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Cardiopulmonary responses to robotic end-effector-based walking and stair climbing

Oliver Stoller[a,b,*], Matthias Schindelholz[a], Lukas Bichsel[a], Kenneth J. Hunt[a]

[a] *Institute for Rehabilitation and Performance Technology, Division of Mechanical Engineering, Department of Engineering and Information Technology, Bern University of Applied Sciences, Burgdorf, Switzerland*

[b] *Department of Epidemiology, Maastricht University and Caphri Research School, Maastricht, The Netherlands*

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ABSTRACT

Background: A recently developed robotic end-effector device (G-EO system, Reha Technology AG) can simulate walking and stair climbing. This approach has the potential to promote cardiovascular exercise training during rehabilitation. The aim of this study was to characterise cardiopulmonary responses of end-effector-based exercise in able-bodied subjects and to evaluate the feasibility of intensity-guided exercise testing.

Methods: Five healthy subjects aged 33.7 ± 8.8 years (mean ± SD) performed a constant load test and an intensity-guided incremental exercise test. The outcome measures were steady-state and peak cardiopulmonary performance parameters including oxygen uptake (VO_2) and heart rate (HR).

Results: Passive end-effector-based stair climbing (VO_2 = 13.6 ± 4.5 mL/min/kg, HR = 95 ± 23 beats/min) showed considerably lower cardiopulmonary responses compared to reference data (VO_2 = 33.5 ± 4.8 mL/min/kg, HR = 159 ± 15 beats/min). Peak performance parameters during intensity-guided incremental exercise testing were: VO_2 = 35.8 ± 5.1 mL/min/kg and HR = 161 ± 27 beats/min, corresponding to a relative VO_2 = 76.0 ± 18.7% of predicted aerobic capacity and a relative HR = 87.3 ± 14.5% of age-predicted HR maximum.

Conclusion: End-effector-based exercise is a promising method for the implementation of cardiovascular exercise. Although end-effector-based stair climbing evoked lower cardiopulmonary responses than conventional stair climbing, active contribution during exercise elicited substantial cardiopulmonary responses within recommended ranges for aerobic training.

1. Introduction

Physical activity promotion has become an important element in the management of stroke rehabilitation [1]. Evidence suggests that regular physical exercise has beneficial effects on physiological, psychological, sensorimotor, strength, endurance, and functional aspects [2–7]. In particular, cardiovascular exercise seems to have strong potential to positively influence cardiovascular health, aerobic capacity and walking endurance after stroke [8,9]. However, routine rehabilitation programmes do not impose adequate load to introduce training effects [10] and severely impaired, non-ambulatory individuals cannot benefit from conventional exercise procedures such as treadmill exercise or leg cycle ergometry. Thus, new concepts are required to promote physical activity for individuals suffering from severe neurological conditions.

There is growing interest in the potential of robotic devices for physical activity promotion [11,12]. Hitherto, the clinical application and research focus of these devices has been the desire to promote neurological adaptations to support recovery of physical functions such as walking. The development of effective protocols to improve exercise capacity would provide a complement to the application of these devices for neurological rehabilitation, thus expanding the field of application and clinical uptake.

To date, a number of robotics-assisted devices have been developed to facilitate walking, stepping, or stair climbing (e.g. Lokomat, Erigo, LOPES, ALEX, AutoAmbulator, Gait Trainer GT I, HapticWalker, LokoHelp). Initial work on a robotic driven gait orthosis (Lokomat) has shown that walking within an automated exoskeleton is not entirely passive [13,14]. Even a subject with motor-complete tetraplegia shows a metabolic response to robotics-assisted treadmill exercise by increasing oxygen uptake, ventilation rate, and heart rate [15]. Intervention studies on robotics-assisted treadmill exercise have shown improvements in left ventricular function, coronary flow reserve, and endothelial

* Corresponding author at: Institute for Rehabilitation and Performance Technology, Division of Mechanical Engineering, Department of Engineering and Information Technology, Bern University of Applied Sciences, Pestalozzistrasse 20, 3400 Burgdorf, Switzerland. Tel.: +41 34 426 41 95.
E-mail address: oliver.stoller@bfh.ch (O. Stoller).

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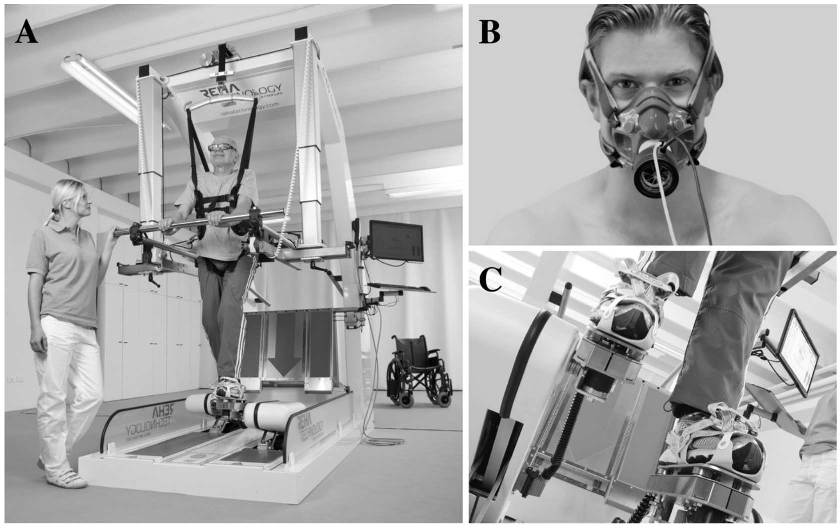

Fig. 1. The experimental setup. (A) The robotic end-effector-based device (G-EO system, Reha Technology AG, Switzerland) for locomotion rehabilitation that can simulate walking and stair climbing (Photo: Reha Technology AG). (B) The breath-by-breath ergospirometry system (MetaMax 3B, Cortex Biophysik GmbH, Germany) (Photo: Cortex Biophysik GmbH). (C) The subject's feet fixed by snowshoe bindings on the footplates (Photo: Reha Technology AG).

dysfunction after incomplete spinal cord injury [16], and a substantial increase in cardiopulmonary fitness within 1 month after stroke [17]. As a new method for exercise testing and prescription, the implementation of feedback–control structures to guide voluntary participation during robotics-assisted treadmill exercise led to promising results for cardiovascular rehabilitation [18,19].

An alternative approach to exoskeleton-based orthoses is provided by end-effector-based robotic devices where the subject's feet are placed on footplates whose trajectories simulate the stance and swing phases of gait. First results using the Gait Trainer GT I yielded cardiopulmonary performance similar to floor walking in healthy controls and in subjects with sub-acute stroke [20]. The implementation of robotics-assisted stair climbing might therefore have high potential to increase cardiopulmonary responses and guide aerobic exercise training in severely impaired populations.

The recently developed G-EO system provides robotics-assisted stair-climbing [21]. The end-effector-based concept allows for a simple setup, and is able to implement various walking and stair climbing trajectories in different conditions. Here, we explore this novel device regarding its potential for cardiovascular rehabilitation. We were interested in the cardiopulmonary responses to end-effector-based exercise and in the technical feasibility of using the device to perform intensity-guided incremental exercise testing for assessment of aerobic capacity.

We hypothesised that end-effector-based exercise can yield similar cardiopulmonary responses to those observed during normal walking and normal stair climbing. The question that arises during end-effector-based exercise is how active subjects are while performing on the G-EO system. For example, the trajectories are fully supported by robotics-assistance, which allows subjects to push upwards (i.e. there could be a mechanical support during stair climbing). This might affect the individual movement strategy and lead to different cardiopulmonary responses compared to performance in a real setting.

We hypothesised further that the end-effector based device will provide the technology to perform intensity-guided incremental exercise testing for assessment of aerobic capacity. While previous studies have demonstrated the feasibility of maximal exercise testing within a robotics-assisted exoskeleton [14,18,22], there is no evidence regarding the technical feasibility of evaluating maximal exercise capacity within an end-effector-based stair climbing device.

The specific aims of this study were: (1) to characterise cardiopulmonary responses from end-effector-based walking and stair climbing exercise, and (2) to assess the technical feasibility of end-effector-based intensity-guided incremental exercise testing for assessment of peak exercise capacity in healthy subjects.

2. Methods

2.1. Subjects

Five healthy subjects with no known cardiovascular, pulmonary or musculoskeletal problems that may have interfered with or contraindicated exercise testing participated in this study (Table 1). Subjects provided written informed consent prior to participation. The study was reviewed and approved by the ethics committee of the Swiss Canton of Bern (KEK-BE: 155-12).

2.2. Material

An end-effector-based robotic device (G-EO system, Reha Technology AG, Switzerland) was used to simulate walking and stair climbing. The subjects' feet were fixed by snowshoe bindings on base plates, which were moved by the device drives on arbitrary trajectories.

Three different trajectory types were available (walking, climbing upstairs, climbing downstairs) that were directly derived from motion tracking data of healthy subjects [23]. The maximal possible gait parameters on the device were a cadence of 70 steps/min, a step length of 55 cm, and a step height of 24 cm. For the current study, only walking and climbing upstairs were used. The integrated body weight support (BWS) system including the harness was not employed due to the able-bodied status of the subjects and our goal to simulate a realistic setting; the subjects bore their full body weight. The subjects were asked to hold the front rail to maintain balance without bracing upwards (the height of the hand rail was adjusted to be above the elbow joint).

Cardiopulmonary performance parameters were measured using a breath-by-breath cardiorespiratory monitoring system (MetaMax 3B, Cortex Biophysik GmbH, Germany). Prior to each test, volume calibration was performed using a volumetric syringe and gas calibration was carried out using ambient air and a certified precision-analysed gas mixture. Heart rate was continually