Review of Robot-Assisted Gait Rehabilitation after Stroke

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Abstract: Regarding classical rehabilitation techniques, there is insufficient evidence to state that a particular approach is more effective in promoting gait recovery than robotic devices. More constraining devices, such as Lokomat, could be helpful at the beginning of rehabilitation and with more severely affected patients, whereas end-effector devices and then treadmill gait training with body weight support, could be more effective in more advanced stages of rehabilitation and/or in less affected patients. Robotic devices need further research to show their suitability for walking training and their effects on over-ground gait.

Keywords: Robotic device, Gait, Rehabilitation, Stroke.

INTRODUCTION

Stroke incidence is approximately two million per year in China and is rising at an annual rate of nearly 8.7%, the mortality was even higher than that of developed countries in Europe and America. Stroke brings up to about 40 billion Yuan to the social and economic burden of China every year [1]. Stroke has become the first pathogenic cause of death in China and survivors can suffer several neurological deficits or impairments, such as hemiparesis, communication disorders, cognitive deficits or disorders in visuo-spatial perception. Patients who suffer blocked-vessel (ischemic) stroke generally have much higher chances of survival than patients who suffer bleeding (hemorrhagic) stroke. Hemiparesis and motor recovery have been the most studied of all stroke impairments. As many as 88% of patients with acute stroke have hemiparesis (Table **1**) [2]. Moreover, after completing standard rehabilitation, approximately 50%-60% of stroke patients still experience some degree of motor impairment, and approximately 50% are at least partly dependent in activities-of-daily-living [3]. Hemiplegia is one of the most common impairments after stroke and contributes significantly to reduce gait performance. Although the majority of stroke patients achieve an independent gait, many do not reach a walking level that enable them to perform all their daily activities [4]. After stroke, gait recovery is a major objective in the rehabilitation program, therefore a wide range of strategies and assistive devices have been developed for this purpose. The review emphasized on robotic devices used for gait rehabilitation.

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Table 1: 30-Day Death Rates for Different Types of Stroke [1]

	Blocked-vessel Stroke	Bleeding Stroke
Women	7%	30%
Men	8%	35%
45 to 64 years old	8% to 12%	37%
65 years or older	8%	45%

ADVANTAGES OF ROBOTIC DEVICES

Conventional gait training does not restore a normal gait pattern in the majority of stroke patients [5]. Robotic devices are increasingly accepted among many researchers and clinicians and are being used in rehabilitation of physical impairments in both the upper and lower limbs [6, 7]. These devices provide safe, intensive and task-oriented rehabilitation to people with mild to severe motor impairments after neurologic injury [8]. Because of robotic rehabilitation is intensive, repetitive and task-oriented, it is generally in accordance with the motor re-learning program [9, 10], more than with the other rehabilitative approaches, such as neurophysiological techniques and motor learning techniques. The efficacy of the human-robot interactions that promote learning depends on the actions either imposed or self-selected by the user. The applied strategies with available robotic trainers aim at promoting effort and self initiated movements. The control approaches are intended to i) allow a margin of error around a target path without providing assistance, ii) trigger the assistance in relation to the amount of exerted force or velocity, iii) enable a compliance at level of the joint and iv) detrend the robotic assistance by means of what has been proposed as a forgetting factor. In the former approach, the assumption is that the human resists applied forces by internally modelling the force and counteracting to it.

ASSIST-AS-NEEDED APPROACH

Regarding current assistance strategies employed in robotic systems, the assist-as-needed control concept has emerged to encourage the active motion of the patient. In this concept, the goal of the robotic device is to either assist or correct the movements of the user. This approach is intended to manage simultaneous activation of efferent motor pathways and afferent sensory pathways during training. Current assist-as-needed strategies face one crucial challenge: the adequate definition of the desired limb trajectories regarding space and time the robot must generate to assist the user during the exercise. Supervised learning approaches that pre-determine reference trajectories have been proposed to this purpose. Assist-as-needed approach has been applied as control strategy for walking rehabilitation in order to adapt the robotic device to varying gait patterns and levels of support by means of implementing control of mechanical impedance. Zero-impedance control mode has been proposed to allow free movement of the segments. Such approach, referred to as "path control" has been proposed with the Lokomat orthosis, (Hocoma, AG; Switzerland) (Figure **1**) [11] resulting in more active electromyography recruitments when tested with spinal cord injury subjects. Kim *et al.* emphasized that the short-term plasticity of locomotor circuits and provide a possible basis for persons learning to achieve more functional gait patterns following a stroke or other neurological disorders [12].

Figure 1: Lokomat robotic gait orthosis (Hocoma, AG, Volketswil, Switzerland).

ROBOTIC DEVICES FOR GAIT REHABILITATION

Regarding rehabilitation strategies, the most common robotic devices for gait restoration are based on task-specific repetitive movements which have been shown to improve muscular strength, movement coordination and locomotor retraining in neurological impaired patients [13, 14]. Robotic systems for gait recovery have been designed as simple electromechanical aids for walking, such as the treadmill with body weight support [15], as end-effectors, such as the Gait Trainer (Reha-Technologies, Germany, GT) [16], or as electromechanical exoskeletons, such as the Lokomat [17]. On treadmills, only the percentage of body weight support and walking speed can be selected, whereas on the Lokomat, the rehabilitation team can even decide the type of guidance and the proper joint kinematics of the patients' lower limbs. On the other hand, end effector devices lie between these two extremes, including a system for body weight support and a controller of end-point (feet) trajectories.

A fundamental aspect of these devices is hence the presence of an electromechanical system for the body weight support that permits a greater number of steps within a training session than conventional therapy, in which body weight is manually supported by the therapists and/or a walker [18, 19]. This technique consists on using a suspension system with a harness to provide a symmetrical removal of a percentage of the patient's body weight as he/she walks on a treadmill or while the device moves or support the patient to move his/her lower limbs. This alternative facilitates walking in patients with neurological injuries who are normally unable to cope with bearing full weight and is usually used in stroke rehabilitation allowing the beginning of gait training in early stages of the recovery process [20].

Several studies support that retraining gait with robotic devices leads to a more successful recovery of ambulation with respect to over ground walking speed and endurance, functional balance, lower-limb motor recovery and other important gait characteristics, such as symmetry, stride length and double stance time [14, 21, 22]. In these studies, body weight support treadmill therapy has sometimes been associated, from a clinical point of view, to the robotic therapies, even if treadmill should not be considered as a robot for their substantial engineering differences. In fact, in a recent Cochrane, electromechanical devices were defined as any device with an electromechanical solution designed to assist stepping cycles by supporting body weight and automating the walking therapy process in patients after stroke, including any mechanical or computerized device designed to improve walking function and excluding only non-weight-bearing devices [23]. Mayr *et al*. [24] found more improvement during the Lokomat training phase than during the conventional physical therapy phase after a rehabilitation program that applied these two different techniques for gait training. Luft *et al*. [25] compared the effects of 6-month treadmill training versus comparable duration stretching on walking, aerobic fitness and in a subset on brain activation measured by functional MRI. The results suggested that treadmill training promotes gait recovery and fitness, and provides evidence of neuroplasticity mechanisms. Visintin *et al*. [26] reported that treadmill gait training with body weight support was more effective than without body weight support in subacute, nonambulatory stroke patients, as well as showing advantages over conventional gait training with respect to cardiovascular fitness and walking ability. On the other hand, Peshkin *et al*. [13] attempted to identify users and therapists' needs through observations and interviews in rehabilitation settings to develop a new robotic device for gait retraining in over-ground contexts. They intended to establish key tasks and assess the kinematics required to support those tasks with the robotic device making the system able to engage intense, locomotor-specific, body weight support training over ground while performing functional tasks.

As most complex robots need to be permanently installed in a room, patients have to be moved from their beds to attend the rehabilitation. This is the main reason why therapy cannot be provided as soon as possible after stroke. In order to overcome this limitation, a robotic platform was developed by Monaco *et al*. [27, 28] that consists of providing leg manipulation, with joint trajectories comparable with those related to natural walking for bedridden patients. Robotic feedback training is an emerging but promising trend to constitute an active rehabilitation approach and novel methods to evaluate motor function. Forrester *et al*. [29] tested the robotic feedback approach in joint mobilization training, providing assistance as needed and allowing stroke patients to reach targets unassisted if they are able. Song *et al*. [30] investigated the effect of providing continuous assistance in extension torque with a controlled robotic system to assist upper limb training in patients with stroke. The results suggested improved upper limb functions after a twenty-session rehabilitation program. Ueda *et al*. [31] tested a computational algorithm that computes control commands (muscle force prediction) to apply target muscle forces with an exoskeleton robot. The authors foresee its application to induce specific muscle activation patterns in patients for therapeutic intervention. Huang *et al*. [32] assessed with an exoskeleton the amount of volitional control of joint torque and its relation to a specific function post injury, e.g. when rehabilitation involves the practice of joint mobilization exercises.

Robotic-assisted walking training after stroke aims to enable highly impaired patients to walk independently. However, estimating rehabilitation effects on motor recovery is complex, due to the interaction of spontaneous recovery, whose mechanisms are still under investigation, and therapy. Some studies have provided conflicting results regarding the effectiveness of robotic devices for ambulatory and/or chronic patients with stroke [33, 34]. A recently updated Cochrane review [23] has demonstrated that the use of electromechanical devices for gait rehabilitation increases the likelihood of walking independently in patients with subacute stroke (odd ratio = 2.56) but not in patients with chronic stroke (odd ratio = 0.63). Furthermore, some other problems are still limiting a wider diffusion of robotic devices for gait restoring, such as their high costs and the skepticism of some members of rehabilitation teams [35] probably based on the lacks of clear guidelines about robotic training protocols tailored on patients' motor capacity [36]. Morone *et al.* [37] have 48 participants with motor and gait dysfunction following subacute stroke and they were stratified by the motricity index into high and low motor impairment groups. The authors found that the lower motricity group assigned to an electromechanical device significantly improved in the functional ambulation category ($P<0.001$) and conventional and robotic therapies were equivalent in the higher motricity group. They authors also concluded that robotic therapy combined with conventional therapy is more effective than conventional therapy alone in severely affected patients.

At the light of all the above studies, the efficacy of each robotic device in neurorehabilitation seems to be related to a correct identification of the target population, in accordance with a generalization of the assist-as-needed strategy. Furthermore, it seems clear that a deeper knowledge about the proper selection of robotic devices, their training parameters and their effects on over ground walking performance for each patient can surely increase awareness of the potentialities of robotic devices for walking training in rehabilitation [36].

OTHER APPROACHES FOR GAIT REHABILITATION

Other approaches used in gait rehabilitation after stroke includes neurophysiological and motor learning techniques, functional electrical stimulation, and brain-computer interfaces. Despite being successful, the main principles of current rehabilitative approaches remain unclear [38]. Regarding neurophysiological and motor learning techniques, there is insufficient evidence to state that one approach is more effective in promoting gait recovery after stroke than any other approach. Furthermore, none of the methods is specifically focused on gait rehabilitation [39, 40]. The use of functional electrical stimulation combined with different walking retraining strategies has been shown to result in improvements in hemiplegic gait [41-47]. Reports on electroencephalography-based brain-computer interfaces for stroke recovery are limited to the rehabilitation of upper limbs, specifically of hand movements. Moreover, only a few of them have shown a real effect of brain-computer interface usage on motor recovery [48-51]. There is enough evidence to support the assumption that brain-computer interfaces could improve motor recovery after stroke, but there are no long term and group studies that show a clear clinical relevance. Lower limbs and gait function have not been studied in combination with brain-computer interfaces yet. However some works suggest that there is a common mechanism influencing upper and lower limb recovery simultaneously, independently of the limb chosen for the rehabilitation therapy [52, 53]. Despite the inherent latency of the hemodynamic response functional near infrared spectroscopy enables researchers to detect signals from specific regions of the cortex during the performance of motor activities for the development of future brain-computer interfaces [54-57]. Future research would make possible the analysis of the impact of rehabilitation on brain plasticity in order to adapt treatment resources to meet the needs of each patient and optimize the recovery process.

CONCLUSIONS

More constraining devices, such as Lokomat, could be helpful at the beginning of rehabilitation and with more severely affected patients, whereas end-effector devices and then treadmill gait training with body weight support, could be more effective in more advanced stages of rehabilitation and/or in less affected patients. Robotic devices need further research to show their suitability for walking training and their effects on over-ground gait.

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