

The Advanced Control Technologies of Lower Limb Exoskeleton Rehabilitation Robots

Xuan Zhang

International Curriculum Center, Nanjing, China

zxuan8465@gmail.com

Abstract. The lower limb exoskeleton rehabilitation robots, a common medical device, are designed to treat people with lower limb disorders, have been widely deployed across the medical sector. In this review, the human gait is analyzed initially since this is the foundation of the lower limb exoskeleton rehabilitation robots research. Through this analysis, the clear relationship is illustrated between the magnitude and direction of support force provided by the lower limb exoskeleton rehabilitation robot to each joint and the control technologies. Then the following discussions will focus on the two advanced control technologies, which are the key to the lower limb exoskeleton rehabilitation robots, called position control and impedance control, respectively. These two control technologies are currently applied in multiple fields, which are an integral part of modern life, and the results of this study are promising for related future research on lower limb exoskeleton rehabilitation robots. This review further provides a theoretical framework for optimizing control strategies and enhancing human–robot interaction efficiency in lower limb rehabilitation systems.

Keywords: Advanced control technologies, lower limb exoskeleton rehabilitation robots, human gait.

1. Introduction

The phenomenon of extended work hours and increasing occupational stress is prevalent. This trend results in a higher likelihood of developing hemiplegia caused by stroke. More than 4 million new stroke patients are diagnosed annually in the United States, Europe, and China [1]. Consequently, a significant disparity exists between the supply of professional rehabilitation therapists and the surging demand from disabled people. The lower extremity exoskeleton rehabilitation robots, serving patients with lower limb paralysis or lower limb motor impairment, are supported by different advanced control technologies during operation.

The invention of lower limb exoskeleton rehabilitation robots started in the 1960s, because of the limitations of the technical device, the products were not fully developed at that time; nevertheless, these efforts made progress to the following invention [2][3]. For around twenty centuries, the lower limb rehabilitation exoskeleton robots became a primary task to study, particularly after the Lokomat was applied in clinical rehabilitation [4]. Currently, some advanced lower limb rehabilitation exoskeleton robots are being produced, like the Restore soft Exo-Suit, which is a lightweight soft exoskeleton focused on providing assistance to the ankle and hip joints for stroke patients. It aims to offer support while walking through textile materials and cable-driven mechanisms that align with the body's natural movement [5].

According to control technologies, Different situations of patient lead to several therapeutic schedules, which need control technologies with different functions, for example the compliance function help the patients avoid severe impacts and the adaptive function offers the quick response. To be specific, there is an international collaborative research project that combines the expertise in rehabilitation robotics from the National University of Singapore with the specialized knowledge in control algorithms from the Chinese Academy of Sciences. The research focuses on using adaptive oscillator control algorithms to correct gait asymmetry through their developed hip exoskeleton with a series elastic actuator (nSEA).

This paper mainly introduces two control technologies, which are position control and compliance control and provides a theoretical basis to the improvement to the technical performance of Lower Extremity Rehabilitation Exoskeleton Robots.

2. Classification of Robots

2.1. Exoskeleton Robots

Exoskeleton robots are a wearable mechanical device that imitate the structure of the human body. The operator's limbs are encased within the mechanical structure, with the robot's joints aligned with the human's joints. It uses actuators to assist or enhance human movement. Then, through Human-Robot Interaction, the robot precisely detects the user's movement intent and then drives the mechanical structure to provide the right amount of assistance at the right time. This design is mainly used in rehabilitation training and focuses on restoring and improving the functional movement of the human body itself, such as walking, grasping, or lifting an arm. Meanwhile, some finished robots are produced, such as Ekso Bionics, a lower limb exoskeleton for rehabilitation training, Rewalk, an exoskeleton that helps paraplegic patients stand and walk, and Sarcos Guardian XO, a full-body, force-feedback industrial exoskeleton. Currently the challenges are existed, the precise alignment of the robot's joints with the user's biological joints is difficult during the wearing process, the average standard of bone length, joint rotation center, muscle mass and distribution is not personal, the improper size of robot structure will provide the wrong data to sensors, sensor failure leads to unsuitable rehabilitation result, and also, the significant weight contributed by the mechanical structure, actuators and batteries is a burden to patients, some of the exoskeleton robots are too heavy to carry, that limit the time of each rehabilitation.

2.2. End-Effector Robot

According to the End-Effector Robot, the user does not wear the robot. Instead, they interact with the robot's end-effector using their extremities, such as hands and feet. The robot drives these end-effectors to guide or train the movement of the user's limbs, and the interaction between the robot and the user occurs only at the point of contact, like hand and handle; it does not directly drive the user's joints. Compared to the Exoskeleton robots, this type of robot is easier to adapt because it does not need to adjust complex mechanical structures for each user to align joints, and obviously simpler to adapt to users of different sizes. Additionally, since it does not directly drive human joints, then a lower risk in abnormal situations. However, the interaction only occurs at the limb extremity, without direct control or assistance of intermediate joints; this can lead to compensatory and abnormal movement patterns, potentially reducing rehabilitation effectiveness.

3. Analysis of Human Gait

Table 1. Range of motion of lower limbs [4]

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
Hip	Vertical rotation	15/15
	Flexion/tension	40/30
	Adduction/abduction	20/20
Knee	Internal/external rotation	15/15
	Flexion/extension	75/0
Ankle	Dorsiflexion/plantarflexion	25/35
	Adduction/abduction	10/10
	Internal/external rotation	10/20

A walking process is based on the proper human gait. Before a successful cooperation between lower limb rehabilitation exoskeleton robots and People with lower limb disabilities is achieved, the data of human gait of normal people needs to be evaluated first.

The lower limbs are mainly composed of the pelvis, hip, knee, and ankle; their ranges of motion are demonstrated in Table 1.

The pelvis is a significant construction located between the trunk and thighs, and the hip is connected by the head of the femur and pelvic bone, allowing sagittal flexion/extension, frontal abduction/ adduction, and transverse external/internal rotation. The knees move in two phases, which allow sagittal flexion/extension and transverse internal/external rotation [6]. It stays curved to transmit the forces through the legs to achieve a shock-absorbing result in the stance phase, meanwhile reducing the leg length in the swing phase. The ankle has a similar shock-absorbing function, and during the walking process, it provides a thrust to the human body.

4. Analysis of the Classification of Control Technology

4.1. Position Control

Position control is the most fundamental and widely used control strategy in robotics, automation systems, and motion control. Its core objective is to drive the output position of a system (e.g., motor, robotic arm) to accurately track the desired position command.

4.1.1 Iterative learning control (ILC)

ILC is a data-based control method; hence, it can often perform well even without an exact mathematical model of the system. Besides, this control technology is a good choice for disabled people who are trained to do repetitive movements in a specific finite time, since it can adjust the tracking error during each task, then complete the tasks better than the last. ILC is a data-based control method; hence, it can often perform well even without an exact mathematical model of the system, and is broadly utilized in Nanopositioning.

4.1.2 Neural network

It is a computational model that attempts to emulate the working principle of the human brain. There are three layers--input layer, hidden layer, and output layer. Each neuron receives inputs from all neurons in the previous layer. Each input is multiplied by a weight to indicate the importance of that input, summed together, a bias is added to adjust how easily the neuron activates, eventually, the result is passed through an activation function (e.g., Sigmoid, ReLU) to produce an output. To operate a lower-limb orthosis efficiently without dynamic models, a multilayer perceptron neural network was proposed by Mefoued, as demonstrated in Fig. 1 [7]. A multilayer perceptron neural network was employed by Peña et al. to estimate joint torque through processing electrical muscle signals, as shown in Fig. 1. Training neural networks requires enormous computing power; therefore, an innovative learning strategy featuring multi-loop modulation was developed by Pan et al. to analyze external disturbances while guaranteeing gait-learning convergence without intricate computational processes [8].

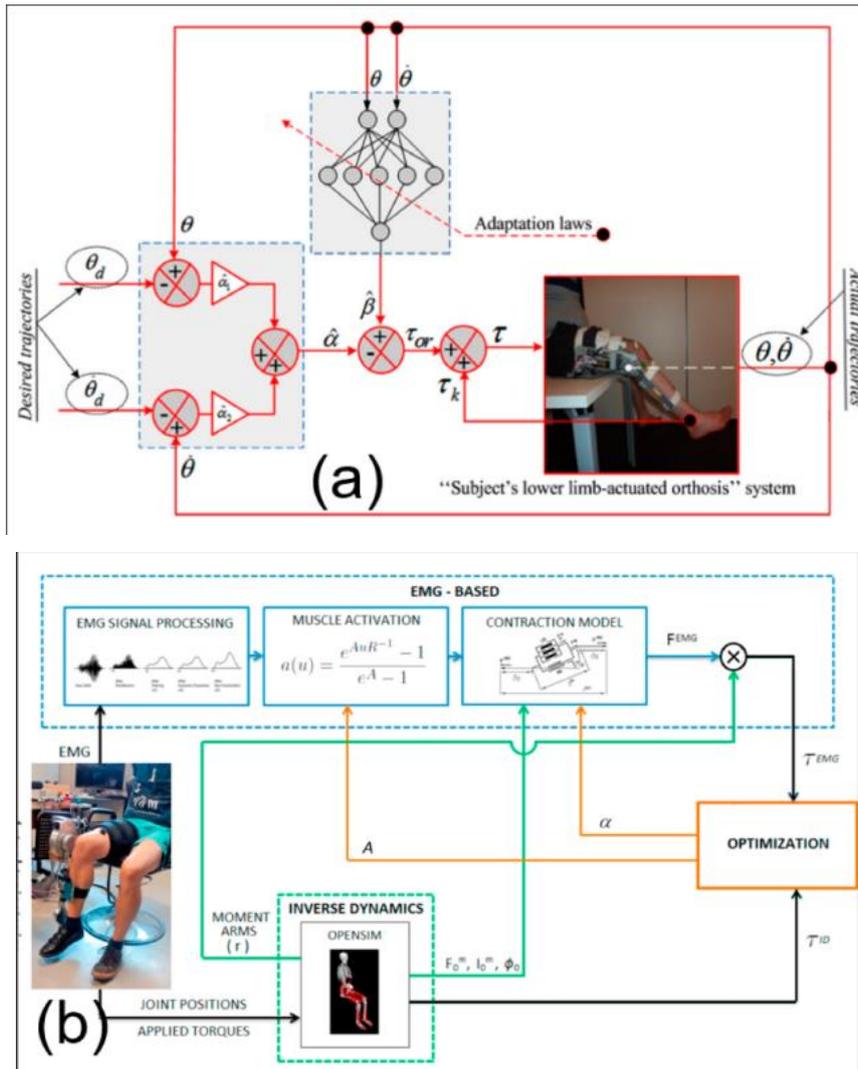


Fig. 1 A multilayer perceptron neural network in control of rehabilitation exoskeletons; (a) the Subject's lower limb-actuated orthosis system [7]; (b) the optimized system based on EMG signal [8].

4.2. Compliance Control

Instead of finishing the task, safety interaction is also significant, especially when ten tasks need both human and robot participation, such as rehabilitation training. Compliance control can ensure the environment stays away from the acute collision with the robot, and try to enhance the experience feeling during training. A biologically-inspired neuromuscular controller (NMC) is applied based on force control, and it adjusts its torque during patients' training. As a result, the study found that this controller produced a near-physiological gait at near normative speeds with few sensors. The increase in walking speed produced greater step lengths ($0.51 \pm 0.02, 0.82 \pm 0.02, 0.89 \pm 0.02$ from slowest to fastest speed) while step width changes showed no trend ($0.24 \pm 0.03, 0.31 \pm 0.02, 0.27 \pm 0.02$ m). Speed increases led to greater magnitudes in joint angle, similar to healthy humans [9].

4.2.1 Impedance control

As a force/torque-based control, impedance control realizes the dynamic relationship by measuring the error between the ideal end-effector's position (X_d) the actual one (x) and calculating the required force (F_c) through the controller. An inner loop applies this torque reference (τ) to the robot actuators once mapped according to its transposed Jacobian (J^t) [10]. The control strategy scheme is demonstrated in Fig. 2 [10].

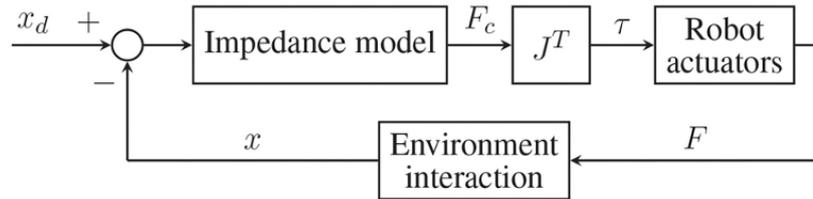


Fig. 2 General scheme of an impedance (torque-based) control [10]

4.2.2 Admittance control

The admittance control has an opposite approach, the input is force(F), then calculate the relative displacement(Δx), tend to the expected difference from the ideal position(x) and the real position. Finally, the output is position deviation(x_d), which guides the robot to go through the position control loop [10]. The demonstration is in Fig. 3.[10]

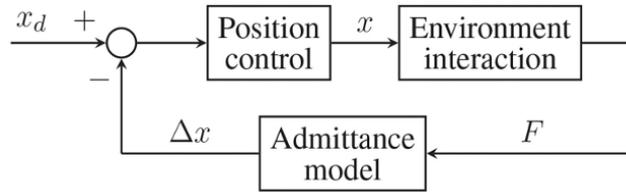


Fig. 3 General scheme of an admittance (position-based) control [10]

5. Conclusion

The robots can be classified into two categories-- exoskeleton robots and end-effector robots in a structural way. Most lower limb rehabilitation robots are exoskeleton robots since they can provide comprehensive vertical support and lateral stability to disable people, driving completely paralyzed limbs through repetitive motions. During the training process, patients with paralysis of the lower limbs get assistance from lower extremity exoskeleton rehabilitation robots. This robot is wearable; hence such robots must have good human compatibility, which requires some particular research data of gait from healthy humans, then the human-robot corporations can provide the proper adjustment to patients' gait. Therefore, this study analyzes the human gait at the initial.

Then the review introduces the three cutting-edge control technologies applied on the lower limb exoskeleton rehabilitation robots, respectively, and illustrates that the trend of control strategies is evolving from traditional and predefined towards intelligent and adaptive. The first category is position control. This technology establishes a collaboration between disable people and robot through learning, that is a remarkable progress to lower extremity rehabilitation exoskeleton robots, the neutral network technology demonstrates the forward-looking quality, the sEMG occurs after the brain has intention to move, and is generated 30 to150 milliseconds before the body perform the movement, which can predict the behavior of patients and input it into the external skeletal control system.

The second one is compliance control, which enables robots to comply with interaction forces from the environment, thereby achieving safe, adaptive, and natural physical interactions. Instead of resisting or ignoring external forces, compliance control actively utilizes and responds to them to establish a safe collaboration between robot and human; this significantly expands the application of robots in diverse environments.

Through continuous innovation from many institutes, more intelligent exoskeleton robots are poised to reshape the future of the rehabilitation healthcare system, and help patients walk individually and restore dignity of life for them.

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<p>This paper provides a relatively systematic review of the key fundamentals and core control technologies of lower limb exoskeleton rehabilitation robots. The authors begin with human gait analysis, clearly demonstrating the correspondence between the exoskeleton's control strategies and the different directions and magnitudes of auxiliary forces provided to each joint. They then focus on the two most critical control technologies—position control and impedance control—and point out that their mature applications in multiple fields provide a solid foundation for the development of lower limb rehabilitation exoskeletons. The paper also proposes a theoretical framework for optimizing control strategies and improving human-computer interaction efficiency. Overall, the paper is clearly structured, accurately argued, and of valuable reference value; direct acceptance is recommended.</p>						