research is warranted to inform the development of adapted physical activity programs incorporating this technology.
Objectives: To determine cardiorespiratory demands during sitting, standing and overground walking with a robotic exoskeleton and to verify whether such overground walking results in at least moderate-intensity physical exercise.
Methods: We enrolled 13 long-term wheelchair users with complete motor spinal cord injury in a walking program with an overground robotic exoskeleton. Cardiorespiratory measures and rate of perceived exertion (RPE) were recorded by using a portable gas analyzer system during sitting, standing and four 10 m walking tasks with the robotic exoskeleton. Each participant also performed an arm crank ergometer test to determine maximal cardiorespiratory ability (i.e., peak heart rate and O_2 uptake [HR_{peak}, VO_{2peak}]).
Results: Cardiorespiratory measures increased by a range of 9%–35% from sitting to standing and further increased by 22%–52% from standing to walking with the robotic exoskeleton. During walking, median oxygen cost ($O_{2Walking}$), relative HR (%HR_{peak}), relative O_2 consumption (%VO_{2peak}) and respiratory exchange ratio (RER) reached 0.29 mL/kg/m, 82.9%, 41.8% and 0.9, respectively, whereas median RPE reached 3.2/10. $O_{2Walking}$ was moderately influenced by total number of sessions and steps taken with the robotic exoskeleton since the start of the walking program.
Conclusion: Overground walking with the robotic exoskeleton over a short distance allowed wheelchair users to achieve a moderate-intensity level of exercise. Hence, an overground locomotor training program with a robotic exoskeleton may have cardiorespiratory health benefits in the population studied.

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https://doi.org/10.1016/j.rehab.2017.12.008
1877-0657/

1. Introduction

Most long-term wheelchair users with a complete motor spinal cord injury (SCI) adopt a sedentary lifestyle with prolonged non-active sitting and limited opportunities to engage in physical activities [1]. As a result, many individuals with a SCI experience progressive physical deconditioning as they age, leading to secondary negative health consequences. Myriad complex multi-factorial health consequences, especially those linked to endocrine and metabolic disorders (e.g., diabetes mellitus, dyslipidemia, obesity), have increased alarmingly over the past few years and have increased the risk of cardiovascular morbidity and mortality among individuals with SCI [1–4]. In fact, cardiovascular disease is now considered the leading cause of mortality among individuals with chronic SCI living in the community [3]. Moreover, individuals with paraplegia present 70% greater risk of developing cardiovascular disease as compared with gender- and age-matched able-bodied individuals [5,6].

Engaging in regular physical activity is a strategy for mitigating secondary negative health consequences and for optimizing fitness in persons with SCI via for the most part, improvement in aerobic capacity [4,7]. It is now recommended that persons with SCI perform prolonged moderate-intensity level of exercise (minimum of 20 min) twice a week in conjunction with strengthening exercises to preserve physical fitness [8]. For long-term manual wheelchair users with paresis or paralysis of the trunk and lower-extremity muscles, arm crank or wheelchair ergometry is typically recommended to achieve prolonged moderate-intensity level of exercise. However, when engaging in these exercise modalities, the upper-extremity muscle mass is recruited to a great extent, whereas the larger thoracohumeral and trunk muscle mass is only minimally recruited.

Thus, to increase the muscular demand of the thoracohumeral and trunk muscle mass, interest has been growing in overground walking with a robotic exoskeleton over the past few years. Robotic exoskeletons typically provide maximal external support that allows for overground walking among wheelchair users with very limited or no ambulatory ability because these exoskeletons reproduce movement strategies and weight-bearing patterns at the lower extremities similar to those documented during typical gait in able-bodied individuals. The upper extremities and trunk muscles greatly contribute to body weight shifts required to initiate steps and to the control of dynamic balance during overground walking with the robotic exoskeleton. This approach is promising given that previous exploratory studies suggested that moderate cardiorespiratory demand and perceived exertion could be anticipated during overground walking with a robotic exoskeleton based only on a few objective measures [9,10]. Moreover, potential beneficial musculoskeletal adaptations (e.g., increased lean body mass, increased bone mineral density at the lower extremities) were recently documented [11]. Hence, overground walking with a robotic exoskeleton, performed in a standing position, may mitigate secondary negative health consequences to a greater extent than arm crank or wheelchair ergometry. Nevertheless, compelling evidence is needed to inform the development of adapted physical activity programs.

One of the steps involved in gathering evidence is gaining additional insight into the cardiorespiratory and metabolic requirements of overground walking with a robotic exoskeleton. Only a few studies have been conducted in this area and the strength of evidence remains low because studies featured, for example, small sample size (typically $\leq$ 8 participants) with a restricted number of outcome measures (heart rate [HR] the most frequently used) [9,10], heterogeneous participants (individuals with complete and incomplete SCI combined) [12] and relative demand estimated from predicted maximal values instead of performance-based peak or maximal values [9]. The oxygen cost of walking with a robotic exoskeleton also remains unknown.

The first objective of this study was to compare cardiorespiratory demand between sitting, standing and overground walking with a robotic exoskeleton with a comprehensive set of outcome measures in long-term manual wheelchair users with chronic SCI. The secondary objective was to investigate whether cardiorespiratory exertion measured and perceived during overground walking with a robotic exoskeleton achieves at least a moderate-intensity level of exercise when normalized with peak values obtained for an arm-crank ergometer test in order to anticipate cardiorespiratory health benefits in this population. We hypothesized that 1) cardiorespiratory demand would progressively increase when transitioning from sitting, standing and walking tasks with a robotic exoskeleton [9] and that 2) a moderate level of physical activity would be achieved during overground walking with a robotic exoskeleton [10].

2. Methods

2.1. Participants

A non-probabilistic convenience sample was recruited for this study. This sample included 13 individuals who sustained a non-progressive complete motor SCI below the 6th cervical vertebra (American Spinal Injury Association Impairment Scale [AIS] = A or B), had no voluntary ambulatory ability, used a manual wheelchair as their primary mode of mobility and previously qualified for overground walking with a robotic exoskeleton after a comprehensive physical therapy assessment. Participants had also completed two familiarization sessions and were participating in an 18 session overground locomotor training program (2–3 sessions/week) with a wearable robotic exoskeleton (i.e., parent intervention trial). Exclusion criteria included history of other neurological disorders, injuries to the skin in areas of contact with the exoskeleton, psychiatric or cognitive impairments that could interfere with the tasks and/or poorly controlled spasticity of the lower extremities. The present sample represents a sub-sample of participants who had initiated this parent intervention trial, had completed at least 4 training sessions with the robotic exoskeleton and had acquired the ability to ambulate at least 50 m with the robotic exoskeleton with proper rhythm and balance strategies with minimal or contact guard assistance. Additional recruitment information on the parent interventional trial, including details about the inclusion and exclusion criteria for overground walking with the robotic exoskeleton, is described elsewhere [13]. The study was conducted at the Pathokinesiology Laboratory of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR) located at the CIUSSS du Centre-Sud-de-l'Île-de-Montréal–Site: Institut de réadaptation Gingras-Lindsay-de-Montréal. All participants gave their written consent to participate in the study after being informed of the objectives and nature of their participation in the study. The Research Ethics Committee of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal approved the present study (CRIR-1083-0515).

2.2. Robotic exoskeleton

The Ekso™ GT overground robotic exoskeleton (EKSO Bionics, CA, USA) was used in this study. This system, which weighs about 28 kg, provides maximal external support and generates flexion and extension movements at the hips and knees via motors in a sequence that replicates and allows for overground walking. Ankles are supported with a non-motorized dynamic orthosis. When walking, steps are initiated by shifting body weight laterally

Please cite this article in press as: Escalona MJ, et al. Cardiorespiratory demand and rate of perceived exertion during overground walking with a robotic exoskeleton in long-term manual wheelchair users with chronic spinal cord injury: A cross-sectional study. Ann Phys Rehabil Med (2018), https://doi.org/10.1016/j.rehab.2017.12.008