Comparison of Exoskeleton Robots and End-Effector Robots on Training Methods and Gait Biomechanics

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Abstract. Rehabilitation robot positively improves walking ability of patients with gait disorders. Over the last decade, rehabilitation robot devices replaced the training of overground and treadmill. In this paper, our discussion focuses on exoskeleton robot and end-effector robot. The purpose of this study was to compare the training methods, gait Kinematic trajectories and muscle activity patterns on subjects when training on exoskeleton robot and end-effector robot.

Keywords: Rehabilitation robot, exoskeleton robot, end-effector robot.

1 Introduction

In traditional locomotor training on overground walking, patients practice gait using walking aids such as, crutches, canes, and walkers. Three or more therapists are required to guide the patient with leg movement and stabilize the patient's pelvis during the process. Over the last decades, training system that incorporates treadmill with a suspension support has been in practice clinically [1]. Studies have shown improved results in terms of the patient's walking ability, walking speed, balance, and symmetric walking control comparative to the traditional methods. Patient's body weight is partly supported by the suspension system on the treadmill to prevent the risk of falling [2]. During the gait training, two therapists are required to assist the patient's movement. One of the therapists stabilizes the patient's pelvis, while the other therapist must control the treadmill speed. Despite of the effectiveness in rehabilitation in traditional locomotor training or the treadmill-suspension system, clinical practice of both methods are still limited by the manpower of therapists. Thus, the duration of the patient's exercise is usually limited by the physical availability of therapists [3].

In the recent years, robotic devices have been widely utilized to replace the manpower and physical needs of therapists in the field of neurological rehabilitation. It also allows patients with nerve damage to receive a lot of exercising. Robotic rehabilitation devices can be divided based on the driven principles: exoskeleton robot (e.g. Lokomat, AutoAmbulator, LOPES, ALEX) [4]-[7], and end-effector robot(e.g. G-EO-systems, Gait Trainer, Gait Master)Type [8]-[10]. A number of research on exoskeleton robot and end-effector robot are studied and will be discussed in this

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study. The proven evidences from many of the studies show the effectiveness of robotic rehabilitation devices in terms of improving gait ability and physiological functions.

Most of the studies are based on the comparison between rehabilitation robots, overground walking and treadmill training. Therefore, three main purposes of this study are: (1) comparison of the training methods between exoskeleton robots and end-effector robots. (2) comparison of the gait activities between exoskeleton robots and end-effector robots. (3) comparison of the muscle activity between exoskeleton robots and end-effector robots.

2 Rehabilitation Robot Device

2.1 Rehabilitation of Exoskeleton Robot

1) Lokomat: Lokomat (Hocoma SA, Switzerland) is the most widely utilized rehabilitation robotic system in the current field of exoskeleton gait training clinically. This system is commonly used to improve gait function of patients with lower limb disorders that are caused by stoke, spinal cord injury, traumatic brain injury, and multiple sclerosis. The structure is composed of driven gait orthosis (DGO), Lokolift, and Andago®. The pelvis joint and the knee joint of DGO are made of a combination of DC motor and lead screws[4]. Before the use of Lokomat, the therapist must pre-measure the lengths of the subject's thighs and lower legs, and the width of the subject's pelvis. This allows the therapist to adjust the exoskeleton robot's upper legs, lower legs and the frame on both sides accordingly to match with the subject. After that, subject's thighs and lower legs are strapped and stabilized on to the exoskeleton's robotic upper legs and lower legs. The dorsiflexion of the subject's feet is controlled by two elastic straps. First, the gait function and the level of damage of the patient are evaluated by the therapist to avoid circumstances such as orthopedic problems and muscle diseases problems. Based on the evaluation result, the gait speed of the exoskeleton and the strength of the suspension support are adjusted in accordance to the patient's weight by the therapist. In the beginning of the training, each subject first walks in the Lokomat for up to 5 minutes in order to acclimate to the device and for the therapist to make minor adjustments for tighten leg cuff straps and optimize joint alignment. Each subject is exercised passively on the Locomat and the kinematic trajectories of the Lokomat are fully programmable. On the same token, gait speed, frequency, distance, duration can all be controlled. At the current state, several studies have proven that Lokomat improves not only the patient's gait function but also slows down muscle atrophy and reduces the problem of muscle tone [11], [12].

2) AutoAmbulator: The AutoAmbulator (HealthSouth, Houston, Texas, USA) is a rehabilitation robotic device located in Health South, USA. Detail specification related to this device has not been released up-to-date. In the previous study by Fisher et al, it is stated that 20 hemiplegic stoke patients were randomly selected to receive regular physiotherapy and rehabilitation robotic therapy. The result stated that patients who received training by the AutoAmbulator showed dramatic improvement on gait function and body balance [5].

3) LOPES: In 2007, lower extremity powered exoskeleton (LOPES), a new gait rehabilitation device was published by Veneman et al. Evaluation measures show that the device allows both "patient-in-charge" mode and "robot-in-charge" mode, in which the robot is controlled either to follow or to guide a patient, respectively. This device integrates the first study of LOPES, which focused on the clinical trials on 5 stoke patients. The patients received a 6-week training, with sessions of 3 times a week, and at maximum of 45 minutes per session. The post-training result stated that 4 of the patients were improved on foot clearance, gait speed and endurance [6].

4) ALEX: Active leg exoskeleton (ALEX), an unilateral exoskeleton robot for stroke patients with side hemiplegic legs was invented at the University of Delaware. The overall setup has four main components to aid the unaffected leg. Two stroke patients received a 6-week training. During the training the speed of the treadmill was increased. The result showed substantial improvement of the patients' gait pattern after the training [7], [13].

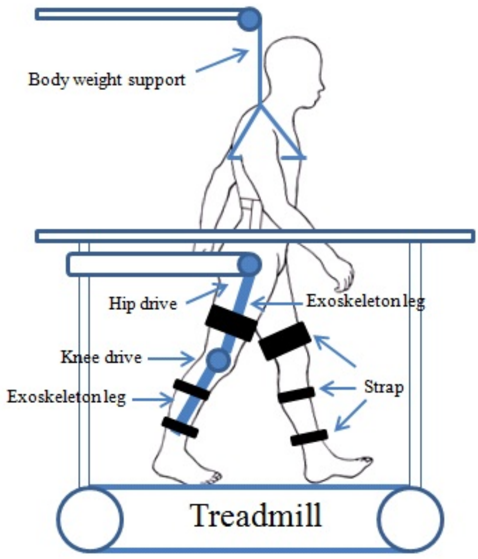

Fig. 1. Rehabilitation of exoskeleton robot

2.2 Rehabilitation of Exoskeleton Robot

1) GT I: The development of mechanized gait trainer(MGT or GT I), for restoration of gait, was based on a doubled crank and rocker gear system. It consists of two footplates positioned on bars, cranks and rockers. The crank propulsion is modified by a gear to provide a ratio of 60 percent to 40 percent between the gait of stance and swing phases. GT I has successfully treated children with cerebral palsy and a large number of stroke patients in the past studies. In most cases, the patients' gait ability and body balance were both improved [9].

2) GM 2: Current commercially available gait machines, such as Lokomat, AutoAmbulator, LokoHelp and GT I, are limited to repetitive exercises of walking on the floor. Hiroaki et al. from University of Tsukuba in Japan released a publication regarding an end-effector rehabilitation device, called Gait Master 2 (GM2). The structural motion principle is based on the relative positions of the base connecting bars, which allows the pedals to move forward and back, up and down. Subject on GM2 is able to perform gait training on normal walking, climbing up and down the stairs. Due to the lack of body support and the lack of fixation of the feet on GM2, the subject can be trained both passively and actively. 3 assessments on 9 healthy subjects were performed on GM2 by Hiroaki et al.: (1) actual overground walking; (2) passive simulated walking on GM2; (3) active simulated walking on GM2. During the tests, the subjects' Physiological Cost index (PCI) and lower limb electromyography (EMG) were being recorded. The result showed no significant differences between actual overground walking and walking passively on GM2. PCI result was most significantly different when subjects were actively walking on GM2. Due to the fact that actual overground walking was more relaxed, and the subjects were driven significantly by the pedal board on GM2, the subjects would involuntary lift their legs to coordinate with the movement of the pedal boards while the subjects were actively trained. In regards to the lower limb EMG, the result was more significant when the subjects were actively trained on GM2 [10].

3) HapticWalker: HapticWalker is an end-effector based gait rehabilitation robot, which was designed in references to the programmable footplate concept [23]. Each of the two manipulators comprises a hybrid serial-parallel robot and a footplate for permanent foot attachment at its end-effector. The subject's feet are fixed to the footplates via safety release bindings, in addition to the use of safety harness to prevent falls and also to enable body weight support.

4) G-EO Systems: Hesse et al. introduced a newly developed gait robot for training gait of stroke patients, called the G-EO Systems. In the report of G-EO Systems, four tests were performed on 6 sub-acute stroke patients: (1)actual overground walking, (2)simulation of overground walking on G-EO-Systems, (3)actual upward stairs climbing, (4)simulation upward stairs climbing on G-EO-Systems. Under the four test circumstances, patients were required to continue for 30 seconds or at least 10 steps, in order to record the lower limb EMG. The study showed very similar muscle activities for stroke patients under actual and simulation walking, as well as actual and simulation stairs climbing on G-EO-Systems. The slight differences found were: (1) thigh muscles activity was initiated slower on stimulated overground walking (compared to actual overground walking), and muscle activity duration was longer, (2)in comparison to the actual upward stairs climbing motion, the gastrocnemius muscles were being most active, while the activity of the lower legs' anterior muscles showed adjustments overtime for 3 of the patients. Step length, step frequency, step height and step speed could be adjusted according to the patients' gait ability [8].

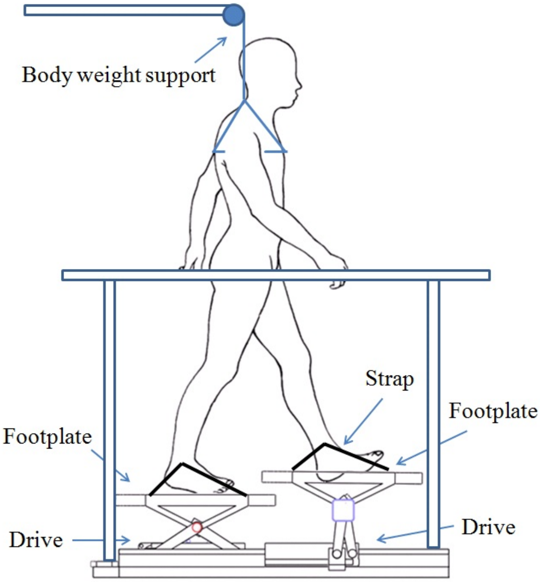

Fig. 2. Rehabilitation of end-effector robot

3 Discussion

3.1 Robot-Assisted Gait Training Methods

In the current robot-assisted gait trainings, training duration, distance and speed are regulated by the therapists in accordance to the patient's degree of injury. As the patient shows improvement, the percentage of body weight support by the suspension system can be gradually decreased. Due to the limitation of structural design, all of the exoskeleton robots only allow overground walking training. These exoskeleton robot gait training lack variations in the gait patterns. End-effector robots of GM2, HapticWalker and G-EO-Systems utilize 6 degrees of freedom in the mechanism design [8], [10]. Therefore, they allow subjects to perform gait training on overground walking, upward and downward stairs climbing, such as Table I. In order to overcome the single training method of the exoskeleton robots, Brütsch et al. integrated virtual reality (VR) with Lokomat, through the so-called biofeedback values, which allowed 10 gait nerve-damaged children to have interaction with VR using very little spontaneous force[14]. In addition, end-effector robots, GM2 device is capable of carrying out 3 training modes: enforced, semi-voluntary and real [10]. Inactive training decreases learning and recovery of walking motion in comparison to active training [15], [16].

Table 1. Rehabilitation robot

Device	DOF	Gait simulation	Training modes
Lokomat	2	Overground walking	Combined virtual reality [14].
AutoAmb-ulator	2	Overground walking	---
LOPES	4	Overground walking	1)Patient-in-charge mode. 2)Robot-in-charge mode [24].
ALEX	2	Overground walking	---
GT I	1	Overground walking	---
GM2	6	Overground walking Stair climbing up Stair climbing down	1)Actual overground walking. 2)Passive simulated walking. 3)Active simulated walking [10].
HapticWal-ker	6	Overground walking Stair climbing up Stair climbing down	---
G-EO-Systems	6	Overground walking Stair climbing up Stair climbing down	---

3.2 Kinematic Trajectories

Previous study showed that Lokomat changed the hip range of motion by almost 7° on healthy subjects. This would not cause much harm on patients whose hip range of motion are severely impaired [12]. Human hip joint, which is usually modeled as a ball-socket joint, is different from other joints since it provides three dimensional motions. The sagittal plane motion is most important for walking, in which hip flexion prepares the clearance for swinging, while the transition from hip flexion to extension facilitates limb advancement during swing phase and it also provides propulsion force in stance phase [25]. As the patient is using the robotic legs, the speed of the motor drive for the exoskeleton must match with speed of the treadmill, in order to ensure the safety of the patient. Further, the knee joints are moving three-dimensionally as human walks, whereas they are restricted to sagittal plane when using the exoskeleton. Patients could be affected by the potential shear forces during alignment between hip joints and the exoskeleton joints [26]. Hidler indicated that Locomat System often runs with 100% guidance force, with which a particular gait pattern would be enforced regardless of the subject's intentions [12]. Thus, with the inability to vary the kinematic patters, the subject could only go from step to step. Hidler found that misalignment of the subject's and Lokomat's knee and hip joints occurred as the subject intentionally alter their gait actively in Lokomat [12]. Any resistance and inertia movements are refrained from the hemiplegic subjects by the Exoskeleton.

In end-effector robots, therapist must pay close attention to the patient's knee motion to prevent knee hyperextension while training on GT I. Knee support is particular important to patients with severe spinal cord injury. Patients may wear any kind of ankle-foot orthosis (AFO) or knee ankle-foot orthosis (KAFO) to prevent knee instability [9], [17].

3.3 Muscle Activation Patterns

Hidler reported the cause of erroneous muscle pattern of healthy subjects as a result of reduced shank muscle activity and falsely bearing of proximal weight on muscles in the swing phase on Lokomat. Minor changes occurred during the terminal swing phase and the loading phase. During terminal swing, the subject's ankle was less dorsiflexed on the gain trainer. That is due to the geometrical constraints of the chosen mechanical solution, thus the rear of the footplate was lowered only minimally [12], [18]. The antagonistic tibialis anterior muscle was remarkably less active on the GT I, possibly due to patient reliance on the mechanical support during the swing phase. The activity of the tibialis anterior muscle was reduced when comparing exoskeleton robot with end-effector robot [9], [17].

Hesse et al. stated that, the activation of the quadriceps muscles was delayed throughout the whole stance phase on the G-EO-Systems during the floor walking condition. The thigh muscles of hemigplegic subjects were inactive during the swing phase on the G-EO-Systems [8]. Subjects' knees are supported by exoskeleton-based system during the stance phase, whereas stabilization of the knees is assisted manually or by stimulating the quadriceps using FES in end-effector based machine. Although FES may be utilized to facilitate quadriceps muscles, it may cause rapid muscle fatigue and often insufficient muscle responses [9], [12].

The tibialis anterior muscle activity is reduced accordingly when patients take advantage of the plates support on the feet during swing phase. Patient's feet have direct contact to the treadmill on the exoskeleton robot. The impact strength of the direct contact is usually unnoticeable to severe or total lower limb disability, thus patient would not be unaware of new injury during training [8], [9], [12]. In comparison to the previous two methods, better performances of vastus muscle, gastrocnemius, and tibialis are observed when subjects were actively walking on GM2. The activity of tibialis, which control the subject's plantar flexion and dorsiflexion is the most essential. Gastrocnemius and tibialis could be strengthened through gait training, hence improve the problem of foot drop [10].

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