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REVIEW

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A Review on Lower Limb Rehabilitation Exoskeleton Robots

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Abstract

Lower limb rehabilitation exoskeleton robots integrate sensing, control, and other technologies and exhibit the characteristics of bionics, robotics, information and control science, medicine, and other interdisciplinary areas. In this review, the typical products and prototypes of lower limb exoskeleton rehabilitation robots are introduced and state-of-the-art techniques are analyzed and summarized. Because the goal of rehabilitation training is to recover patients' sporting ability to the normal level, studying the human gait is the foundation of lower limb exoskeleton rehabilitation robot research. Therefore, this review critically evaluates research progress in human gait analysis and systematically summarizes developments in the mechanical design and control of lower limb rehabilitation exoskeleton robots. From the performance of typical prototypes, it can be deduced that these robots can be connected to human limbs as wearable forms; further, it is possible to control robot movement at each joint to simulate normal gait and drive the patient's limb to realize robot-assisted rehabilitation training. Therefore human–robot integration is one of the most important research directions, and in this context, rigid-flexible-soft hybrid structure design, customized personalized gait generation, and multimodal information fusion are three key technologies.

Keywords: Control method, Lower limb exoskeleton, Mechanical design, Rehabilitation robot

1 Introduction

A rehabilitation robot, which is a robot directly serving humans, has extensive application prospects in rehabilitation therapy with high professional requirements. Therefore, it is of great importance to develop advanced rehabilitation robots.

Research on lower limb rehabilitation robots for patients with limb movement disorders is an important part of rehabilitation robot research. By 2030, 18.2% of China's population will be over the age of 65. Due to an aging society and improving living standards, the number of people with limb dyskinesia is increasing rapidly. Limb movement disorders can lead to abnormal gait and affect normal walking. For patients with lower limb movement disorder, active rehabilitation training should be started as early as possible. In China, which has the highest stroke rate in the world [1], there are nearly 15 million disabled people with lower limb motor dysfunctions, such as cerebral palsy, hemiplegia, and paraplegia, and nearly 40 million disabled elderly people who have lost the ability to walk, due to aging. About 350,000 people are in urgent need of rehabilitation technical personnel, but less than 20,000 personnel are available. Therefore, lower limb rehabilitation robots are of great significance. The use of rehabilitation robots can reduce the burden on therapists, realize data detection during training, and aid the quantitative evaluation of recovery in a controllable and repeatable manner [2].

Lower limb rehabilitation exoskeleton robots, which are a major class of rehabilitation robots, connect with the human body in a wearable way and can control the movement of all joints in the training process. Research on lower limb rehabilitation exoskeleton robots began in the 1960s [3, 4]. Due to technical limitations, these early robots failed to reach the expected targets, but laid the foundation for follow-up studies. In recent decades, especially after Lokomat was applied in clinical rehabilitation, lower limb rehabilitation exoskeleton robots have gradually become a major research topic.

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Figure 1 Treadmill-based lower limb rehabilitation exoskeletons

Figure 2 Overground lower limb rehabilitation exoskeletons

They are mainly used to provide power assistance and rehabilitation to the elderly and patients with lower limb motor dysfunctions. Exoskeleton robot technology is a comprehensive technology that integrates sensing, control, information and computer science to provide a wearable mechanical device. Many enterprises and research institutions have carried out relevant research work and achieved several milestones in the theory and application of these robots. According to their application, these robots are divided into two types, namely for treadmill-based and overground applications. Patients can receive gait training from treadmill-based exoskeleton robots on a treadmill. In these robots, in addition to the exoskeleton that is used to provide assistance to leg movement [3], a body weight support (BWS) system is required to reduce gravitational forces acting on the legs, ensure safety, and maintain balance; some examples of such robots include ALEX [2], Lokomat [4], and LOPES [5], as shown in Figure 1. Overground exoskeleton robots help patients in regaining overground gait, as shown in Figure 2; examples include eLEGS (Exoskeleton Lower limb Gait System) [6, 7], Indego [8], ReWalk [9], MINDWALKER [10, 11], and HAL (Hybrid Assistive Limb) [12].

At present, a large gap exists in rehabilitation robot technology between China and the developed countries. China urgently requires rehabilitation-assistive devices and has the largest market potential in the world. By 2020, the industrial scale is expected to exceed 700 billion. Universities and institutes in China [13–22] have conducted a number of studies and achieved some promising results. However, deep disparities exist between Chinese and overseas research, and no systematic industry has yet been formed. Therefore, China's lower limb rehabilitation exoskeleton robot research has the potential to produce another revolution in the robot industry.

Table 1 Range of motion of lower limbs

Part/joint	Degree of freedom	ROM (m; degree)
Pelvis	Superior/inferior	0.1/0.1
	Lateral	0.15/0.15
	Anterior/posterior	0.2/0.2
	Obliquity	10/10
	Tilt	6/6
	Vertical rotation	15/15
Hip	Flexion/extension	40/30
	Adduction/abduction	20/20
	Internal/external rotation	15/15
Knee	Flexion/extension	75/0
Ankle	Dorsiflexion/plantarflexion	25/35
	Adduction/abduction	10/10
	Internal/external rotation	10/20

Hence, in this paper, we present a review on lower limb rehabilitation exoskeleton robots. Research and results in mechanical design and control methods are discussed after collating a summary on human gait analysis. The state-of-the-art research on lower limb rehabilitation exoskeleton robots is described and human–robot integration, which is one of the most important research directions, is discussed.

2 Human Gait Analysis

Wearability is one of the most vital features of lower limb rehabilitation exoskeleton robots and hence such robots must have good human compatibility. Therefore, an illustration of lower limb anatomy and human gait analysis can provide the underlying basis for the design and control of lower limb exoskeleton rehabilitation robots.

2.1 Anatomy of Lower Limbs

The human walking process is mainly accomplished by lower limbs, and hence, analyzing their structure and movement characteristics is necessary.

Walking is achieved by coordination between the pelvis, hip, knee, and ankle. Their ranges of motion (ROM) are illustrated in Table 1. The pelvis is located between the trunk and thighs. As a ball-and-socket joint, the hip is formed by the head of the femur and pelvic bone and it allows simultaneous movement between the thighs and pelvis [23]. It allows sagittal flexion/extension, frontal abduction/adduction, and transverse external/internal rotation [24]. Knee is a joint complex containing tibiofemoral and patellofemoral joints. Their movement occurs in two planes, allowing sagittal flexion/extension and transverse internal/external rotation [23]. During walking, knees perform important functions. In the swing phase, knees shorten leg length by flexion [25]. In the stance phase, they remain flexed to absorb shock and transmit forces through legs. The ankle/foot is a complex structure that absorbs this shock and imparts thrust to the body. Ankle movements mainly occur about talocrural and subtalar joints [24]. The talocrural joint is located between the talus, distal tibia, and fibula to provide plantar/dorsiflexion as a hinge joint, in which the surface of one bone is spool-like and the surface of the other bone is concave. The subtalar joint is located between the calcaneus and talus and allows eversion/inversion and internal/external rotation. The basis for the mechanical design of rehabilitation exoskeleton robots is provided by an analysis of the lower limb structure.

2.2 Analysis on Human Gait

The normal gait pattern of patients cannot be measured directly because of their impaired motor functions. Therefore, it is necessary to conduct rehabilitation training and evaluate normal gait data, which is significant in clinical applications. Patients with hemiplegia or physical disabilities often follow a predetermined trajectory in their rehabilitation. These predetermined trajectories can be obtained from normal gait data collection. Through gait analysis, the relevant characteristics of human gait can be revealed. Step length, width, and speed are all used for human walking gait characterization. Thus, human body movement parameters and structural parameters have a significant influence on human gait characteristics.

Human gait is affected by walking speed [26, 27] as confirmed by an analysis of gait parameters [28] and joint angles [29], as confirmed by recording and analyze the gait data with different walking speeds on a walkway [30] or treadmill [31]. Because most rehabilitation robots use a body support system during rehabilitation training, analyzing human gait on a treadmill is necessary. Additionally, studies have revealed that body height, as a structural parameter, has limited effect on the human gait as compared to walking speed. This was proved by comparing the difference in the correlation between regression models when using speed and normalized speed (normalized to leg length) [30, 32] or by using step-wise regression in regression models by including body height [31] as a parameter. Further, these studies focused on the effect of these parameters on joint angles. Studies have also outlined the relationship between gait parameters and the body mass index (BMI) [26, 33]. These studies provide a foundation for control over lower limb rehabilitation exoskeleton robots.

3 Mechanics of Lower Limb Rehabilitation Exoskeleton Robots

Lower limb rehabilitation exoskeleton robots need a mechanical structure matching human lower limbs to realize force and energy transmission through the wearable connection. These can be achieved by designing the appropriate robot mechanism and actuation. An overview of the mechanics involved is presented in Table 2.

3.1 Anatomy of Human Upper Limbs

The mechanism of lower limb rehabilitation exoskeleton robots should realize movement matching with human lower limbs. The mechanism design of the Berkeley exoskeleton system (BLEEX) laid a foundation for subsequently developed robots. To ensure safety and avoid collisions maximally with users, BLEEX is almost anthropomorphic but does not include all the degrees of freedom available for human legs (Figure 3). Additionally, BLEEX joints are purely rotary joints and hence, are different from human joints [34]. The hip is simplified as three rotatory joints to achieve flexion/extension, abduction/extension, and internal/external rotation. The knee is simplified as a rotating joint to achieve pure sagittal rotation. The ankle is simplified into three rotation joints to achieve plantar/dorsiflexion, eversion/inversion and internal/external rotation. The configuration of the current lower limb exoskeleton robots, such as ALEX [35], Lokomat [4, 36], LOPES [37, 38], Rewalk [9], Rex [39] and HAL [40], is mainly based on BLEEX.

Due to the existence of the BWS system and the fact that the robot body is often connected to a fixed platform, an important feature of treadmill-based exoskeleton robots is that the patient does not need to carry the entire weight of the robot, which complicates the mechanical structure of the robot. At the same time, rehabilitation training on a treadmill requires less room, but there is a difference between gait on the treadmill and natural gait [42, 43], which is an important aspect in clinical evaluations [44–47]. Additional mechanisms were designed for pelvic movement. Pelvis motion is also being integrated into new robotic devices, such as KineAssist [48–50]. ALEX III can actively control motions of the pelvis [45, 51]. The new version of Lokomat includes an optional FreeD module to improve therapy by allowing for pelvic lateral translation and transverse rotation, as shown in Figure 4.

Table 2 Overview of lower limb exoskeletons

Human		Treadmill-based exoskeletons			Overground exoskeletons					
Part/joint	**Degree of freedom**	**Lokomat**	**LOPES**	**ALEX III**	**eLEGS**	**Indergo**	**Rewalk**	**Rex**	**Mindwalker**	**HAL**
Pelvis	Superior/inferior	Passive	Passive	Passive	–	–	–	–	–	–
	Lateral	Passive	Actuated	Passive	–	–	–	–	–	–
	Anterior/posterior	Passive	–	Passive	–	–	–	–	–	–
	Obliquity	–	–	–	–	–	–	–	–	–
	Tilt	–	–	–	–	–	–	–	–	–
	Vertical rotation	Passive	–	Passive	–	–	–	–	–	–
Hip	Flexion/extension	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated
	Adduction/abduction	–	Actuated	Actuated	Passive	Passive	Passive	Passive	Passive	–
	Internal/external rotation	–	–	–	–	–	–	Passive	–	–
Knee	Flexion/extension	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated	Actuated
Ankle	Dorsiflexion/plantarflexion	Passive	–	Actuated	Passive	Passive	Passive	Actuated	Passive	Passive
	Adduction/abduction	–	–	–	–	–	–	Passive	–	–
	Internal/external rotation	–	–	–	–	–	–	–	–	–
Actuation	–	Electric	Cable-driven SEA	Electric	Electric	Electric	Electric	SEA	Electric	Electric

Figure 3 Biomechanical design of BLEEX [41]

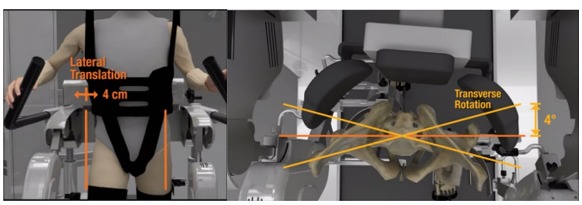


Figure 4 The optional FreeD module

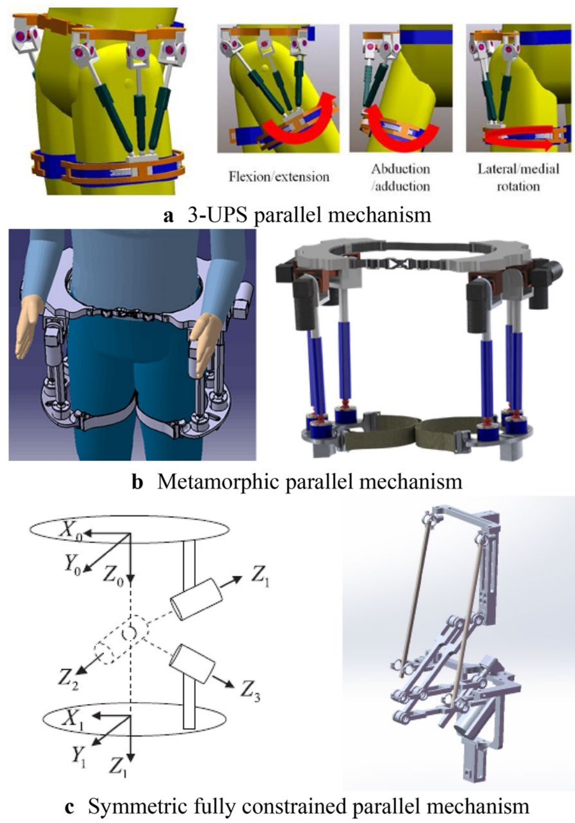


Figure 5 Parallel mechanisms for hip joint assistance

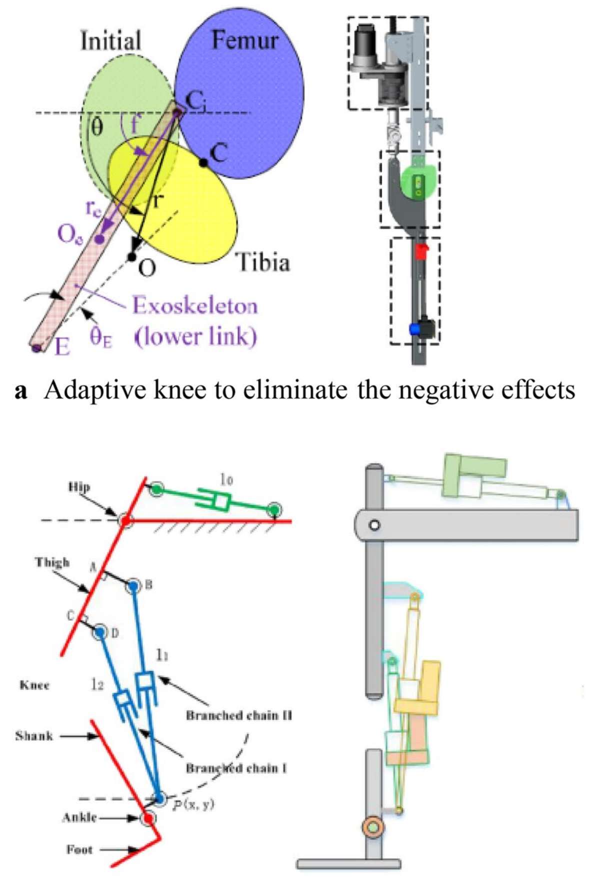
Such simplified design means that there is a motion mismatch between the robot and human, which is manifested in the mismatch between the joint centers of the robot and human. Designing an innovative mechanism can offer a solution to this problem. For hip joints, a parallel structure is adopted to realize three rotational motions and automatic centering with the human hip [52–54] as shown in Figure 5. When a 3-UPS parallel mechanism is mounted on the human waist and thigh, the thigh of the human and the mechanism are connected as a whole, which can be considered as a 3-UPS/1-S parallel mechanism [52] (Figure 5(a)). A novel metamorphic parallel mechanism was applied for lower limb rehabilitation using two configurations, 3-UPS/S and 2-RPS/UPS/S, by taking into account the human hip joint to satisfy different demands of patients at different phases of rehabilitation therapy [53] (Figure 5(b)). An asymmetric fully constrained parallel mechanism prototype is designed for hip joint assistance and rehabilitation and employs pantographs as three-rotation constrained legs instead of using three serial rotation joints-leg to avoid disadvantages such as singularity, uncertainty, or interference with other legs [54] (Figure 5(c)).

The knee joint is treated as a rotating joint in the simplification process and only the flexion and extension motion are considered. In fact, knee motion is relatively complex and hence different mechanisms have been designed to solve this problem, as shown in Figure 6. For the knee joint, an adaptive knee was used and it could effectively eliminate negative effects on human knees [55] (Figure 6(a)). Based on the knee joint complex, axial translational motion was coupled with rotational motion and a serial-parallel hybrid mechanism was designed for lower limb rehabilitation [17] (Figure 6(b)).

The human body is a coupled structure based on bone-muscle tissue structure and characteristics. According to this principle, some scholars have suggested a new kind of structure for lower limb rehabilitation robots. There is no rigid support for the mechanical structure but it includes a soft body and software structure using cables to provide power; this reduces response to muscle contractions and energy consumption of the body. This design for coupled wearable robots is expected to pave a new research direction [56] (Figure 7).

3.2 Actuation Design

Most lower limb exoskeleton rehabilitation robots are driven by electric motors. In eLEGS, only sagittal flexion/extension for the hip and knee are actuated using motors



a Adaptive knee to eliminate the negative effects

b Serial-parallel hybrid mechanism

Figure 6 Novel mechanisms for knee joints

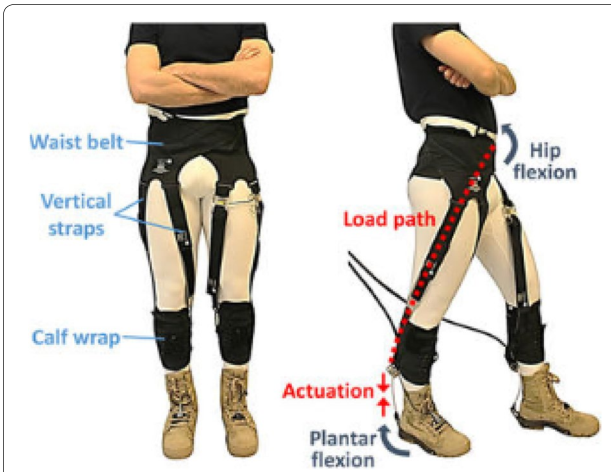
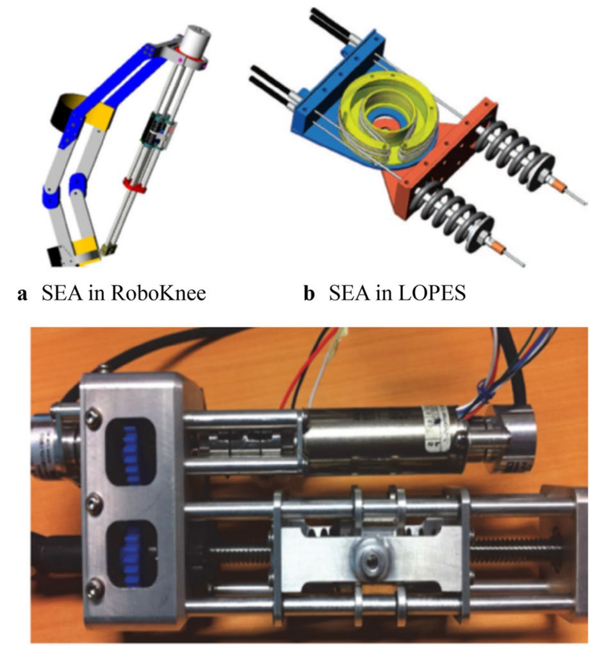


Figure 7 Soft exosuit

while the ankle remains passive [57]. The hip and knee of Lokomat are actuated by motors with linear ball screws [58].



a SEA in RoboKnee **b** SEA in LOPES

c Variable stiffness elastic actuator

Figure 8 A series elastic actuator

A remarkable feature of the above method is that the driver is directly placed on the robot body, which increases its mass and complexity. Therefore, using cable-driven motors can reduce the mass of the exoskeleton robot itself, because the motor and driver are placed on the platform instead of directly on the exoskeleton [59].

Lower limb rehabilitation exoskeletons are mainly driven by rigid transmission without compliance. This causes a large vibration impact, difficulty in directly controlling the force, and leads to a complicated robot system. Therefore, a series elastic drive (SEA) was designed to achieve force control and enhance drive flexibility in RoboKnee [60] (Figure 8(a)). SEA with a combination of cable-driven actuation was applied in LOPES [59] (Figure 8(b)). A variable stiffness elastic actuator was designed for lower limb exoskeletons by adjusting the stiffness of the elastic elements driven by series elasticity [61] (Figure 8(b)).

4 Control of Lower Limb Rehabilitation Robots

4.1 Trajectory Planning

The main purpose of rehabilitation training is to restore the lower limb motor functions of disabled patients to normal levels [62]; therefore, in the process of rehabilitation training, a normal gait pattern is required as a reference input to the control system, as a training goal, and as a rehabilitation evaluation standard. For patients with hemiplegia or physical disabilities, a predetermined

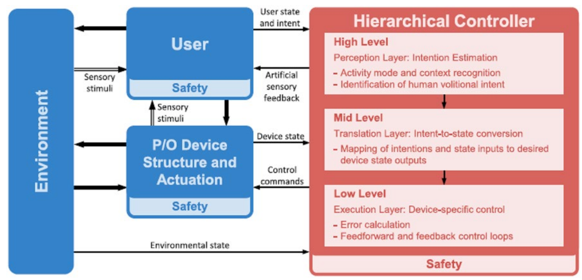


Figure 9 Generalized control framework for lower limbs [67]

There is another type of gait planning that does not rely on specific data; however, it depends on the given gait parameters, such as step length and swing duration to generate gait patterns. The model predictive control (MPC) is used for online trajectory generation based on gait parameters [66].

4.2 Control System

A hierarchical control strategy is used in most lower limb rehabilitation exoskeleton robots. Generally, the control system is divided into two levels. The upper level is the decision-making layer, which realizes control decisions and trajectory generation, and the lower level is the servo layer, which realizes servo control of the drive system [65]. As for overground rehabilitation exoskeletons, they are divided into three layers due to the large number of movements involved (Figure 9). In particular, a human–robot interaction layer is added to adapt to the training needs of a variety of movements [6]. An overview of the control method of lower limb exoskeletons is shown in Table 3.

Table 3 Overview of the control methods used for lower limb exoskeletons

Control strategies	Method	Devices	Features
Position control	Finite state machine	eLEGS, Indergo	A finite state machine is used to indicate the intended option of a series of maneuvers. The user's intended maneuver is then determined based on the provided inputs. Each state is defined by a set of joint angle trajectories, which are enforced by position control loops
	Trajectory tracking control	Rewalk, Rex, MINDWALKER	After selecting the walk mode based on sensors, the participant initiates and propagates programmed motions like walking, turning, sitting, standing and shuffling. This also enables a person to move using a joystick and remote controller
Force controller	Selective control of subtasks	LOPES	Human gait is divided into different subtasks. These subtasks are controlled separately based on the impedance controller
	Impedance control	Lokomat	Torque is supplied by the robot using a PD controller based on the deviation between the actual and desired angular trajectories. Thresholds of maximum allowed deviations are determined around the reference angular trajectory
EMG-based control	Virtual torque control	HAL	Human joint torque is estimated based on EMG signals to generate virtual torque for controlling the motors
Assist-as-needed control	Force field control	ALEX	Tangential and normal forces are applied at the ankle of the subject based on the deviation of the actual path from the desired path

trajectory is often used. These predetermined trajectories can be obtained from data on normal gait. However, due to the limited amount of data, it is difficult to match the obtained motion data with different human motion characteristics, and hence, a parameterized motion pattern generation method was proposed to predict data not present in the test sample.

The trajectories of Lokomat can be adjusted to a specific patient and step length [58]. In LOPES, trajectories are generated by a method based on regression analysis to reconstruct the body height and speed-dependent trajectories [31]; further, "complementary limb motion estimation" may be used to generate reference motion using the motion of healthy limbs [63]. When the collected number of samples is large enough, statistical learning techniques, such as the radial basis function neural networks (RBFs) [64] and multi-layer perceptron neural network (MLPNN) [65], are often used for motion prediction.

In early rehabilitation stages, the lower limbs of patients are dragged for continuous passive motion (CPM) for passive training, which can effectively keep joints flexible for a long time. Correspondingly, position control ensures that the robot can accurately follow the desired position. In this case, movement information of the robot is measured by sensors, such as linear and rotary potentiometers [40, 68, 69], inertia measurement units (IMUs) [70, 71], torque sensors to measure torque [70, 71], and foot pressure sensors to measure the ground reaction to detect gait events [72, 73]. Control methods widely used in servo control have also been used in lower limb rehabilitation exoskeleton robots. For example, proportional derivative control (PD control) [68], computed torque control [74], fuzzy control [74], robust variable structure control [75], fuzzy proportional integral derivative control (PID contro), and sliding mode variable structure control [76] have been used for lower limb exoskeleton robots. Such position control is actually a type of tracking control. Force-position hybrid control was also used to adjust the output force exerted on the patient. This was the first impedance or admittance control strategy ever developed. It has been applied in the Lokomat to guide patients' legs and supply hip and knee joint torque [4]. In LOPES, the robotic support was controlled using a virtual model controller (VMC) [69, 77].

All the control systems described above are passive in nature because the wearer is not considered in the system. By increasing active participation, the dependence of patients on robot assistance can be reduced by improving the effect of rehabilitation training. To achieve this effect, it is important to integrate people into the control system. As mentioned earlier, sensors have been used to measure human movement information and human–robot interaction information to control a robot. In ALEX a force field control is used to guide patients' legs [45, 70].

Another way is to measure human biological signals such as electromyography (EMG) and electroencephalogram (EEG) signals, to perceive body movement. Currently, EMG signals are being used in robots such as HAL [78]. The EMG signal to be detected is used as a trigger switch to judge the timing of assistance provided by the robot [78, 79]. As continuous control, a proportional myoelectric control is used in the robotic ankle exoskeleton [80, 81]. However, EMG-based robot-assisted rehabilitation is only suitable for patients who are able to produce a sufficiently high level of muscle activity. Brain-machine interfaces to restore mobility in severely paralyzed patients [82] have been applied in many lower limb rehabilitation exoskeletons [39, 83–85]. However, this research is still in the early stages. All the systems described above rely on the presence of sensors and control the signals measured by sensors. Recently, robots not based on sensors have been developed. In this case, an admittance shaping controller is used [86].

5 Conclusions and Outlook

5.1 Conclusions

Lower limb rehabilitation exoskeleton robots integrate sensing, control, and other technologies and exhibit characteristics of bionics, robotics, information and control science, medicine, and other interdisciplinary fields and therefore, have become a major research hotspot. In recent years, remarkable progress has been achieved in mechanical design and control system design, based on which, several products have been commercialized. However, there is still a large research gap with respect to human–robot integration. The wearer (patient) should organically combine with the robot to form a whole. Only when true integration of the human body and robot is realized can rehabilitation training be truly effective.

5.2 Outlook

The problem of human–robot integration is a current research hot spot. The National Natural Science Foundation of China (NSFC) has launched the Tri-Co Robot (i.e., the Coexisting-Cooperative-Cognitive Robot), a major research program in 2017, with research themes of robot structure design and control, multi-mode dynamic perception, and natural interaction [87]. Human–robot integration is a key issue in the design and control of lower limb rehabilitation exoskeleton robots. In summary, such integration should include three components, namely structure, movement, and response.

Humanoid structures and flexible drive systems should be designed to achieve structural integration between robots and patients. Currently, a simplified human movement model and a rigid structural design are adopted, causing movement mismatch between a robot and human and affecting wearability and rehabilitation training. Therefore, SEA is being used to increase the flexibility of the local structure. The addition of flexibility inevitably leads to structural complexity and difficulty in control. An ideal robot structure is a rigid-flexible-soft hybrid structure. However, rigid-soft-soft coupling configurations should be designed to effectively transfer energy from a robot to a human. At the same time, modular designs for exoskeleton mechanism should be explored. In fact, many active orthosis devices can also be referred to as modular single-joint exoskeletons.

Customized and personalized gait patterns should be generated to achieve motion integration between robots and patients. A normal movement mode is often required as a reference and input to the control system as the expected robot movement, training target, and evaluation standard. For patients with hemiplegia or other physical disabilities, a predetermined trajectory is often used in rehabilitation. These predetermined trajectories can be obtained from normal gait data collection. However, due to the limited amount of data collected, it is difficult for the obtained motion data to match different motion characteristics of the human body, and hence, a parameterized motion pattern generation method has been proposed. However, the current planning and gait generation methods based on the biped robot control theory and human natural gait cannot achieve a perfect match; gait generation is mainly focused on the sagittal plane and does not account for human three-dimensional gait characteristics. The mechanism of how human gait is affected by motion and structural parameters is not yet fully understood, and hence, it is difficult to realize a perfect integration of motion levels.

Multimodal information fusion should be used to achieve motion integration between humans and machines. Current research on the design of sensing systems indicates that it is not enough to measure a robot's movement information; instead, people also should be included in the system, not only to measure human body movement information and biological signals but also to collect interaction information between a human and the force exerted by the robot. However, it can be imagined that more information is not always better as redundant information increases the complexity of a system and affects its practical application. In the process of rehabilitation training, lower limb rehabilitation exoskeleton robots need to participate in effective dynamic interaction with the patient. Such rehabilitation training can effectively improve the level of active participation of the patient and significantly enhance the rehabilitation effect. However, the evaluation method of the robot itself lacks a set of system indicators for the adaptability and degree of matching with the human body. Hence, it is necessary to study multimodal information to realize effective human–robot integration.

Authors' Contributions

XD was in charge of the whole trial; DS wrote the manuscript; WXZ and WZ assisted with structure and language of the manuscript. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

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