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Review

Control strategies for effective robot assisted gait rehabilitation: The state of art and future prospects

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ABSTRACT

A large number of gait rehabilitation robots, together with a variety of control strategies, have been developed and evaluated during the last decade. Initially, control strategies applied to rehabilitation robots were adapted from those applied to traditional industrial robots. However, these strategies cannot optimise effectiveness of gait rehabilitation. As a result, researchers have been investigating control strategies tailored for the needs of rehabilitation. Among these control strategies, assisted-as-needed (AAN) control is one of the most popular research topics in this field. AAN training strategies have gained the theoretical and practical evidence based backup from motor learning principles and clinical studies. Various approaches to AAN training have been proposed and investigated by research groups all around the world. This article presents a review on control algorithms of gait rehabilitation robots to summarise related knowledge and investigate potential trends of development.

There are existing review papers on control strategies of rehabilitation robots. The review by Marchal-Crespo and Reinkensmeyer (2009) had a broad cover of control strategies of all kinds of rehabilitation robots. Hussain et al. (2011) had specifically focused on treadmill gait training robots and covered a limited number of control implementations on them. This review article encompasses more detailed information on control strategies for robot assisted gait rehabilitation, but is not limited to treadmill based training. It also investigates the potential to further develop assist-as-needed gait training based on assessments of patients' ability.

In this paper, control strategies are generally divided into the trajectory tracking control and AAN control. The review covers these two basic categories, as well as other control algorithm and technologies derived from them, such as biofeedback control. Assessments on human gait ability are also included to investigate how to further develop implementations based on assist-as-needed concept. For the consideration of effectiveness, clinical studies on robotic gait rehabilitation are reviewed and analysed from the viewpoint of control algorithm.

Contents

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1. Introduction

About 8800 New Zealanders suffer new stroke annually [1]. This figure in the United States is about 610,000 [2]. With a survival rate at approximately 80%, it is estimated that there are 60,000 stroke survivors in New Zealand and the number in the United State is about 7,000,000. This makes stroke the leading cause of disability in both countries [1–3]. According to World Health Organisation, 15 million people suffer stroke every year globally, among whom about one third die and another one third are left permanently disabled [4].

Majority of the stroke survivors suffer the gait disorder and almost a half of these people cannot walk independently without any assistance. This thus urges the researchers to investigate in the area of walking ability recovery or gait rehabilitation. Bonita and Beaglehole [5], who investigated the motor recovery of the stroke population in Auckland New Zealand, reported that at 6 month post-stroke 62% still suffered motor deficits. Duncan [3] reported that inability to walk is one of the most common problems in the population who suffered acute stroke. Kelly-Hayes et al. [6] also states that 30% stroke survivors are unable to walk without any assistance.

Ultimately, development of new rehabilitation techniques should rely on a thorough understanding of underlying recovery mechanism [7]. Gait rehabilitation training or locomotor recovery is a process of neurological rehabilitation. Neural plasticity, which is defined by Sharma et al. [8] as the ability of the central nervous system (CNS) to adapt in response to changes in the environment or lesions, is also believed to be the basis underlying motor function recovery after cortical lesions, such as stroke [8]. Neuroscientists and physiotherapists are working together to investigate the neurological theories behind the rehabilitation. So far, neurological research has not yet uncovered the correlative brain events underlying motor recovery [9].

'Rehabilitation, for patients, is foundationally a process of relearning how to move to carry out their needs successfully' [10]. Motor learning is thought to be a prerequisite factor in the development of representational plasticity in the CNS [11]. General motor learning principles are hypothesised to be still valid for motor recovery [12]. One fundamental principle is that the degrees of performance improvement are dependent on the amount of practice [13]. Large amount of practice or repetition alone is not enough to induce ideal motor learning outcome [14]. Animal experiment conducted by Plautz et al. [11] indicated that practice needs to be task-related to produce representational plasticity in motor cortex. Introducing training variability in the skill acquisition session improves the overall session performance compared to single task repetition in one session [15]. Motor learning theories have driven the development of both conventional and robotic rehabilitation strategies.

Conventional rehabilitation strategies can be categorised into three groups, which are compensatory approaches, neurofacilitatory approaches and task-specific repetitive approaches. Some neurological lesions, such as stroke, result hemiplegia and hemiparesis, which only affect limbs on a single side of human body. Compensatory approach involves training patients to utilise their unaffected end effectors (e.g. unaffected hand) or body segments (e.g. unaffected muscles in the hemiplegic side) to achieve the same functional abilities before the injury [16,17]. For gait rehabilitation, therapists concern less on reproducing a more normal gait pattern after injuries, but more onto teaching patients more stable and functional gait pattern which allows them to walk safely to achieve a certain level of physical independency [18]. Compensatory approach is effective in functional recovery, but it may be associated with reduced joint range and pain in long term [18]. Moreover, patients may tend to rely on compensations for certain tasks instead of using affected effectors. This thus causes a pattern of learned non-use [19,20], which subsequently limits the gain of motor function of the impaired limb.

Unlike compensation, neurofacilitatory approach focuses on the rejuvenation of lost motor abilities. Bobath therapy, also known as neurodevelopmental therapy (NDT), is one representative concept of the neurofacilitatory approach. It was first developed in 1950s and is still a widely adopted post-stroke physiotherapy approach in Europe [21–23]. The last publication of Bobath on adult hemiplegia was in 1990 [24]. Bobath therapy involves tone-inhibiting manoeuvres and gait-preparatory tasks in sitting and standing postures to control spasticity and facilitate normal movement pattern of hemiplegic limbs. Very limited articles have been published to standardise the rehabilitation therapies based on the Bobath concept. To a great extent, training and application of the therapy are experience based [23].

Compared to the Bobath approach, the task-specific repetitive approach is more compliant with the modern motor learning concepts described previously. Neuroscientists have proven that repetition plays a major role in inducing and maintaining brain changes [25]. Bayona et al. [26] reviewed the related experiments and concluded that tasks meaningful to animal rather than repetitions alone are more likely to generate functional reorganisation. For human, daily practice of task-specific motor activities can also lead to reorganisation of the adult primary motor cortex [27,28]. Randomised controlled trials (RCT) conducted by Langhammer and Stranghelle both concluded that for acute patients task-specific training programme was more effective than Bobath programme [29,30].

Body weight support treadmill training (BWSTT), which was first developed by Finch and Barbeau in 1986 [31], is a well-researched task-specific repetitive gait rehabilitation strategy. Compared to neurofacilitatory approaches, BWSTT enables patients practice complex gait pattern repetitively. Usually during BWSTT, a patient walks on the treadmill with a body weight support (BWS) system attached via harness. Therapists guide patient's legs to follow desired trajectories, as well as promote correct pelvis and trunk movements during gait [22]. Hesse et al. compared BWSTT to conventional physiotherapy according to the Bobath concept on chronic stroke patients. It was concluded that BWSTT is superior with regard to restoration of gait and improvement of over ground walking speed. In terms of intensity, these investigations also indicated that more gait cycles were achieved by the BWSTT, for the sessions with same duration [32,33].

During the BWSTT, patients are trained to produce rhythmic gait cycles. The repetitive movements make the automation of this training process possible. It is a tiring job for therapists, since they have to manually move the patients' paretic legs continuously. This results the sustaining time of each training session to be short. There could also be patients with excessive spasticity, for whom manual training is nearly impossible [34]. Secondly, therapists are required to provide optimal and identical leg swing in every gait cycle. However, assistances provided by therapists are largely based on their experience. Optimal gait movements cannot always be achieved. There are always inter/intra-therapist variances; so leg swing trajectories are hardly to be identical. Robotic training has provided a solution to these problems. Moreover, a variety of technologies can be integrated into robotic training process, for example, dynamic feedback [35], biological feedback [36], and virtual reality [37].

To date, a number of robotic gait trainers have been developed and some of them are even commercially available. From the viewpoint of mechanism, gait rehabilitation robots can be allocated to three categories: treadmill training robots, end effector robots and ambulatory robots. Robots designed for rehabilitating a single lower limb joint not during walking are not included in this paper,