Robotics and Autonomous Systems 73 (2015) 44–58

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Hybrid therapy of walking with Kinesis overground robot for persons with incomplete spinal cord injury: A feasibility study☆

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HIGHLIGHTS

- We investigate the feasibility of providing the hybrid therapy of walking with Kinesis hybrid exoskeleton.
- We compare and investigate the role of the stimulation and the compliant robot control.
- Three case studies are presented. The cooperative controller of Kinesis adapted to patients and voluntary actions.
- No noticeable differences were observed between compliant and trajectory control.

ARTICLE INFO

Article history:
Available online 11 November 2014

Keywords:
Incomplete spinal cord injury
Rehabilitation robot
Walking rehabilitation
Functional electrical stimulation

ABSTRACT

Rehabilitation of walking ability is one of the most important objectives after a spinal cord injury. Robotic and neuroprosthetic technologies hold a considerable potential for driving walking rehabilitation therapies. However, new developments are needed in order to improve the walking rehabilitation interventions based in these technologies.

We recently presented a cooperative control strategy of Kinesis, a lower limb exoskeleton for providing hybrid therapy of walking (Del-Ama, 2014). Its design aimed to actively manage muscle fatigue caused by surface electrical stimulation, and to implement the assist-as-needed control paradigm in which both stimulation and robotic controller cooperate with the residual functionality of the user. In this article we present three case studies for investigating the feasibility of the hybrid therapy of walking delivered with Kinesis in patients with incomplete spinal cord injury. Besides, the adaptability features of Kinesis stimulation–robot cooperative control are assessed, characterizing the behavior of the cooperative controller while providing hybrid therapy of walking.

Patients with incomplete spinal cord injury participated in the experiments. The protocol consisted of walking with Kinesis during 6 min. Three configurations of the cooperative controller were tested for each patient in separate sessions in order to investigate its adaptability features. The immediate impact of the hybrid therapy of walking was assessed through several variables that represent the physiological impact, user–exoskeleton physical interaction, stimulation intensity and user subjective perception of the hybrid therapy of walking.

Results show that the cooperative controller of Kinesis adapted to patient functional deficits and voluntary actions during walking, modulating stimulation and robotic assistance, which was the aim of the controller design. Nevertheless, no noticeable differences were observed in the comparison between compliant and trajectory exoskeleton control. Further work is envisioned regarding several aspects of hybrid walking control: stimulation control based on muscle activation estimate, improved semi-automatic control of walking, and improved muscle fatigue monitoring. The hybrid walking therapy was tolerated by the patients without adverse effects, along with a tolerable physical demand. This shows a potential for walking rehabilitation in motor incomplete SCI patients, guaranteeing further research on this topic.

☆ This work was supported by grant CSD2009-00067 HYPER-CONSOLIDER INGENIO 2010. The authors thank all the participants who volunteered for the experiments, and the clinical staff from National Hospital for Spinal Cord Injury.

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http://dx.doi.org/10.1016/j.robot.2014.10.014
0921-8890/

1. Introduction

Spinal Cord Injury (SCI) is any alteration of the spinal cord that affects the sensory-motor and autonomous systems under the level of lesion [1]. It is a devastating clinical circumstance due to the functional loss resulting, impacting on the functional independence of the person. The absence of spontaneous recovery and the lack of a cure, makes the SCI a serious social, economic and physical problem. Rehabilitation of SCI is aimed towards maximization of user independence and adequate management of secondary lesion-related diseases [2]. Maximization of mobility has been identified as one of the main objectives for the injured individuals [3], regardless of other important functions.

Most therapies for rehabilitation of walking rely on the assumption that task-oriented practice promotes mechanisms of neural plasticity, muscle strength and learning of compensation strategies that increase walking ability [4,5]. Robotic technology has emerged as response to therapist's and therapeutic needs. Robotic technology can automate movement training, replicating some features of therapist's manual assistance, delivering intense training. Besides, robotic technology can offer new control and assessment methods that are beyond hands-on methods [4]. The assist-as-needed (AAN) control paradigm emerged to encourage the active motion of the patients, modulating the robotic assistance depending on the magnitude of the deviation of the gait trajectory, which can be generated for each patient and gait scenario separately [6,7]. However, the efficacy of robotic systems for walking rehabilitation is controversial, providing in the better cases similar functional outcomes than conventional therapy [8–10]. Several recommendations have been recently proposed for further design of improved robotic-driven rehabilitation interventions, exploiting the environmental context of the gait training and implementation of combinational approaches, among others [11–13]. In this sense, ambulatory robots that have been developed mainly for functional compensation of walking can offer a challenging and rich walking therapy, putting the patients in a real-world context, in which environmental challenges can be overcome and are highly motivating.

An example of a combinational approach is the hybrid exoskeletons, reviewed in [14]. These devices combine neuroprosthetic and robotic technologies in a single system, providing hybrid therapy of walking, exploiting the advantages of each technology while mitigating the respective disadvantages. The use of functional electrical stimulation (FES) has been widely investigated as alternate for rehabilitation and compensation of motor disorders [15,16]. The artificial activation of paralyzed muscles with a functional aim provides several physiological and psychological benefits, which are dependent on the nature of the injury [8]. However, FES poses several unresolved limitations that prevent its use for rehabilitation or functional compensation of walking. The low performance achieved by artificially stimulated muscles needs long training periods prior to implementing a walking-related intervention [17,18]. Furthermore, the multi-dimensionality of the muscle–skeletal system, the non-linear characteristic of muscle activation and the dramatic effect of muscle fatigue are also the main concerns of FES [19–21].

In this context, hybrid exoskeletons are regarded as a promising approach that blends complementary robotic and neuroprosthetic technologies. Initially developed in an attempt of optimizing the energy requirements (and therefore the overall weight) of lower limb ambulatory exoskeletons, hybrid exoskeletons hold a considerable potential for driving gait rehabilitation interventions. The robotic exoskeleton can manage the unavoidable loss of performance of FES-driven muscles due to muscle fatigue, providing accurate control of joint trajectories. Besides, the assist-as-needed control strategy applied within the redundant neuroprosthetic–robotic system can promote a cooperative behavior between the systems and the patient, optimizing the outcome of the active control of the lower limb motion while providing assistance during ambulatory walking.

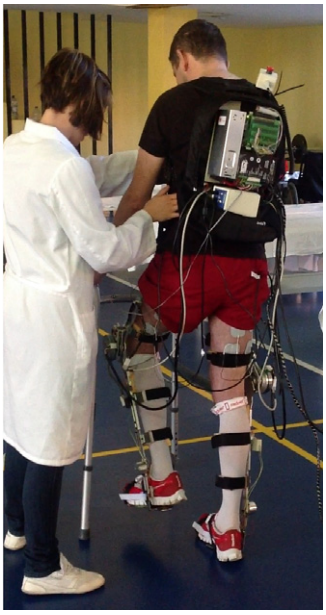

Fig. 1. Experimental setup for walking experiments.

We recently presented a cooperative control strategy of a lower limb exoskeleton for providing hybrid therapy of walking [22,23]. Kinesis, the name of the robotic exoskeleton, aimed to actively manage muscle fatigue caused by surface electrical stimulation, along with an implementation of the AAN control paradigm in which both stimulation and robotic assistance cooperate with the residual functionality of the user. Kinesis design and control approach is extensively described in [22,23] along with experimental results of a validation study conducted with healthy volunteers. The objective of this article is to investigate the feasibility of the hybrid therapy of walking delivered with Kinesis in patients with incomplete spinal cord injury. Besides, the adaptability features of Kinesis FES-robot cooperative control are assessed, characterizing the behavior of the cooperative controller while providing hybrid therapy of walking.

2. Material and methods

2.1. Description of Kinesis lower limb exoskeleton

Kinesis is a lower limb rehabilitation robot designed for providing hybrid therapy of walking to patients with incomplete spinal cord injury (Fig. 1). Specifically, Kinesis targets patients whose prognosis of functional recovery of walking is that patients can walk short distances but depend on the wheelchair for community ambulation [24]. Therefore, a successful overground hybrid walking therapy may provide benefits to this population. The inclusion criteria considered patients with low level of spinal cord injury, whose functional characteristics of the lesion in relation to the walking function were: (a) preserved hip flexion ability, (b) partial ability to generate voluntary knee extension, (c) paralysis of ankle joint and (d) presence of mild to severe spasticity.

Kinesis is a knee–ankle–foot robotic orthosis. Hip actuation was discarded due to preservation of hip functionality of the patients. The knee joint features a bio-inspired mechanism which mimics the displacement of the physiological knee joint, improving the kinematic compatibility with respect to a hinge joint. More