Biomedical Signal Processing and Control 10 (2014) 296–307

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Technical Note

A software module for cardiovascular rehabilitation in robotics-assisted treadmill exercise

M. Schindelholz [a,b], O. Stoller [a,b], K.J. Hunt [a,b,*]

[a] Institute for Rehabilitation and Performance Technology, Division of Mechanical Engineering, Department of Engineering and Information Technology, Bern University of Applied Sciences, CH-3400 Burgdorf, Switzerland

[b] Reha Rheinfelden, Salinenstrasse 98, CH-4310 Rheinfelden, Switzerland

ARTICLE INFO

Article history:
Received 10 August 2012
Received in revised form
26 November 2012
Accepted 14 December 2012
Available online 9 February 2013

Keywords:
Rehabilitation engineering
Rehabilitation robotics
Exercise physiology
Cardiovascular training
Software module

ABSTRACT

A new software module for cardiovascular rehabilitation in robotics-assisted treadmill exercise is described; it is designed to evaluate and improve aerobic capacity for individuals with different neurological diseases.

The Lokomat device was used in conjunction with a breath-by-breath cardiopulmonary monitoring system and a heart rate monitoring module to quantify the subjects' exercise intensity and capacity, managed by the new software module.

The intensity of the individuals' exercise participation was estimated by a novel method which respects passive stiffness of the lower limbs and was guided by a custom human-in-the-loop feedback control system. Severely affected individuals' participation was controlled by modifying body weight support or guidance force of the Lokomat system.

Standard assessment and testing protocols were implemented and adapted to the target populations for cardiovascular rehabilitation tasks. Further intensity-control mechanisms provided by the software are feedback control of heart rate, oxygen uptake and metabolic work rate.

The results demonstrated the technical feasibility of the software module for cardiovascular assessment and training in robotics-assisted treadmill exercise. Using one of the intensity control methods, cardiovascular responses were activated and controlled in healthy people, moderately to severely affected individuals early after stroke and also in individuals with spinal cord injury.

1. Introduction

The majority of post stroke individuals have cardiac disease. They are often deconditioned and predisposed to a sedentary lifestyle. This limits the performance of daily living activities, increases the risk for falls, and may contribute to an increased risk for recurrent stroke and cardiovascular disease [1]. Individuals with spinal cord injury and other neurological conditions suffer from similar disabilities and limitations.

In the field of robotics-assisted treadmill training, the focus is mainly set on developing new methods for feasible neurological and orthopaedic rehabilitation which include the patient's participation and which make the robotic behaviour more patient-cooperative [2]. On the other hand, rehabilitation-robotics devices also have the potential to evaluate exercise capacity and guide cardiovascular rehabilitation for individuals with neurological disease [3–8]. A satisfactory level of cardiovascular fitness leads to better management of the condition and better performance in the activities of daily living [1]. The main goal of the work was to develop a new software module, which provides several functions for cardiovascular rehabilitation in robotics-assisted treadmill exercise (RATE) independent of the type of disease. The present work describes the technical development and modification of the rehabilitation device employed (Lokomat) as well as the structure and function of the module in detail. Several possibilities for cardiovascular assessment and training were implemented in one software module including an innovative graphical user interface.

In the area of cardiovascular exercise research in neurology, different approaches have been employed to estimate the active participation level of an individual during RATE [9,10]. A novel method for estimation and visualisation of the subject's participation is provided. The article illustrates the technical feasibility of these approaches. A pilot study [11], based on this module, aimed to assess the feasibility of using feedback-controlled RATE to evaluate and improve aerobic capacity early after stroke. Further possibilities based on the present work are feedback control of heart rate, oxygen uptake and metabolic work rate [12–15].

* Corresponding author.
E-mail address: kenneth.hunt@bfh.ch (K.J. Hunt).

1746-8094/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.bspc.2012.12.006

List of Abbreviations and Symbols

HR	heart rate
P_{raw}	unfiltered total mechanical work rate
P_{total}	low pass filtered total mechanical work rate
$P_{passive}$	passive mechanical work rate (constant value), estimated in passive test
P_{mean}	active mechanical work rate, $P_{mean} = P_{total} - P_{passive}$
P^*_{mech}	target mechanical work rate
P_{mech_max}	individual active work rate maximum estimated in maximum test by MVC-W
P_{mean_30s}	averaged P_{total} over 30 seconds
$RMSE$	root mean square error. The root mean square error is calculated by: $RMSE = \sqrt{\sum_{i=1}^{N}(x_i - x_{target,i})^2/N}$ Here, x corresponds to the actual and target signals; N corresponds to the number of samples in the chosen time range.
$\dot{V}O_2$	rate of oxygen uptake
$\dot{V}CO_2$	rate of carbon dioxide output
ω	force
F	moment of force (torque)
M	frequency
f	lever arm length (radius)
r	angular speed angle
BWS	body weight support level (%)
CLT	constant load test
IET	incremental exercise test
GF	guidance force level (%)
MVC-W	maximal voluntary contraction during walking
RATE	robotics-assisted treadmill exercise
SBW	self-borne weight, $SBW = 100\% - \text{BWS}$
SBF	self-borne force, $SBF = 100\% - \text{GF}$

2. Methods

2.1. Basic system and modifications

We used a motor-driven gait orthosis[1] [16,17] with an integrated treadmill[2] and a dynamic body weight support (BWS) system[3] [18], (Fig. 2A). The motorized orthosis actively controls and supports the knee and hip joint movement of both legs. A sensor interface unit[4] provides analogue signals from the joint angles θ and forces F. The mechanical rate of work done on the orthoses is computed from these signals and represents the intensity of interaction between the subject and the mechanical device.

A human-in-the-loop feedback control loop was implemented (Fig. 1) to guide the subject's active mechanical work rate P_{mech}. A target mechanical work rate P^*_{mech}, which represents the participation goal of the subject, and P_{mech} are visualized for the subject on a large screen (Fig. 2A). The subject is instructed to change P_{mech} by varying volitional forces at the knee and hip joints applied on the orthoses in order to make P_{mech} and P^*_{mech} overlap in the 2D Graph (Fig. 2A) or, alternatively, to walk next to the reference avatar (Fig. 2B) in the 3D environment. This visual feedback approach and also the estimation of the subject's active participation extend previous proposals from Hunt et al. [9,19].

Heart rate (HR) is measured in real time using a heart rate chest strap and a receiver board.[5] The rates of pulmonary oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$) are measured using a breath-by-breath metabolic monitoring system.[6] These measuring systems are fully integrated in the software module and are used to obtain synchronous real time data. These variables were filtered over 10 s by a moving average filter. Blood pressure was periodically checked using a manual blood pressure monitor.[7]

These modifications of the basic system were implemented in a single software module represented by a virtual instrument developed in LabVIEW 2011 (National Instruments, Austin, TX, USA). This VI provides full control of the system functionality in a flexible way, including a graphical user interface (GUI). The module is described in depth in the sequel (Section 2.3).

2.2. Participation of the subject

The participation of the subject is represented by the relative mechanical work rate measured at the human-orthosis interface. If there is no active participation of the subject, the device has to generate a certain work rate to overcome the passive resistance of the legs, denoted as the passive mechanical work rate $P_{Passive}$. The raw mechanical work rate P_{raw} is dependent on the moments of force M and the gait kinematics ω at each joint. It is necessary to calculate the moment of force in dependence on the moment arm r and the force F of the respective joint. Angle and force sensors located at each joint, accessible via the sensor interface unit, allow calculation of the work rate (denoted as power P in Watts) using the common equation for rotational motion:

$$P = M * \omega = F * r * \frac{d\theta}{dt}$$

The angular speed ω is calculated by taking the derivative of the angle θ. The moment of force M is calculated using the force F and the lever arm r of the joint. The latter was estimated in relation to the geometries of the hip and knee joints and the angle θ of the respective joint. For both knee and hip joints, a Simulink/SimMechanics model (Version 7.5/3.2, MathWorks, Natick MA, USA) was developed and simulated using the geometry of the orthosis. The lever arms r were simulated dependent on the angle θ of the respective joint. A polynomial of 3rd order was fit to the data for the hip and knee joints (Fig. 3). The polynomial for the hip lever arm [mm] as a function of the hip angle [°] is

$$r_{Hip} = 0.00004261 * {\theta_{Hip}}^3 - 0.01298823 * {\theta_{Hip}}^2 + 0.34342519 * \theta_{Hip} + 71.43372684$$

The polynomial for the knee lever arm [mm] as a function of the knee angle [°] is

$$r_{Knee} = 0.00003634 * {\theta_{Knee}}^3 - 0.01278123 * {\theta_{Knee}}^2 + 0.72373301 * \theta_{Knee} + 49.61323405$$

The estimated polynomial functions are used in the calculation of the work rate for every joint. The absolute values of force F and angular speed ω are taken for direction-independent work rate calculation due to the fact that positive and negative forces represent

[1] LokomatPro version 5, Hocoma AG, Volketswil, Switzerland.
[2] h/p/cosmos GmbH, Nussdorf-Traunstein, Germany.
[3] Lokolift, Hocoma AG.
[4] Lokomaster Output Box, Hocoma AG.
[5] T31, Polar Electro, Kempele, Finland and HRMI, Sparkfun, Boulder, CO, USA.
[6] Metamax 3B, Cortex Biophysik GmbH, Leipzig, Germany.
[7] HEM-907, Omron, Hoofddorp, The Netherlands.