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Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation

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ABSTRACT

Robot-assisted rehabilitation and therapy has become more and more frequently used to help the elderly, disabled patients or movement disorders to perform exercise and training. The field of robot-assisted lower limb rehabilitation has rapidly evolved in the last decade. This article presents a review on the most recent progress (from year 2001 to 2014) of mechanisms, training modes and control strategies for lower limb rehabilitation robots. Special attention is paid to the adaptive robot control methods considering hybrid data fusion and patient evaluation in robot-assisted passive and active lower limb rehabilitation. The characteristics and clinical outcomes of different training modes and control algorithms in recent studies are analysed and summarized. Research gaps and future directions are also highlighted in this paper to improve the outcome of robot-assisted rehabilitation.

1. Introduction

According to the data from World Health Organization (WHO), the proportion of world's people over 60 years will be doubled from 11% to 22% between 2000 and 2050. During the same period, the number of elderly people aged over 60 years will increase from 605 million to 2 billion. More than half of the worldwide elderly people live in Asia (54%), followed by Europe (22%) [1]. Many countries have gradually entered the aged society. Meanwhile, there are about 650 million people with disabilities worldwide, accounting for about 10% of the world's total population, where 80% of disabled people live in developing countries [2]. The report "2013 China Statistical Yearbook of Disabled People" shows that the total number of people with disabilities in China is approximately 37.95 million [3], in which the physically limbs disabled is 15.64 million, occupying 59% of the total disabilities. Among the aged society and increasing disabled population, there will be obvious recession in these people's physiological functions, which will severely affect their daily lives.

The rehabilitation and training of elderly, disabled and other movement disorders has become a major social problem to be resolved, however, the conventional manual therapy mainly relies on therapist's experience, making it difficult to meet the requirements of high-intensity and repetitive training [4]. The number of physiotherapists is severely lacking, and the evaluation methods are mostly subjective, so the treatment effects cannot be guaranteed [5]. In this situation, there is a considerable increase in the needs of advanced rehabilitation devices, which are expected to assist patients to perform training exercise precisely, quantitatively and scientifically [6]. Rehabilitation robotics has become a research field that attracts more and more attentions in the last decade. Applying robots to rehabilitation cannot only release physicians from the heavy burden of training missions, but also evaluate patients' recovery status by analysing the data recorded in robotic training process. Due to its advantages in terms of accuracy and reliability, rehabilitation robotics is able to provide an efficient approach to improve the recovery outcomes after stroke or surgery.

Nowadays, there have been several published review papers on control strategies of robotic rehabilitation and training. For example, a review on categories of control strategies of all kinds of rehabilitation robots was conducted in [7], however, very few details of mechanisms and control algorithms were given to the lower limb rehabilitation robots. Diaz et al. conducted a comprehensive survey of existing robotic systems for lower limb rehabilitation [8]. This review is quite informative. It covered most current lower limb robots, however, the robotic training modes and control strategies were not emphasized somehow. Kwakkel

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et al. presented a systematic review on the effects of robot-assisted therapy and mainly focused on the clinical outcomes of different robots [9], in which the detailed discussion of robot control strategies was also included. On the other hand, Hussain et al. provided a review of the treadmill based robotic gait training devices but specifically focused on the control strategies related to treadmill robots [10]. Mohammed et al. reviewed the state of the art of the lower limb wearable robots [11,12], which mainly focused on actuated exoskeletons and the control strategies in them. Another review concentrating on lower limb exoskeletons and active orthoses was done by Dollar and Herr [13], but it only covered devices that operate in parallel with human legs. In recent years, novel control strategies (such as adaptive control and assist-as-needed control) have been widely used in lower limb rehabilitation robots, but they are not specifically discussed in previous papers. With the emerging human–robot interaction techniques, biofeedback and hybrid control have also become more and more popular in newly developed rehabilitation robots. Although many review papers mentioned that bio-signals based control strategies have been regarded as effective strategies and become a popular research area, however, none of them have investigated or summarized the recent studies on this kind of strategies [14].

This paper gives a review and analysis of mechanisms, training modes and control strategies of lower limb rehabilitation robots, especially the control methods considering hybrid data fusion and adaptive laws. It provides an introduction of the most recent development of robot-assisted lower limb rehabilitation, and also summarizes the research gaps and potential future directions. The rest of paper is organized as follows. Section 2 compares different mechanisms of lower limb rehabilitation robots. In Section 3, the robot-assisted training modes for different recovery stages are analysed. Section 4 presents recent development of robotic control strategies, including position control, impedance control, biofeedback control and adaptive control. In Section 5, the research limitations and future directions are discussed and concluded.

2. Mechanisms of lower limb rehabilitation robots

Mechanical design is the basis of robot-assisted rehabilitation system, and should follow a basic principle of keeping its structure simple, lightweight, and easy to control. In recent years, various types of robots have been developed for lower limb rehabilitation. Generally, these robots can be divided into two categories: exoskeleton and end-effector robots [15]. For example, Lokomat [16], BLEEX [17] and LOPES [18,19] are typical exoskeleton robots, while Rutgers Ankle [20], and Haptic Walker [21] are end-effector robots. According to their mechanisms and rehabilitation principles, exoskeleton robots can be grouped as the treadmill-based devices and the orthosis-based robots, while the end-effector robots have footplates-based and platform-based types. An overview of recent representative robots and their characteristics is demonstrated in Table 1.

Table 1
Overview of recent lower limb rehabilitation robots.

Groups	Devices	Institutions/researchers	Actuated DOF	Characteristics
Treadmill based exoskeleton robots	Lokomat [16]	Hocoma, Switzerland	Two-leg DOFs for treadmill walking	Treadmill training with body weight support system; it provides powered assistance at the hip and knee by strapping patient's legs
	Lokohelp [22]	Woodway & Lokohelp Group, Germany	Two-leg DOFs for walking with levers on treadmill	It can be placed on a treadmill with weight support mechanism; it transmits movement of treadmill to levers for patients to track
	LOPES [18,19]	Veneman et al. from University of Twente, Netherlands	Three rotational DOFs in each leg for walking on treadmill	A leg exoskeleton containing three actuated rotational joints: two at the hip and one at the knee; it can move in parallel with the legs when walking on a treadmill
	ALEX [23]	Banala and Agrawal et al. from University of Delaware, US	Seven DOFs for translations and rotation of a leg	It is a powered leg orthosis with actuators at hip and knee joints; it provides assistance to the patient walking on a treadmill
Leg orthoses and exoskeletons	AAFO [24]	Blaya and Herr from Massachusetts Institute of Technology (MIT)	Two motion DOFs for ankle joint	It is an active ankle–foot orthosis, uses SEA as the actuation; ankle joint was fabricated to fit; allows free motion in sagittal plane
	KAFO [25]	Sawicki and Ferris from University of Michigan, US	Free motion DOFs in sagittal plane for ankle and knee	It is a knee-ankle–foot orthosis; six artificial pneumatic muscles are attached to orthosis to power ankle and knee movements
	HAL [26]	Tsukuba University & Cyberdyne, Japan	Full-body exoskeleton for arms, legs, torso	It is a full-body exoskeleton for rehabilitation and heavy works support; and EMG signals are used to map patient's intention
	BLEEX [17,27]	Kazerooni et al. from University of California, US	Seven DOFs for each leg in hip, knee and ankle joints	It is a pair of wearable robotic legs developed to increase the abilities of the wearer, provide power to carry major loads
Foot plates based end-effector devices	Gait Trainer GTI [28]	Reha-Stim, Germany	Two footplates for foot/leg movement	Patient's feet are positioned on footplates with movements are controlled to simulate foot motion during stance and swing
	Haptic Walker [21]	Hesse et al. from Charité University Hospital, Germany	Arbitrary movement DOFs for two feet	It allows simulation of various gait patterns and walking speeds; force/torque sensors are located under each footplate
	G-EO-Systems [29]	Reha Technology AG, Switzerland	Two footplates for walking and climbing DOFs	It is an end-effector gait robot with freely programmable footplates; can be controlled to stimulate walking and climbing stairs
Platform based end-effector robots	Rutgers Ankle [20]	Girone et al. from Rutgers University, US	Six DOFs for ankle and foot based on a Stewart platform	It supplies 6-DOF resistive forces to patient's ankle with virtual reality, and later extended to a dual platform for gait rehabilitation
	ARBOT [30,31]	Saglia et al. from Istituto Italiano di Tecnologia, Italy	Two ankle DOFs in plantar/dorsiflexion, inversion/eversion	It is a parallel robot for ankle rehabilitation with patient's foot fixed on the moving platform, a customized linear actuator used
	Parallel Ankle robots [32,33]	Xie et al. from The University of Auckland, New Zealand	Three ankle DOFs provided by 4-axis parallel robot	A 4-link robot driven by DC motor actuators and a 4-axis parallel robot driven by pneumatic muscles designed for ankle rehabilitation

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