OVERVIEW OF THE ROBOTIC REHABILITATION SYSTEMS FOR LOWER LIMB REHABILITATION

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Abstract
The purpose of this paper is to document a review of robotic devices for lower limb rehabilitation in order to provide a comprehensive reference about existing solutions and facilitate the development of new and improved devices.

Key words: robotic rehabilitation, degrees of freedom, end-effector, exoskeleton

INTRODUCTION
Because of the ageing of our population, there is a growing necessity for new technologies that can assist the disabled and elderly in their daily living. There are two main arguments for this. First, it is expected that countries will face a tremendous shortage on staff and qualified healthcare personnel in the near future. Second, people prefer more and more to live in their own homes as long as possible instead of being institutionalized in sheltered homes, or nursery homes when problems related to ageing appear.

To address these issues, we not only need sufficient health care personnel, but also the presence and appliance of high-tech devices. ICT technology and robotics are developing quickly nowadays, resulting in products that have the potential to play an important role in assisting to the disabled and elderly. In order to use new technology in an effective and efficient way, robust information with respect to their effects is needed, especially when used in healthcare.

Robotic rehabilitation systems consist of two main types of rehabilitation robots. They can be distinguished by the mechanism of human-robot interaction and the number of segments which the robot can directly “control”:

- End-effector based devices
- Exoskeleton based devices

The basic division of robotic rehabilitation systems is displayed at the fig. 1.

End-effector based devices are often adapted from industrial robots with more or less degrees of freedom (DoF) but only one point of physical contact between the distal and of the limb and the extremity of the robot, for example the patient holds a handle or has the forearm strapped to a support. The typical representative of this type of device is MIT Manus – robotic rehabilitation device for upper limb rehabilitation. The MIT Manus is the most famous and has been the object of the most clinical trials. It is a 2 DoF manipulandum with which the patient can interact to make planar pointing movements. During the session, the patient’s arm is supported in a non-motorised orthosis and he holds the handle of the manipulandum.

Fig. 1 Categorization of rehabilitation robots

More recently, exoskeleton based robotic devices have begun to be developed. These “orthoses” allow contact at several key points of the limb and can therefore control the different segments of the limb. This means that they can influence coordination patterns and/or better follow the particularities of the patient’s postures of movements.

There are also two sub-groups in this category: anthropomorphic robots which are in contact practically with the whole limb (exoskeletons such as ARMIn, RUPERT) and robots which have discontinuous contact with the limb (ARMguide, Dual Robotic Systems from Leeds).

Robotic Systems for Lower-Limb Rehabilitation

Traditional rehabilitation therapies are very labour intensive especially for gait rehabilitation, often requiring more than three therapists together to assist manually the legs and torso of the patient to perform training. This fact imposes an enormous economic burden to any country’s health care system thus limiting its clinical acceptance. Furthermore, demographic change (aging), expected shortages of health care
personnel, and the need for even higher quality care predict an increase in the average cost from first stroke to death in the future. All these factors stimulate innovation in the domain of rehabilitation in such way it becomes more affordable and available for more patients and for a longer period of time.

The rehabilitation process toward regaining a meaningful mobility can be divided into three phases:
1. the bedridden patient is mobilized into the chair as soon as possible,
2. restoration of gait, and
3. improvement of gait (i.e., training of free walking if possible).

Over the last decade, several lower-limb rehabilitation robots have been developed to restore mobility of the affected limbs. These systems can be grouped according to the rehabilitation principle they follow (fig. 2):
- treadmill gait trainers (fig. 2 a),
- foot-plate-based gait trainers (fig. 2 b),
- overground gait trainers (fig. 2 c),
- stationary gait trainers (fig. 2 d),
- ankle rehabilitation systems,
  - stationary systems,
  - active foot orthoses (fig. 2 e).

**Treadmill Gait Trainers**

Traditional therapies usually focus on treadmill training to improve functional mobility. This rehabilitation technique is known as partial bodyweight support treadmill training (PBWSTT). Three therapists assist the legs and hip of the patient walking on a treadmill while part of the patient’s body weight is supported by an overhead harness. Many robotic systems have been developed with the aim to automate and improve this training technique as a means for reducing therapist labor. Usually these systems are based on exoskeleton type robots in combination with a treadmill (fig. 2(a)). This group includes robotic systems such as Lokomat, LokoHelp and ReoAmbulator, ARTHuR, POGO and PAM, ALEX, LOPES, ALTRACO, RGR, String-Man.

Of the 10 systems that compose the group, only three of them are on the market: the Lokomat (fig. 3), the LokoHelp, and the ReoAmbulator.

The Lokomat (Hocoma AG) consists of a robotic gait orthosis and an advanced body weight support system, combined with a treadmill. It uses computer controlled motors (drives) which are integrated in the gait orthosis at each hip and knee joint (fig. 3). The drives are precisely synchronized with the speed of the treadmill to assure a precise match between the speed of the gait orthosis and the treadmill. Till date, it is the most clinically evaluated system and one of the firsts of its type.

**Foot-Plate-Based Gait Trainers**

Some rehabilitation machines are based on programmable foot plates. That is, the feet of the patient are positioned on separate foot plates, whose movements are controlled by the robotic system to simulate different gait patterns (fig. 2(b)). This

Fig. 2 Robotic systems types for lower-limb rehabilitation: (a) treadmill gait trainers, (b) foot-plate-based gait trainers, (c) overground gait trainers, (d) stationary gait and ankle trainers, and (e) active foot orthoses.

Fig. 3 Lokomat system
group consist of robotic systems such as: Gangtrainer GT I, HapticWalker, GM5, LLRR and Univ. Gyeongsang. Only one system (Gangtrainer GT I) is on the market, although many others have done some clinical testing.

Fig. 4 Gangtrainer GT I

The Gangtrainer GT I (fig. 4), commercialized by Reha-Stim, can assist the patient in the recovery of his freedom of movement by relieving the body of its own weight and adapting speed from the individual ability of the patient. Harness-secured patients are positioned on two foot plates, whose movements simulate stance and swing, and ropes attached to the patient can control the vertical and lateral movements of the center of mass. Many clinical studies have been conducted worldwide with this device, and it is considered as one of the pioneering robotic systems for rehabilitation. Similarly as for treadmill gait trainers, the Gangtrainer GT I is at least as effective as the manual treadmill therapy but requiring less input from the therapist.

**Overground Gait Trainers**

This group of systems consist of robots that servo-follow the patient’s walking motions overground. They allow patients move under their own control rather than moving them through predetermined movement patterns (fig. 2(c)). It is very noticeable that almost all systems reviewed have been commercialized.

**Stationary Gait Trainers**

Robotic system based on this principle are focused on guided movements of limbs in order to have an optimal effect from a therapeutic and functional perspective (fig. 2(d)). The objective of these systems is to obtain efficient strengthening of the muscles and the development of endurance, as well as joint mobility and movement coordination. This group consist of following robotic systems: MotionMaker, Lambda and AIST Tsukuba.

The KineAssist is a robotic device (fig. 5), commercialized by Kinea Design, LLC, for gait and balance training. It consists of a custom designed torso and pelvis harness attached to a mobile robotic base. The robot is controlled according to the forces detected from the subject by the load cells located in the pelvic harness. A recent clinical trial has been conducted in order to evaluate overground walking speed changes when using the KineAssist system.

**Fig. 5 KineAssist**

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**Fig. 6 MotionMaker**

The MotionMaker (Swortec SA) (fig. 6) is a stationary training system which allows to carry out fitness exercises with active participation of the paralyzed limbs. The limbs are only attached to the orthoses at the foot level to simulate natural ground reaction forces. The advantage of the MotionMaker is its real-time sensor-controlled exercises, combined with the controlled electrostimulation,
adapted to the patient’s efforts. First clinical trials have been carried out with the system, showing an improvement of the patient’s ability to develop a higher voluntary force during a leg-press movement.

Two other robotic systems that have been developed with a similar working principle: the Lambda, a rehabilitation and fitness robot used for mobilization of lower extremities that provides the movement of the lower extremities in the sagittal plane, including an additional rotation for the ankle mobilization; and a wire-driven leg rehabilitation system developed by the National Institute of Advanced Industrial Science and Technology (AIST) of Tsukuba.

Ankle and Knee Rehabilitation Systems

Neurological impairment after stroke can lead to reduced or no muscle activity around the ankle and knee causing the inability of an individual to lift their foot (drop foot). Ankle motion is very complicated due to its complex bone structures. The overall motions of the ankle can be arranged as dorsiflexion/plantarflexion, inversion/eversion, abduction/adduction, and pronation/supination.

Many systems have been developed to enforce or restore this ankle and knee motions specifically. These systems can be grouped into stationary or active foot orthoses.

Stationery Systems

Stationary systems are those robotic mechanism designed to exercise the human ankle and knee motions without walking. The patient is positioned always in the same place, and only the target limb is exercised (fig. 2(d)), this group consist of following robotic systems: Rutgers Ankle, IIT-HPARR, AKROD, Leg-Robot, NUVABAT and other systems developed by the Gwangju Institute of Science and Technology (GIST) and Universities such as University of London, Aucland, Cheng Kung, Fuzhou and AIST Tsukuba.

The Rutgers Ankle (fig. 7) was the first of this kind. It is a Stewart platform-type haptic interface that supplies 6 DoF resistive forces on the patient’s foot, in response to virtual reality-based exercises. Many clinical trials have been conducted with this system, showing the improvement of the patient on clinical measures of strength and endurance.

Active Foot Orthoses

On the contrary to stationary systems, active foot orthoses are actuated exoskeletons that the user wears while walking over ground or in a treadmill (fig. 2(e)). They are intended to control position and motion of the ankle, compensate for weakness, or correct deformities. They are an evolution of traditional passive lower limb orthoses, with additional capabilities to promote appropriate gait dynamics for rehabilitation.

Two early attempts to develop such systems were the Powered Gait Orthosis (PGO) and the Pneumatic Active Gait Orthosis (PAGO). Both devices underwent testing on human participants, but they were not commercialized.

Currently, the only commercialized system for rehabilitation is the Anklebot (Interactive Motion Technologies, Inc.) (fig. 8), an ankle robot developed at the Massachusetts Institute of Technology (MIT) to rehabilitate the ankle after stroke. It allows normal range of motion in all 3 DoF of the foot relative to the shank while walking over ground or on a treadmill. Pilot controlled trials with such device were presented in, showing a carry over to characteristics of gait with a general improvement in the walking distance covered and time.
CONCLUSION

In this paper there were presented an overview of the robotic rehabilitation devices for lower limb rehabilitation. The presented robotic rehabilitation systems are the most famous and utilized in robotic rehabilitation practice.

Reference


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