Lower limb rehabilitation exoskeleton robot: A review

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Abstract
Lower limb rehabilitation exoskeleton robots (LLRERs) play a positive role in lower limb rehabilitation and assistance for patients with lower limb disorders, and they are helpful to improve patients’ physical status. More and more experiments pay more attention to the kinematic and dynamic data characteristics of different patient groups. However, it is not clear whether these devices have broad adaptability and their clinical significance, so it is necessary to summarize and analyze these research results. This paper summarizes the LLRERs prototype and product in recent years, also compares the advantages and disadvantages of the theory and technology used in these research, and compares the functional characteristics of the devices, finally summarizes the aspects of the LLRERs to be improved. These devices apply advanced theories, techniques or structures, as well as human kinematics and dynamics data. However, due to the complexity of human body characteristics and movement rules, the theory or technology applied in the study design of LLRERs remains to be further studied, which can be improved in many aspects, such as improve the human-computer cooperation of equipment or carry out clinical trials. This paper can provide reference for researchers and designers in the future study, as well as understanding and selecting LLRERs for all kinds of therapist and patients.

Keywords
Lower limb rehabilitation, gait rehabilitation, joint rehabilitation, lower limb exoskeleton, rehabilitation devices

Introduction
One of the main reasons that people with lower limb dysfunction can’t autonomously complete basic activities of daily life is that their neural pathways are blocked. Medical knowledge has shown that repeated exercise reactivates the patient’s neural pathways.¹ LLRERs combine artificial intelligence and mechanical power device to help patients with lower limb movement and enhance muscle vitality,² which is a direct and effective means to compensate, replace or repair physical dysfunction, it is also one of the important ways to solve the problem of nursing shortage caused by population aging.³ LLRERs are sturdy and durable, which can enhance the self-care ability of patients. LLRERs provides the possibility for the patients with lower limb disorders to return to society.⁴ LLRERs also could reduce the burden on families and society.

In recent years, scholars have designed a variety of LLRERs, which can realize the movement and rehabilitation assistance for different joints, gait, as well as the daily life activities. The hip exoskeleton robot can improve the stability of the trunk, reduce the metabolic consumption, has a global impact on lower limb.⁵,⁶ Shi et al.⁷ studied the torque field control for robot rehabilitation. The proposed control method can realize...
proper posture control of joints with three degrees of freedom or posture control of extremity end effectors. It is suitable for hip joint rehabilitation and can provide reference for controlling rehabilitation robots. The knee exoskeleton designed by Luo et al.\textsuperscript{8,9} can provide power for the knee joint of the patient, effectively generating assistance that are voluntary and intuitively controlled by the user’s muscle activity. The ankle exoskeleton designed by McCain et al.\textsuperscript{10} could realize speed adaptive adjustment, improve the stress condition of the ankle joint, and protect the user from further injury during robot assisted movement or rehabilitation. Pan et al.\textsuperscript{11} designed the LLRE system for gait rehabilitation and proposed the multi-loop modulation method (MMM; 3M), with better gait tracking response and stability, can assist the user to achieve normal gait. The rehabilitation robot designed by Singh et al.\textsuperscript{12} can realize joint trajectory control. There are also some commercial devices that have been widely used in clinical practice. For example, LOKOMAT\textsuperscript{13} is a new type of robot that can simulate physiological gait trajectory, drive the patient’s unilateral or bilateral lower limbs, and accurately control the speed of the treadmill to match the patient’s gait. Consistent, organically integrate functional exercise therapy with the patient’s assessment and feedback system. Ekso Bionics\textsuperscript{14} is a wearable exoskeleton that provides power to the legs. Designed to help patients stand and walk during rehabilitation, EksoNR works with clinicians to give the necessary support to the spine, trunk, and legs including hip, knee, and ankle joints promoting correct movement patterns in physical rehabilitation and challenging patients toward walking out of the EksoNR rehabilitation setting and back into their communities. EksoNR is also become the first exoskeleton cleared by the US Food and Drug Administration (FDA) for medical applications in treating patients with strokes, brain injuries, and SCI.

From these research results, it can be found that LLRERs plays a positive role in lower limb rehabilitation and assistance for patients with lower limb disorders, and is helpful to improve patients’ physical status. More and more experiments pay more attention to the kinematic and dynamic data characteristics of different patient groups. It is necessary to summarize and analyze these research results.

**Materials and methods**

The main purpose of this review is to summarize the state of the art of LLRERs and its control methods that are effective, advanced, and practically applicable through scholars’ research and experimental verification. According to the position of the LLRERs and the functions, it is divided into joints rehabilitation exoskeleton robots (JRERs), gait rehabilitation exoskeleton robots (GRERs), and daily life assistive exoskeleton robots (DLAERs). And summarizing the advantages and disadvantages of various robots and the applied technologies, providing a reference direction for subsequent LLERs research, and can also help people with disabilities to understand and choose LLRERs.

We conducted an extensive search of articles related to LLRERs. The literature search was conducted from April to July 2020. The detail search results of each database are as follows:

- IEEE Xplore (33 records) and Springer link (291 records) and Mendeley (35 records), by using the following groups of descriptors: “(Lower limb rehabilitation) AND (Exoskeleton) AND (Hip joint, Knee joint, and ankle joint).”
- Science Direct databases (269 records), by using the following groups of descriptors: “(Rehabilitation assistive devices) AND (Rehabilitation) AND (Hip, Knee, ankle joint) AND (Exoskeleton) AND (Lower-limb Rehabilitation Robot).”
- SAGE journals (97 records), by using the following groups of descriptors: “(Rehabilitation) AND (Hip, Knee, ankle joint) AND (Exoskeleton) AND (Lower-limb Rehabilitation Robot).”
- PubMed (58 records), by using the following groups of descriptors: “(Exoskeleton) AND (rehabilitation) AND (lower limb joint) AND (lower-limb rehabilitation robot).”
- Web of Science (136 records), by using the following groups of descriptors: “(Exoskeleton) AND (rehabilitation) AND (lower limb joint) AND (lower-limb rehabilitation robot) AND (lower limb).”

The inclusion criteria were: Original articles written in English, published until 2020, and articles related to the use of LLRERs to treat symptoms. Articles related to exoskeleton design such as lower limb joint rehabilitation and gait rehabilitation.

Data analysis: The references is divided into single-joint exoskeleton, gait rehabilitation exoskeleton, and daily life assisting robots according to the functional parts and names of the equipment designed by the author of these articles. In addition, the included articles all have structural design and experiments (design paper and test paper).

The exclusion criteria were: papers not related to the research topic, repetitive articles, articles related to walking aids for the blind and children’s rehabilitation aids, and papers other than English. On this basis, we first searched 919 papers. After reading the title and abstract and applying the inclusion and exclusion criteria, we excluded some papers related to children’s rehabilitation aids and walking aids for the blind, and finally 95 papers an overall assessment is required.
Result

Joint rehabilitation exoskeleton robots (JREs)

Hip exoskeleton robots (HERs). Ding et al.\(^{15}\) designed an IMU-based iterative controller for hip extension assistance, which can evaluate the user’s state from the aspects of biomechanics and physiological responses, so as to determine the most suitable assistance mode for hip joint extension for patients during walking. Xue et al.\(^{16}\) designed a new wearable hip joint exoskeleton, the flexible hip assistive exoskeleton with 4 DOF aligned with hip, which reduces the inherent mechanical impedance of the robot, realizes the compliant man-machine interaction, and realizes the walking intention estimation, provides comfortable and effective walking assistance for patients and reduce their metabolic consumption. Zhang et al.\(^{17}\) designed an asymmetric fully constrained parallel mechanism prototype that has three rotation degrees of freedom and three actuations, as shown in Figure 1. Novel parallel mechanism is synthesized and designed to provide assistance for the movement of hip joint. The asymmetric parallel mechanism (PM) with constrained is easy to design and the requests of machining and assembling are relatively low compared with symmetric PM. Developed a robotic hip exoskeleton called GEMS driven by motor. As shown in Figure 2, the thigh frame consists of two flexible plates that are constrained to slide on each other along the longitudinal direction. The exoskeleton can improve the gait function of users and reduce the metabolic cost of walking. The device is beneficial to the rehabilitation of patients after stroke and muscle strength of the elderly. Zhang et al.\(^{18}\) developed the robot hip exoskeleton named NREL Exo, as shown in Figure 3. The exoskeleton is driven by series elastic actor (SEA), which can help users actively participate in walking, and provide balance assistance for individuals with muscle weakness. The rehabilitation robot designed by Zhang et al.\(^{19}\) used an asymmetrical three-degree-of-freedom parallel mechanism to assist patients with hip joint stroke or trauma. As shown in Figure 4. The device using the reciprocal and closed-loop motion conditions, an improved force transmission index based on the previous method is proposed. A multi-objective optimization model is established. The device allows patients to use prone position for training, reducing physical burden. Mahdavian et al.\(^{20}\) proposed a wearable HER based on ground reaction force and moment (GRF/M), as shown in Figure 5. It can help users to perform hip joint flexion and extension exercises and help users walk normally. Guzmán et al.\(^{21}\) proposed a control strategy based on generalized proportional integral (GPI) controller. Although patients’ weight is different, the gain of GPI controller does not need to be changed. This make HERs have higher adaptability. However, there is a common problem in the adaptability of robots that there will be a time delay between self-
learning and reaction, and the delay may increase with the increase of time and reduce the safety. Improving the efficiency of adaptive adjustment should also be the focus of future research.

The structure of the hip exoskeleton is similar, mostly worn on the hip and the root of the thigh. These HERs can assist patients with hip joint flexion/extension/abduction and adduction rehabilitation exercises. However, the degree of freedom of the human hip joint in space is multi-dimensional. Although the current degree of freedom design can achieve a good auxiliary effect, it still needs to be improved to improve the human-machine cooperation.

**Knee exoskeleton robots (KERs).** The knee joint is the main lower limb motor joint and the most vulnerable and susceptible joint. The KERs can improve the leg movement ability, reduce the movement consumption, and provide power and assistance for the lower limb movement. Kamali et al. proposed a kind of knee exoskeleton, as shown in Figure 6. The equipment uses a linkage mechanism. The inverse dynamic model is used to calculate the power and torque distribution of the knee joint, the initial joint angles as the input to predict the user’s intended sit-to-stand trajectory. Experimental results showed that the exoskeleton could provide strength support for the patient’s knee joint during sitting to standing. Gams et al. proposed a prototype of robot knee exoskeleton, as shown in Figure 7, the equipment uses a linkage mechanism. It can provide power for users to squat. Experiments have proved the feasibility of the equipment.

Kim et al. designed a modular knee exoskeleton system to support the knee joint of hemiplegic patients. The knee joint is designed to actively follow the polycentric path using a four-bar linkage structure, which could realize the multi-center motion of real human knee. The device weighs only 3.5 kg. The foot is equipped with a force sensitive resistor (FSR) sensor, the knee joint is equipped with a torque sensor. This exoskeleton could identify the movement intention of users, and provide walking assistance and sitting

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**Figure 3. NREL-Exo prototype.**

**Figure 4. HipBot.**

**Figure 5. Optical marker placements for motion tracking while wearing the hip exoskeleton.**
posture correction for users. Aguirre-Ollinger et al.\textsuperscript{26} designed a single DOF knee exoskeleton, which could improve the swinging movement of the legs of the elderly. The increase of inertia compensation enables subjects to recover their normal motion frequency. Lee et al.\textsuperscript{27} designed a knee exoskeleton with a multi-center (multi-axis) structure to minimize the misalignment between user and robot. Torque transfer can be carried out effectively and can provide a slightly lower speed than normal walking speed, which is suitable for passive walking rehabilitation training. This technology is expected to be developed to simulate the multi-dimensional motion of the human knee joint.

The exoskeleton designed by Sherwani et al.\textsuperscript{28} applied an adaptive RISE (Robust Integral of Sign Error) controller, which has good robustness and the efficiency of tracking the reference trajectory. It can calculate the patient’s intention to control the walking trajectory or movement according to the electromyogram signal, and can assist users to achieve knee flexion/extension movement. Zhang et al.\textsuperscript{29} proposed a wearable soft knee exoskeleton. The IMUs control system could measure the knee joint angle information. The average metabolic cost of walking can be reduced by 6.85% by helping the knee joint move during walking. The patient’s movement intention and the actual movement of the lower limbs are not uniform. The combination of these two technologies can make the knee exoskeleton more intelligent and make the patient more secure.

**Ankle exoskeleton robot.** The ankle joint supports the human body’s activities such as standing, walking, sitting, and standing transfer, the ankle joint provides most of the energy to support the individual’s activities.\textsuperscript{30,31} The lightweight passive ankle exercise device studied by Wang et al.\textsuperscript{32} consists of four parts: the clever clutch, an extension spring, a shank brace, and a shoe, the spring can store and release energy, as shown in Figure 8. The device can assist the walking process, allow the ankle to move freely, which is suitable for nearly all users. Shao et al.\textsuperscript{33} proposed an adaptive ankle exoskeleton for walking assistance. A new compact variable stiffness SEA (PVS-SEA) with nonlinear spring is developed. The physical stiffness of exoskeleton can be changed with the change of ankle joint, which can adapt to walking tasks at different speeds. Zhang et al.\textsuperscript{34} proposed to use electromyography (EMG) signal to control the ankle exoskeleton. Four layer feed-forward neural network model and back propagation training algorithm are used. The experimental results shows that this method can accurately control the ankle dorsiflexion and plantar flexion. If PVS-SEA can be combined with EMG, the exoskeleton will become very flexible, and the stiffness of the device can be directly adjusted according to the patient’s body state instead of calculation and prediction, which will greatly improve the comfort of the patient.

The ankle foot orthosis (AFO) proposed by Li et al.\textsuperscript{35} allows users to change the stiffness of AFO to complete different lower limb activities. A quick release
concept for AFO was presented and validated, the equipment has good strength. Kim et al.\textsuperscript{36} designed a foot ankle orthosis, including a basic single degree of freedom exoskeleton and an artificial pneumatic actuator. The feed-forward control can reduce the muscle stiffness of soleus muscle, and the plantar flexion torque of the ankle joint can be reduced, which can provide ankle plantar flexion motion for the elderly.

\textbf{Gait rehabilitation exoskeleton (GREs)}

\textit{Gait rehabilitation exoskeleton robots (GRERs).} GRERs can assist patients to complete walking in a normal gait and provide power for them, which is suitable for patients with abnormal gait trajectory or joint trajectory. Shi et al.\textsuperscript{37} designed a novel force field control for the three-dimensional gait adaptation. Trajectories of ankle center position in the 3D space measured by motion capture system were fitted to establish the Frenet frame. The force field controller was designed to guide the ankle center to move on a target trajectory in the 3D space. Simulation results showed that the designed system can effectively realize motion control in different modes. The actuator can improve the adaptive control ability of exoskeleton robots, so that robots can provide patients with an acceptable working state, which is more conducive to gait rehabilitation or standing posture improvement of users.\textsuperscript{38–41}

The use of EEG signals for user intention recognition and robot state control can further increase the human-computer interaction function of GRERs. Wall et al.\textsuperscript{42} designed HAL (Hybrid Assistive Limb) as shown in Figure 9, a Hybrid gait machine, and its control system can capture the intention of the user. The Autoencoder-based Transfer Learning (ATL) framework designed by Tan et al.\textsuperscript{1} can use EEG signals to classify tasks, which can help the rehabilitation robot to understand the intention of the patient and help the patient to carry out rehabilitation exercise effectively. Sanguantrakul et al.\textsuperscript{43,44} have shown that if the use of EEG signals to assist patients to exercise with imagination can give play to the initiative of patients’ movement intention, then the working mode provided by rehabilitation robot may be the most suitable for users.

EMG signal recognition is also effective. Xie et al.\textsuperscript{45} established an surface Electromyography (sEMG) signal and interactive force (IF) fusion model based on the results of plantar pressure and flexion and extension recognition, which can identify the flexion and extension state of the lower limbs according to the EMG signal, and the trajectory of the robot can be planned online based on the sEMG-IF model to improve human-robot interaction and adaptability of lower limb rehabilitation robot. Chen et al.\textsuperscript{46} Proposed the “Assist When Needed (AWN)” control strategy of gait rehabilitation robot, which provides flexible adaptive robot assistance function only when the user needs it. If this control strategy is combined with EEG or EMG signal recognition technology, it may be more flexible to provide patients with the required movement mode. The nonlinear control strategy can also achieve good gait tracking function.

Zhou et al.\textsuperscript{47} proposed a triple-step nonlinear control strategy based on dynamic model. The results show that each joint of the human-robot system can follow the reference gait trajectory well under different interaction torque levels. Wu et al.\textsuperscript{48} designed a LLERR with
3 DOF, as shown in Figure 10, which has an adjustable yet simple structure with hip, knee and ankle joints for different heights of patients. This research result is conducive to the realization of the personalized development of LLERs.

Shao et al.\textsuperscript{49} introduced the conceptual design and size synthesis of the cam linkage mechanism for gait rehabilitation. The original movement mechanism is a two-degree-of-freedom seven-bar crank slider mechanism. A constant speed motor is sufficient to control the mechanism. The experimental results show that the generated trajectory is in good agreement with the expected trajectory.

Lowell et al.\textsuperscript{50} designed a prototype of gait rehabilitation exoskeleton, as shown in Figure 11. It can be used to customize and verify the gait mode and modify the gait in the process of rehabilitation. It can be used to specify personalized gait mode in the future.

Some promising structures/devices. Pneumatic artificial muscle is a promising development direction because soft robots offer advantages over rigid robots in adaptability, robustness to uncertainty, and human safety.\textsuperscript{51} Gu et al.\textsuperscript{52} proposed a soft wearable orthopedic device for gait assistance, with Pneumatic artificial muscle (PAM) the actuator, which reduces the weight of the equipment. The orthopedic device weighs only 680 g. Hashimoto et al.\textsuperscript{53} developed a gait assist device composed of PAM and a common bracket, which is small in size, light in weight, and low in cost. The user has little discomfort in the process of using the device. This device has important commercial value.

The lower limb training with sitting and lying posture can reduce the weight burden of the user’s buttocks and legs, and increase the range of motion of the lower limb joints.\textsuperscript{54} Cheng et al.\textsuperscript{55} have designed a sitting and lying exoskeleton robot for lower limb rehabilitation, as shown in Figure 12, which can be used to improve the stability of patient rehabilitation training. The sitting and lying rehabilitation robot designed by Chen et al.\textsuperscript{56} as shown in Figure 13, can realize adaptive and compliant control of reference trajectory. The robot can better protect patients and provide effective rehabilitation training for patients.

Cable driven is a new direction. Veneman et al.\textsuperscript{57} designed LOPES, a newly developed gait rehabilitation device, which can realize two-way man-machine interaction. There are two modes, “patient in charge” and “robot in charge,” which control the robot to follow or guide the user respectively. Wang et al.\textsuperscript{58} designed a modular cable driven lower limb rehabilitation robot prototype, as shown in Figure 14, which can complete the rehabilitation training task of human lower limbs with high stability, but subjects have not been recruited for real gait experiment.

\textbf{Daily life assistive robot (DLAR)}

\textbf{Daily life assistive exoskeleton robots (DLAERs).} DLAERs can provide users with protection, support and assistance, reduce the burden of lower limbs, and assist patients to complete activities. It is suitable for stroke patients, patients with brain trauma, patients with movement disorders caused by spinal cord injury (SCI), and elderly people with muscle weakness and insufficient joint strength. DLAERs can provide power to lower limb\textsuperscript{59} and can assist patients to climb stairs, squat, sit-to-stand, and walk.\textsuperscript{60,61} Wu et al.\textsuperscript{62} designed a lower-limb-driven exoskeleton robot using linkage mechanism to help patients with SCI complete sit-to-
stand, walk, and stand-to-sit by driving the hip and knee joints, as shown in Figure 15. Two participants with a complete SCI were recruited for this clinical study. The results indicated that with a lower level of exertion and walked faster and farther without any injury or fall incidence when using the powered exoskeleton than when using a knee–ankle–foot orthosis.

Chen et al.\textsuperscript{63} designed the exoskeleton CUHK-EXO, as shown in Figure 16, to provide users with assistive force/torque, the user is able to transfer his/her center of gravity (COG) left and right more easily during walking. The left hip joint has two DOFs including the hip flexion/extension and hip external rotation. The antiflexion bar is designed to be adjustable with three DOFs to better fit for different wearers.

The passive assisted walking device for the lower limbs proposed by Martin and Li\textsuperscript{64} helps the user by negative work on the knee joint at the end of the swing, the device is capable of reducing metabolic energy expenditure equal to the amount of additional energy required to carry the weight of the device. Zheng et al.\textsuperscript{65} designed a simple wearable walking assisted LLER which adopts unbundled lifting method, the mechanical structure is more flexible. The device can adjust the working state through the sensor to adapt to the user’s physical state. Zhou et al.\textsuperscript{66} designed a gravity-assisted walking LLER with a compact layout, which improves the acceptance and safety for users when using the assistive device; this LLER could reduce the user’s hip and knee torque when walking at the same time helps to maintain balance at a lower walking speed.

Dong et al.\textsuperscript{67} proposed an electric lower limb exoskeleton: “Human Universal Mobility Assistance (HUMA).” This device can be adapted to patients of different weights and can help patients walk at various speeds. Poliero et al.\textsuperscript{68} designed a soft modular, energy-saving lower limb exoskeleton that integrates quasi-passive actuation into the soft exoskeleton to assist low to moderate intensity activities in daily life. For patients whose lower limb movement chain is damaged due to limb loss, prosthesis is needed to make up the missing lower limb parts and functions, promote physical activities, and make lower limb activities tend to be normal.\textsuperscript{69–71} Li et al.\textsuperscript{72} designed an asymmetric exoskeleton, as shown in Figure 17, the left leg is an exoskeleton mechanical leg worn on the healthy leg of the amputees. The right leg is an assisted lower limb prosthesis composed of intelligent lower limb prosthesis and exoskeleton mechanical leg, which is connected to the stump of the disabled thigh through the prosthetic receiving cavity. The assistive lower limb prosthesis can be used as an intelligent prosthesis alone. The length of the thigh and shank of the device can be adjusted to adapt to different people.

\textbf{Technology to improve the safety of DLARs.} For organisms and robots, the ability to perceive and respond to disturbances and changes in the environment is essential.\textsuperscript{73}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image12.png}
\caption{Prototype of the robot.\textsuperscript{55}}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image13.png}
\caption{Mechanical structure of rehabilitation exoskeleton.\textsuperscript{54} (1-Man-machine interactive display device; 2-Telescopic mechanical leg structure; 3-Patients; 4-Seat structure with adjustable backrest; 5-Mobile platform structure.)}
\end{figure}
The DLARs should have the ability to recognize obstacles to improve safety. Some scholars have proved the practicality of some obstacle detectors.\textsuperscript{74,75} Obstacle detectors can detect terrain and make adjustments to working conditions to replace the user in making some action decisions. Researchers should improve the accuracy of detection technology, so as not to let the wrong decision cause harm to users.

Some advanced learning algorithms and control algorithms are also could improve the human-machine coordination ability. For example, Gaussian process learning algorithm can improve the accuracy of joint torque prediction,\textsuperscript{76} active disturbance rejection control (ADRC) can improve the anti-interference and tracking performance.\textsuperscript{77} Nonlinear model predictive controller (NMPC) can improve the robustness and stability of the system.\textsuperscript{78} Kalinowska et al.\textsuperscript{79} proposed an algorithm, it can identify contact events without touching the sensor, which is particularly useful when providing real-time assistance during walking. The sensor\textsuperscript{80} can collect the lower limb state signal, improve the robot’s prediction and recognition ability, so as to predict gait events.

**Other medical methods for lower limb rehabilitation**

The researchers have conducted studies and shown that the combination of multiple rehabilitation medical methods can play a better effect, such as the functional electrical stimulation (FES) or acupuncture therapy.

Functional electrical stimulation (FES) could stimulate muscles to produce joint movement, or to stimulate the lower limbs in motion to cooperate with exoskeleton.\textsuperscript{81,82} The overall physical condition of patients with FES assisted training has been significantly improved: Hwan et al.\textsuperscript{83} combined robot assisted exercise with FES, the system can be operated in three different modes allowing both passive and active exercises, it can better protect the user from secondary injury. Ama et al.\textsuperscript{84} designed a dynamic hybrid exoskeleton called Kinesis that can effectively balance muscular and robotic actuation during walking. Li and Yin\textsuperscript{85} realized the time control of electrical stimulation, which can adjust the working mode according to the muscle fatigue state. Hmed et al.\textsuperscript{86} designed a real-time FES system used model-free control (MFC) strategy to calculate the pulse width in the stimulation mode.

FES has some shortcomings. Users need high-intensity stimulation, sometimes even beyond the necessary stimulation intensity, to try to stand up.\textsuperscript{87} FES supported standing requires the user to have sufficient muscle strength, which is achieved through muscle training.\textsuperscript{88,89}

The acupuncture and moxibustion therapy is beneficial to correct the posture, muscle shape and gait of the lower limbs,\textsuperscript{90,91} restore the lower limb movement function of patients.\textsuperscript{92}

In the future, an acupuncture module could be set on the corresponding acupoint according to the position of the human body. The aforementioned joint rehabilitation robot, gait/lower limb function rehabilitation robot, daily life assistive robot could all be combined with acupuncture and FES, this will achieve better training results.

**Discussion and conclusion**

The details of the rehabilitation robot mentioned in this paper are shown in Table 1.

After statistics and analysis, it can be seen from the full text that the existing research still has problems that need improvement in the following aspects:

1. **Structure/mechanism design.** Most robots currently use linkage mechanisms. Such as Sit-to-
Stand Knee Exoskeleton, Robotic Knee Exoskeleton, modular knee exoskeleton using a 4-bar linkage structure. Some equipment uses a cable structure, such as literature. Some scholars have designed new motion structures, such as multi-center (multi-axis) knee exoskeleton. Each device has different DOF, such as flexible hip assistive exoskeleton with 4 DOF, 1-DOF knee exoskeleton. Some devices use linkage mechanisms, and some devices have limited DOF, and they cannot fully simulate the multi-dimensional motion of the lower limbs, and will limit the freedom of movement of the lower limbs.

(2) Control methods. As can be seen from the “control strategy” and “Equipment test data & results” column in the Table 1, researchers have used many different control methods, such as feedback control, feed-forward control, Speed-adaptive proportional myoelectric

Figure 16. CUHK-EXO: (a) a patient with CUHK-EXO supported by a pair of smart crutches, (b) diagram of the overall mechanical structure, (c) waist structure, (d) thigh structure, (e) shank structure, and (f) foot structure.

Figure 17. Asymmetric exoskeleton.
Table 1. Details of each rehabilitation robot.

| Devices                                      | Subjects                                      | Control strategy                                                                 | Equipment test data and results                                      |
|----------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| A wearable hip assist robot                  | 30 elderly adults (15 males/15 females)       | GEMS that uses a particularly-shaped adaptive oscillator (PSAO) to estimate the gait phase. | Provide 16% of walking torque                                         |
| EMG Power hip exoskeleton                    | 10 healthy subjects                           | EMG.                                                                            | A 5.4° reduction in hip extension                                      |
| A knee exoskeleton                           | N/A                                           | Feedback control with an enchanced disturbance observer, Sliding Mode Control (SM) and Integral Sliding Mode Control (ISM). | The peak of the joint motion is around 20°                             |
| A knee exoskeleton device based stiffness and motion augmentation | One healthy male | Tele-impedance based assistive control scheme based on the variability of human joints impedance. IMU-based control. | Stiffness parameter is varying from 0 Nm/rad to 200 Nm/rad           |
| A powered ankle exoskeleton                  | Six subjects (three males, three females)     | Speed-adaptive proportional myoelectric control.                                | Applying ~25% of normal biological ankle plantarfexion moment          |
| Lower limb rehabilitation exoskeleton         | One healthy subject                           | Multi-loop modulation method (MMM; 3M)                                           | The tracking error of the maximum amplitude was reduced to as little as ~3% |
| A Passive Lower-Body Mechanism               | N/A                                           | PID control                                                                     | Desired force delivers around 30% of the hip extension power          |
| A soft exosuit                               | Three subjects                                | IMU-based control                                                               | Contributing up to 16.7% of the nominal biological moment during walking |
| Flexible Hip Assistive Exoskeleton           | One healthy male subject                      | Walking intention estimation approach based on gait synchronizer, direct torque control |                                                                 |
| A hip joint rehabilitation robot             | Two subjects                                  | Generalized proportional integral (GPI) control                                  | The maximum torque output is 12 Nm                                     |
| Sit-to-Stand Knee Exoskeleton                | A single male adult                           | Trajectory prediction Control based on joint Angle Compensation and oscillator   | The average knee strength was reduced by about 30%                     |
| Robot knee exoskeleton prototype             | Seven healthy young males                     | Control based on gravity compensation and oscillator                             | N/A                                                                   |
| A Knee Exoskeleton                           | One healthy person                            | The control algorithm is based on a finite state machine (FSM)                  | The range of motion is 120°                                           |
| A one-degree-of-freedom exoskeleton          | 10 male healthy subjects                      | Emulated inertia compensation method                                             | Cable drive combination is capable of delivering a continuous torque output of about 20.0 Nm |
| A Polycentric Knee Exoskeleton               | N/A                                           | Sliding mode control (SMC) based control                                        | The robot's knee movement angle was designed to be limited from 0° to 90° |
| EICoSI exoskeleton                           | N/A                                           | Robust Integral of the Sign of the Error (RISE) with differentiable high gain feedback | The whole actuator can provide a maximum torque of 18 Nm               |
| A wearable soft knee exoskeleton             | Eight subjects (seven female subjects and one male subject) | IMUs based control                                                             | The actuator can produce a maximum rotational angle of 60°            |
| Ankle Exoskeleton                            | Four healthy subjects                         | Iterative learning control (ILC) algorithm based control                       | The designed ankle exoskeleton can provide a peak pulling force around 545.3 N |
| Ankle Exoskeleton                            | Eight healthy subjects                        | Human-in-the-loop (HIP) optimization control method                            | N/A                                                                   |

(continued)
| Devices | Subjects | Control strategy | Equipment test data and results |
|---|---|---|---|
| Adaptive Ankle Exoskeleton<sup>33</sup> | One healthy subject | Genetic algorithm | The peak power of the ankle joint is 2.91 W/kg during normal walking, and it reaches 3.52 W/kg at high speed and 4.45 W/kg under 22.5 kg added load |
| Ankle Exoskeleton<sup>34</sup> | Nine male subjects | Feed-forward neural network model and EMG signal control | N/A |
| Powered ankle exoskeleton<sup>36</sup> | 15 young adults and 15 elderly people | Feed-forward control | The maximal torque of plantarflexion following a pneumatic support was 122.34 ± 15.31 Nm in young adults and 94.89 ± 9.30 Nm in elderly people |
| A controllable knee ankle foot orthosis<sup>38</sup> | One woman subject whose left limb impaired by poliomyelitis and one male subject affected by poliomyelitis during childhood | The knee joint state (intermittent stiffness) was controlled by segmental angular rotation and segmental angular velocity | The plantar fall is limited at maximum 5 (mean, 4.5) |
| A variable-impedance ankle-foot orthosis<sup>39</sup> | One healthy subject | Torque-control | It has a ROM of 32° in plantarflexion and 21° in dorsiflexion |
| Lower limb rehabilitation robot<sup>45</sup> | Five male and one female able-bodied subjects | EMG signal control | In 0-3 s, the end’s velocity of robot was raised in the direction of lower limb motion with the increase of human-robot interactive force. In 6.9–9.8 s, the velocity began to decrease |
| Gait Rehabilitation Robot<sup>46</sup> | One healthy subject | Assist-When-Needed (AWN) control | The mean peak knee joint angle decreased significantly from 53° in zero-assistance mode to 30° |
| A passive lower limb exoskeleton for walking assistance<sup>47</sup> | One healthy subject | Triple-step nonlinear control strategy | The average absolute driving torque of hip joint was reduced by 79.0%, and that of knee joint was reduced by 66.4% |
| Powered lower limb exoskeleton robot<sup>48</sup> | One healthy male subject | Closed-loop control, adaptive robust (AR) sub-control | Provide rated torque of 35 Nm and peak torque of more than 100 Nm |
| A wearable exoskeleton suit<sup>63</sup> | One healthy subject | Assistive torque and position control based on wearer’s motion intention | N/A |
| A lower extremity exoskeleton for walking assist<sup>65</sup> | N/A | Control based on direct force feedback | 3 kg for walking assistance and 10 kg for standing assistance |
| A passive lower limb exoskeleton for walking assistance<sup>66</sup> | One healthy subject | N/A | The average absolute driving torque was reduced by 79.0% at the hip joint and 66.4% at the knee joint. The mean maximum torque provided during knee bending was 42.9 ± 0.46 Nm and 28.4 ± 0.28 Nm during stretching |
| Soft wearable device for lower limb assistance<sup>68</sup> | One healthy person | Gait segmentation algorithm | Provides 9.3% of hip torque |
control,10 3 M control method11 PID control,12 Directed torque control.16 The assistance types, data and metabolic reduction rate provided by these devices are different. Although the control system can well adjust the human-machine interaction relationship between users and devices, it cannot fully achieve personalized assistance to a certain extent.

(3) **Rehabilitation effect evaluation.** As can be seen from the “subject” column in the Table 1, in the process of the study of exoskeleton, the most subjects are healthy people, the test was conducted under the laboratory environment, the test time and the number of subjects is limited, some devices has not been carried out clinical test. Some of the device studies have not yet recruited subjects to test the device. Scholars have designed various types of exoskeletons, but the long-term effects of various types of exoskeletons of the same type lack comparisons to further clarify their advantages and disadvantages.

(4) **Safety and human-machine cooperation.** Rehabilitation robots cannot completely replace the lower limb function, or replace human to make decisions and adjustments in the complex environment, and the ability to identify obstacles and sense the environment still needs to be improved.

Therefore, future research can be improved in the following aspects:

1. **Improve man-machine cooperation.** The structural design should be as close as possible to the multi-dimensional movement of the lower limbs of the human body. Due to the rigidity of the material or structure, and the patient’s poor limb flexibility, it will cause a certain degree of damage to the human body. The flexibility of equipment movement should also be improved, so that patients will not lose balance or get injured due to the passive movement of limbs when the equipment is started. What’s more, the design of LLRERs should be simple, easy to understand, easy to use, easy to carry, or less affected by the place of use.

2. **The control method should be further improved, tested, and more intelligent.** The control system should be improved to specify more parameters (such as inertia, damping, stiffness) to adapt to different patients, to achieve personalized auxiliary services.

3. **Every device should be clinically tested, and the source of data used in the research should be improved.** Physiological data used in the design process of LLRERs should be close to the patient’s daily life state, or data tracking and collection is conducted in the patient’s daily life. Because whether the gait is abnormal or healthy, the state in laboratory conditions is not exactly the same as in daily life.93 In addition, the sample size of the subjects was need to be increased to make the data more representative. Researchers should clarify the effect of long-term use, because LLRERs will reduces the energy consumption of patients, if patients rely on exoskeleton for a long time, it may cause muscle degeneration.

4. **Lightweight.** For example, with the increase of environmental recognition function, degree of freedom or some assistive treatment functions, corresponding equipment modules or drive system should also be added, this will increase the weight of LLRERs. Although LLRERs can balance the weight of the devices by providing torque and changing power, it will also affect the working efficiency of LLRERs.

5. **Personalized customization.** LLRERs can be personalized as much as possible, and patient initiative can be fully mobilized. Some modular design and pattern adjustment systems can be added to LLRERs. For example, add EMG signal, EEG signal recognition function. Studies have shown that patient-driven control strategies can stimulate patient participation and speed up the recovery process, compared with robot-driven control strategies that allow patients to remain passive during training.94 In addition, patients should be specifically trained in the use of LLRERs so that each patients can receive maximum rehabilitation assistance.

6. **The cost.** The poor financial situation of some patients has affected their choice and use of LLRERs. Therefore, improve the appearance design and popularize the corresponding basic knowledge, and reduce the cost of LLRERs, so as to help patients accept, select and use LLRERs.

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References

1. Tan C, Sun F, Fang B, et al. Autoencoder-based transfer learning in brain-computer interface for rehabilitation robot. Int J Adv Robot Syst 2019; 16(2), pp.1–12.
2. Liu W, Yin B and Yan B. A survey on the exoskeleton rehabilitation robot for the lower limbs. In: 2016 2nd international conference on control, automation and robotics (ICCAR), Hong Kong, China, 28–30 April 2016, pp.90–94. New York: IEEE.
3. Yang J, Li J, Bai D, et al. Assistive standing of omni-directional mobile rehabilitation training robot based on support vector regression algorithm. In: 2016 IEEE international conference on information and automation (IICA), Ningbo, China, 1–3 August 2016, pp.1050–1055. New York: IEEE.
4. Shi D, Zhang W, Zhang W, et al. A review on lower limb rehabilitation exoskeleton robots. Chin J Mech Eng 2019; 32: 1–11.
5. Lee HJ, Lee S, Chang WH, et al. A wearable hip assist robot can improve gait function and cardiopulmonary metabolic efficiency in elderly adults. IEEE Trans Neural Syst Rehabil Eng 2017; 25: 1549–1557.
6. Lenzi T, Carrozza MC and Agrawal SK. Powered hip exoskeletons can reduce the user’s hip and ankle muscle activations during walking. IEEE Trans Neural Syst Rehabil Eng 2013; 21: 938–948.
7. Shi D, Zhang W, Zhang W, et al. Assist-as-needed attitude control in three-dimensional space for robotic rehabilitation. Mech Mach Theory 2020; 154: 104044.
8. Luo Y, Wang C, Wang Z, et al. (2018). Comparison of different control algorithms for a knee exoskeleton. In: 2018 15th international conference on control, automation, robotics and vision (ICARCV), Singapore, 18–21 November 2018, pp.585–590.
9. Karavas N, Ajoudani A, Tsagarakis N, et al. Tele-impedance based stiffness and motion augmentation for a knee exoskeleton device. In: 2013 IEEE international conference on robotics and automation, Karlsruhe, 6–10 May 2013, pp.2194–2200. New York: IEEE.
10. McCain EM, Dick TJM, Giest TN, et al. Mechanics and energetics of post-stroke walking aided by a powered ankle exoskeleton with speed-adaptive myoelectric control. J Neuroeng Rehabil 2019; 16(1): 1–12.
11. Pan CT, Chang CC, Yang YS, et al. Development a multi-loop modulation method on the servo drives for lower limb rehabilitation exoskeleton. Mechatronics 2020; 68: 102360.
12. Singh G, Singh A and Virk GS. Modeling and simulation of a passive lower-body mechanism for rehabilitation. In: Conference on mechanical engineering and technology (COMET-2016), at: department of mechanical engineering, IIT (BHU), Varanasi, 15–17 January 2016, pp.123–128.
13. Jezernik S, Colombo G, Keller T, et al. Robotic orthosis lokomat: a rehabilitation and research tool. Neuromodulation 2003; 6: 108–115.
14. https://eksobionics.com/
15. Ding Y, Galiana I, Asbeck A, et al. Multi-joint actuation platform for lower extremity soft exosuits. In: Robotics and automation (ICRA), 31 May–7 June 2014, pp.1327–1334. Hong Kong, China: IEEE.
16. Xue T, Wang Z, Zhang T, et al. The control system for flexible hip assistive exoskeleton. In: 2018 IEEE international conference on robotics and biomimetics (ROBIO), Kuala Lumpur, Malaysia, 12–15 December 2018, pp.697–702. New York: IEEE.
17. Zhang W, Zhang W, Shi D, et al. Design of hip joint assistant asymmetric parallel mechanism and optimization of singularity-free workspace. Mech Mach Theory 2018; 122: 389–403.
18. Zhang T, Tran M, Huang HH. NREL-Exo: a 4-DoFs wearable hip exoskeleton for walking and balance assistance in locomotion. In: 2017 IEEE/RSJ international conference on intelligent robots and systems (IROS), Vancouver, Canada, 24–28 September 2017, pp.508–513.
19. Zhang W, Zhang W, Ding X, et al. Optimization of the rotational asymmetric parallel mechanism for hip rehabilitation with force transmission factors. J Mech Robot 2020; 12: 1–23.
20. Mahdavian M, Arzanpour S and Park EJ. Motion generation of a wearable hip exoskeleton robot using machine learning-based estimation of ground reaction forces and moments. In: 2019 IEEE/ASME international conference on advanced intelligent mechatronics (AIM), Hong Kong, China, 8–12 July 2019, pp.796–801. New York: IEEE.
21. Guzmán CH, Blanco A, Brizuela JA, et al. Robust control of a hip-joint rehabilitation robot. Biomed Signal Process Control 2017; 35: 100–109.
22. Zhang L, Liu G, Han B, et al. Knee joint biomechanics in physiological conditions and how pathologies can affect it: a systematic review. Appl Bionics Biomech 2020; 1: 1–22.
23. Kamali K, Akbari AA and Akbarzadeh A. Trajectory generation and control of a knee exoskeleton based on dynamic movement primitives for sit-to-stand assistance. Adv Robot 2016; 30: 846–860.
24. Gams A, Petric T, Debevec T, et al. Effects of robotic knee exoskeleton on human energy expenditure. IEEE Trans Biomed Eng 2013; 60: 1636–1644.
25. Kim JH, Shim M, Ahn DH, et al. Design of a knee exoskeleton using foot pressure and knee torque sensors. Int J Adv Robot Syst 2015; 12: 112.
26. Aguirre-Ollinger G, Colgate JE, Peshkin MA, et al. Inertial compensation control of a one-degree-of-freedom exoskeleton for lower-limb assistance: initial experiments. IEEE Trans Neural Syst Rehabil Eng 2012; 20: 68–77.
27. Lee T, Lee D, Song B, et al. Design and control of a poly-centric knee exoskeleton using an electro-hydraulic actuator. Sensors 2019; 20: 211.
28. Sherwani KIK, Kumar N, Chemori A, et al. RISE-based adaptive control for EICoSI exoskeleton to assist knee joint mobility. Robot Auton Syst 2020; 124: 103354.
29. Zhang L, Huang Q, Cai K, et al. A wearable soft knee exoskeleton using vacuum-actuated rotary actuator. IEEE Access 2020; 8: 61311–61326.
30. Xu H, Li Y, Tang B, et al. The mechanical design and torque control for the ankle exoskeleton during human walking. *Intell Robot Appl* 2019(11744): 26–37.

31. Yan H, Tang B, Xiang X, et al. Human-in-the-loop optimization control for the ankle exoskeleton during walking based on iterative learning and particle swarm optimization algorithm. In: *2019 IEEE 4th international conference on advanced robotics and mechatronics (ICAR-M)*, Toyonaka, Japan, 3–5 July 2019, pp.570–574. New York: IEEE.

32. Wang X, Guo S, Qu B, et al. Design of a passive gait based ankle foot exoskeleton with self adaptive capability. *Chin J Mech Eng* 2020; 33: 86–96.

33. Shao Y, Zhang W, Xu K, et al. Design of a novel compact ankle exoskeleton for walking assistance. *Adv Mech Mach Sci* 2019; 173: 2159–2168.

34. Zhang Z, Jiang J, Peng L, et al. *A method to control ankle exoskeleton with surface electromyography signals*. ICIRA, Shanghai, China, 10–12 November 2010. pp.390–397. Berlin, Heidelberg: Springer.

35. Li W, Lemaire E D and Baddour N. Design and evaluation of a modularized ankle-foot orthosis with quick release mechanism. In: *2020 42nd annual international conference of the IEEE engineering in medicine & biology society (EMBC)*, 20–24 July, 2020, pp.4831–4834. Montreal, QC, Canada: IEEE.

36. Kim K, Kim JJ, Kang SR, et al. Analysis of the assistance characteristics for the plantarflexion torque in elderly adults wearing the powered ankle exoskeleton. In: *International conference on control automation and systems, ICCAS*, Gyeonggi-do, Korea, 27–30 October 2010, pp.576–579. New York: IEEE.

37. Shi D, Zhang W, Zhang W, et al. Force field control for the three-dimensional gait adaptation using a lower limb rehabilitation robot. In: Uhl T (ed.) *Advances in Mechanism and Machine Science*. Cham: Springer, 2019. pp.1919–1928.

38. Moreno JC, Brunetti F, Roccon E, et al. Immediate effects of a controllable knee ankle foot orthosis for functional compensation of gait in patients with proximal leg weakness. *Med Biol Eng Comput* 2008; 46: 43–53.

39. Moltedo M, Baček T, Langlois K, et al. Design and experimental evaluation of a lightweight, high-torque and compliant actuator for an active ankle foot orthosis. In: *2017 international conference on rehabilitation robotics (ICORR)*, London, 17–20 July 2017, pp.283–288. New York: IEEE.

40. Kim JY and Durfee W. The application of series elastic actuators in the hydraulic ankle-foot orthosis. In: *2018 design of medical devices conference*, Minneapolis, Minnesota, 9–12 April 2018, ASME.

41. Li X, Pan Y, Chen G, et al. Multi-modal control scheme for rehabilitation robotic exoskeletons. *Int J Rob Res* 2017; 36: 759–777.

42. Wall A, Borg J, Vreede K, et al. A randomized controlled study incorporating an electromechanical gait machine, the hybrid assistive limb, in gait training of patients with severe limitations in walking in the subacute phase after stroke. *PLoS One* 2020; 15: e0229707.
56. Chen J, Huang Y, Guo X, et al. Parameter identification and adaptive compliant control of rehabilitation exoskeleton based on multiple sensors. *Measurement* 2020; 159: 107765.

57. Veneman JF, Kruidhof R, Hekman EEG, et al. Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. *IEEE Trans Neural Syst Rehabil Eng* 2007; 15: 379–386.

58. Wang YL, Wang KY and Zhang ZX. Design, comprehensive evaluation, and experimental study of a cable-driven parallel robot for lower limb rehabilitation. *J Braz Soc Mech Sci Eng* 2020; 42: 1–20.

59. Aguirre OG. Learning muscle activation patterns via nonlinear oscillators: application to lower-limb assistance. In: 2013 *IEEE/RSJ international conference on intelligent robots and systems*, Tokyo, Japan, 3–7 November 2013, pp.1182–1189. New York: IEEE.

60. Carrera I, Moreno HA, Marín SDS, et al. Technologies for therapy and assistance of lower limb disabilities: sit to stand and walking. In: *Exoskeleton robots for rehabilitation and healthcare devices*. 2020. Singapore: Springer Briefs in applied sciences and technology, pp.43–66.

61. Baek E, Song S, Oh S, et al. A motion phaseased hybrid assistive controller for lower limb exoskeletons. In: 2014 *IEEE 13th international workshop on advanced motion control (AMC)*, Yokohama, Japan, 14–16 March 2014, pp.197–202. New York: IEEE.

62. Wu CH, Mao HF, Hu JS, et al. The effects of gait training using powered lower limb exoskeleton robot on individuals with complete spinal cord injury. *J Neuroeng Rehabil* 2018; 15: 14.

63. Chen B, Zhong CH, Zhao X, et al. A wearable exoskeleton suit for motion assistance to paralysed patients. *J Orthop Translat* 2017; 11: 7–18.

64. Martin JP and Li Q. The metabolic cost of walking with a passive lower limb assistive device. *Lect Notes Electr Eng* 2016; 301: 305.

65. Zhou L, Chen W, Chen W, et al. Design of a passive lower limb exoskeleton for walking assistance with gravity compensation. *Mech Mach Theory* 2020; 150: 103840.

66. Deng JH, Hyunseok P, Ha T, et al. Biomechanical design of an agile, electricity-powered lower-limb exoskeleton for weight-bearing assistance. *Robot Auton Syst* 2017; 95: 181–195.

67. Poliero T, Natali DC, Sposito M, et al. Soft wearable device for lower limb assistance: assessment of an optimized energy efficient actuation prototype. In: 2018 *IEEE international conference on soft robotics (RoboSoft)*, Livorno, 24–28 April 2018, pp.559–564. New York: IEEE.

68. Littman AJ, Haselkorn JK, Arterburn DE, et al. Pilot randomized trial of a telephone-delivered physical activity and weight management intervention for individuals with lower extremity amputation. *Disabil Health J* 2019; 12: 43–50.

69. Christiansen CL, Miller MJ, Murray AM, et al. Behavior-change intervention targeting physical function, walking, and disability after dysvascular amputation: a randomized controlled pilot trial. *Arch Phys Med Rehabil* 2018; 99: 2160–2167.

70. Pandit S, Godiyal A, Vimal A, et al. An affordable insole-sensor-based trans-femoral prosthesis for normal gait. *Sensors* 2018; 18: 706.

71. Li F, Wang Q, Xie Y, et al. Admittance control of four-link bionic knee exoskeleton with inertia compensation. *Technicki Vjesn* 2020; 27: 891–897.

72. Krausz NE, Hu BH and Hargrove LJ. Subject- and environment-based sensor variability for wearable lower-limb assistive devices. *Sensors* 2019; 19: 4887.

73. Khademi G and Simon D. Convolutional neural networks for environmentally aware locomotion mode recognition of lower-limb amputees. In: *Proceedings of the ASME dynamic systems and control conference (DSCC)*, Utah, 8–11 October 2019. ASME.

74. Zhang K, Xiong C, Zhang W, et al. Environmental features recognition for lower limb prostheses toward predictive walking. *IEEE Trans Neural Syst Rehabil Eng* 2019; 27: 465–476.

75. Yang J and Yin Y. Dependent-Gaussian-process-based learning of joint torques using wearable smart shoes for exoskeleton. *Sensors* 2020; 20: 3685.

76. Yang S, Han J, Xia L, et al. An optimal fuzzy-theoretic setting of adaptive robust control design for a lower limb exoskeleton robot system. *Mech Syst Signal Process* 2020; 141: 106706.

77. Tahamipour Zarandi SM, Hosseini Sani SK, Akbarzadeh Toootoonchi MR, et al. Design and implementation of a real-time nonlinear model predictive controller for a lower limb exoskeleton with input saturation. *Iran J Sci Technol Trans Electr Eng* 2021; 45: 309–320.

78. Kalinowska A, Berrueta TA, Zoss A, et al. Data-driven gait segmentation for walking assistance in a lower-limb assistive device. In: 2019 *international conference on robotics and automation*, Montreal, Canada, 20–24 May 2019, pp.1390–1396. IEEE.

79. Hu BH, Krausz NE and Hargrove LJ. A novel method for bilateral gait segmentation using a single thigmounted depth sensor and IMU. In: *Proceedings of the IEEE international conference on biomedical robotics and biomechatronics (Biorob)*, Enschede, 26–29 August 2018, pp.807–812. New York: IEEE.

80. Stauffer Y, Allemand Y, Bouri M, et al. The WalkTrainer—A New Generation of walking reeducation device combining orthoses and muscle stimulation. *IEEE Trans Neural Syst Rehabil Eng* 2009; 17: 38–45.

81. Ambrosini E, Parati M, Peri E, et al. Changes in leg cycling muscle synergies after training augmented by functional electrical stimulation in subacute stroke survivors: a pilot study. *J Neuroeng Rehabil* 2020; 17(1): 1–14.

82. Bong JH, Jung S, Park N, et al. Development of a novel robotic rehabilitation system with muscle-to-muscle interface. *Front Neuroworobot* 2020; 14(3): 1–13.

83. del-Ama AJ, Gil-AgudoA, Pons JL, et al. Hybrid FES-robot cooperative control of ambulatory gait rehabilitation exoskeleton. *J Neuroeng Rehabil* 2014; 11: 27.

84. Li Z and Yin Z. A method for FES control of human knee joint with time-dependent model parameters. In: 2019 *IEEE 15th international conference on control and
86. Hmed AB, Bakir T, Binczak S, et al. Model free control for muscular force by functional electrical stimulation using pulse width modulation. In: 2016 4th international conference on control engineering & information technology (CEIT), Hammamet, 16–18 December 2016, pp.1–6.

87. Triolo RJ, Bevelheimer T, Eisenhower G, et al. Inter-rater reliability of a clinical test of standing function. J Spinal Cord Med 1995; 18: 14–22.

88. Ibitoye MO, Hamzaid NA, Hasnan N, et al. Strategies for rapid muscle fatigue reduction during FES exercise in individuals with spinal cord injury: a systematic review. PLoS One 2016; 11: e0149024.

89. Gera S, Tharion G, Devasahayam S, et al. Electrical stimulation and assessment of the induced force in the denervated muscle. In: TENCON 2019 IEEE Region 10 Conference (TENCON), Kochi, India, 17–20 October 2019, pp.2046–2050. New York: IEEE.

90. Ruan CL, Chen RL, Lin ZH, et al. Effect of Jiaotong Qiaomai needling technique of acupuncture on the morphology of lower limb muscle based on muscle-skeleton ultrasound measurement in patients with post-stroke strephenopodia. Zhongguo Zhen Jiu 2020; 40: 251–255.

91. Wang H-Q, Hou M, Li H, et al. Effects of acupuncture treatment on motor function in patients with subacute hemorrhagic stroke: a randomized controlled study. Complement Ther Med 2020; 49: 102296.

92. Dolkun R, Li YK, Guo H, et al. Zhishen Tiaosui acupuncture on the unilateral spatial neglect after stroke: a randomized controlled trial. Chin Acupunct Moxibustion 2019; 39: 1041–1045.

93. Kim J, Colabianchi N, Wensman J, et al. Wearable sensors quantify mobility in people with lower limb amputation during daily life. IEEE Trans Neural Syst Rehabil Eng 2020; 28: 1282–1291.

94. Wang X, Lu T, Wang S, et al. A patient-driven control method for lower-limb rehabilitation robot. In: 2016 IEEE international conference on mechatronics and automation. Harbin, 7–10 August 2016, pp.908–913. New York: IEEE.