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Research on the Structural and Control Design Scheme of the Rehabilitation Upper Limb Exoskeleton Robot

Sicheng Li*

School of Mechanical Engineering, Sichuan University, Chengdu, 610065, China

*Corresponding Author Email: 2591522440@qq.com

Abstract

With the increasing trend of global population aging, there are many problems in physical rehabilitation treatment. Rehabilitated upper limb exoskeleton robots have become one of the important technical means to improve rehabilitation effectiveness by virtue of their precise joint support and neurofeedback stimulation functions. This paper comprehensively reviews the research progress of the mechanical structure design and control strategy of the upper limb exoskeleton robot, summarizes the current main research results in the aspects of mechanical structure design, intention recognition technology, and control methods, and puts forward suggestions for possible future research directions, aiming to promote the rehabilitation exoskeleton to move towards more efficient, comfortable and popular.

Keywords

Upper Limb Exoskeleton; Robot; Structural Design; Intention Understanding; Control Assistance.

1. Introduction

Traditional rehabilitation therapy faces challenges such as low efficiency, prolonged treatment cycles, and uneven resource distribution. Under conventional manual intervention models, rehabilitation programs often rely heavily on the personal experience and judgment of therapists. This approach introduces uncertainties in training plans and lacks standardized protocols, ultimately compromising the overall effectiveness of rehabilitation outcomes.

As a novel assistive device integrating biomechanics, sensing technology, and intelligent control, rehabilitation upper limb exoskeleton robots significantly enhance active patient participation and treatment effectiveness through precise joint motion support and neural feedback stimulation. The elbow joint, in particular, plays a crucial role in performing daily activities such as grasping, pushing, and pulling. Therefore, its operational accuracy, flexibility, and the safety of human–robot interaction are essential for improving the practical utility of such devices in clinical settings [1].

This paper aims to explore the key technologies related to rehabilitation upper limb exoskeleton robots, with a specific focus on structural design, intention recognition, and assistive control strategies.

2. Analysis of Mechanical Design for Upper Limb Exoskeleton

2.1. Mechanical Structure and Degree-of-Freedom Configuration

2.1.1. Common Structural Designs of Upper Limb Exoskeletons

The design of upper limb exoskeletons must replicate the complex movement patterns of the human shoulder and elbow joints. The primary structural types include serial, parallel, and hybrid configurations. Serial structures are renowned for their simplicity and low cost but exhibit limitations in flexibility. In contrast, parallel structures significantly enhance load-bearing capacity through multi-branch transmission mechanisms, making them particularly suitable for applications requiring high rigidity. Hybrid designs, on the other hand, ingeniously combine the advantages of both aforementioned structures-for instance, employing a spherical parallel mechanism at the shoulder and a rotational joint at the elbow.

When applying upper limb exoskeletons in the field of rehabilitation, it is essential to ensure that these devices align with the individual physiological characteristics of the patient and emphasize harmonious human-machine integration. This integration involves not only physical interaction but also cognitive coordination. To achieve this goal, exoskeleton design should adhere to several key principles: first, ensuring safety in use; second, providing a natural and smooth operational experience; third, offering sufficient adaptability to meet the needs of different users; and finally, minimizing the overall weight without compromising functionality.

In Refeience [2], Jiang conducted an in-depth exploration of the design principles for robotic systems and the kinematic characteristics of the human upper limb. Most existing exoskeletal upper-limb rehabilitation robots incorporate four degrees of freedom at the shoulder joint: elevation/depression, adduction/abduction, internal/external rotation, and flexion/extension. The corresponding structural design can be referred to in Figure 1.

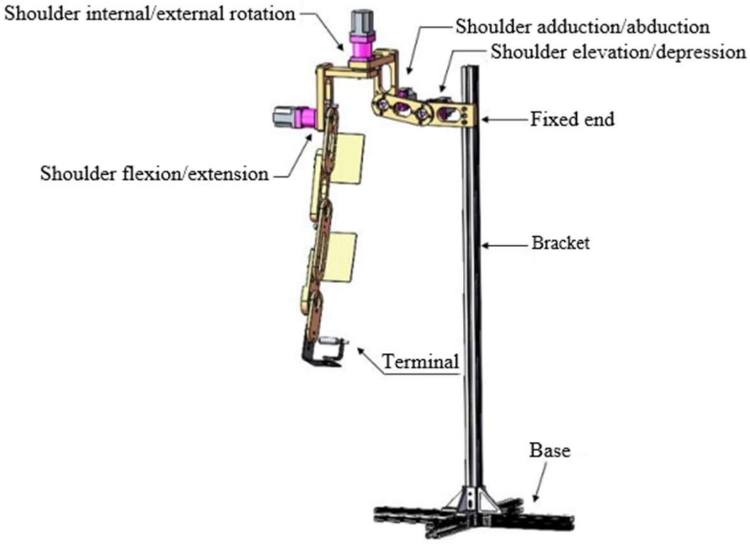

Figure 1. Structural design schematic of the exoskeleton robot

Moreover, the upper limb rehabilitation robot adopts a serial structure design, with its mechanical arm mounted on a height-adjustable aluminum frame. By flexibly adjusting the height of the fixation points, the device can accommodate patients performing rehabilitation exercises in standing, seated, or left/right arm training scenarios. Furthermore, the positions of the upper arm segment, forearm segment, and end-effector handle of the exoskeleton system are all adjustable to meet the specific needs of patients with different body sizes.

2.1.2. Structural Design Optimization Recommendations

In practical applications, the human shoulder possesses far more degrees of freedom than the four typically implemented. Therefore, incorporating flexible components can significantly enhance the naturalness of human-robot interaction. The current design does not sufficiently consider cushioning materials at contact surfaces or ergonomic factors, which may lead to skin irritation or discomfort during prolonged use. The adoption of flexible cushioning materials can markedly improve the comfort, flexibility, and adaptability of the exoskeleton robot-particularly in areas directly contacting the body. Such materials help distribute pressure, enhance wearability, and promote more harmonious collaboration between the user and the exoskeleton, without compromising kinematic performance.

For instance, integrating silicone-based structures around the shoulder rotation axis-capable of axial compression/extension and lateral bending-can facilitate multi-degree-of-freedom movements such as abduction, adduction, and rotation. This approach replaces traditional metal hinges, not only reducing noise caused by friction but also better accommodating the complex kinematics of the shoulder joint.

In the elbow flexion-extension region, foldable flexible materials arranged in diamond or honeycomb patterns can be employed. These structures achieve bending and extension through geometric deformation, reducing weight and eliminating the need for lubrication, thereby minimizing pressure and shear forces on the skin caused by rigid linkages.

2.2. Understanding of Control Design Intent (Perception Function)

2.2.1. Intention Understanding Design Scheme

Limb perception technology utilizes devices such as angle sensors, electromyography (EMG) sensors, and brain-computer interfaces (BCI) to recognize upper limb movements [3].

The technology for decoding upper limb movement intent aims to achieve real-time perception of the user's motion status by monitoring human biomechanical characteristics or electromyographic signals. Intelligent systems built on this technology enable upper limb exoskeleton rehabilitation devices to dynamically adjust output torque parameters, thereby providing mechanical support that aligns with the user's movement requirements. This facilitates precise motion assistance and personalized adaptation of rehabilitation training. However, it is important to note that biomechanical signals exhibit certain delays in reflecting actual movements, which limits the system's ability to predict future movement intent [4].

Compared to biomechanical signals, bioelectrical signals originating from motor neuron discharges contain limb movement characteristics even before motion execution. This pre-activation enables upper-limb exoskeletons to potentially predict human movement states. Among these signals, surface electromyography (sEMG)-detected non-invasively on the skin surface-reflects not only muscle activation levels but also the modulation process of the central nervous system in limb motor control. As a physiological signal embodying neural control characteristics, sEMG offers a new technical pathway for developing more biologically adaptive control strategies.

In the field of lower-limb motion intent decoding, typical applications of sEMG signals include discrete motion pattern recognition and continuous trajectory prediction. However, control systems for lower-limb exoskeletons based on discrete motion libraries often struggle to meet the requirements for continuous inter-joint coordination. Notably, technical approaches that establish joint dynamic models or employ regression algorithms for motion parameter estimation have demonstrated significant advantages in achieving multi-joint coordinated control [5].

2.2.2. Limitations of the Intent Recognition Design Scheme

Although surface electromyography signals can directly reflect neuromuscular activity, they still exhibit significant limitations in practical applications. Specifically, sEMG signals are susceptible to interference from external environmental factors. In his study, Wang conducted cycling experiments with multiple participants and collected corresponding sEMG data, the results of which are shown in Figure 2.

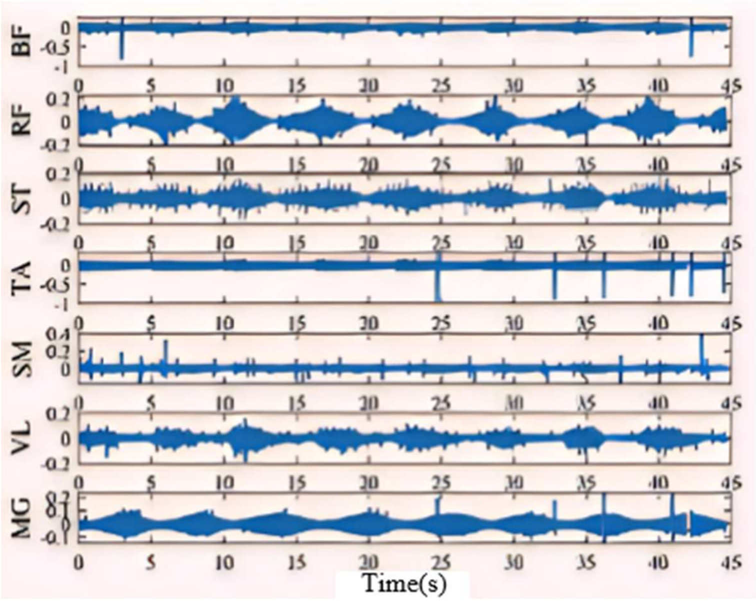

Figure 2. Raw sEMG signals acquired during cycling tasks

Although the skin surface was preprocessed following standard procedures before the experiment to minimize environmental interference with the sEMG signals, the raw signal waveforms presented in Figure 2 still exhibit noticeable contamination-particularly persistent motion artifacts that were not fully eliminated. Using these signals directly as model inputs may increase the complexity of the prediction model and compromise recognition accuracy.

Since exoskeleton devices often remain in prolonged contact with the user's skin, the electrode-skin contact impedance can vary due to factors such as sweat and sebum, necessitating frequent recalibration or repositioning of electrodes. This not only compromises user experience but also increases operational costs. Furthermore, significant inter-subject variability-including differences in muscle activation patterns, subcutaneous fat thickness, and electrode placement-requires model parameters to be individually tuned for each user, making it difficult to deploy a universal model directly.

Even for the same individual, surface electromyography signal characteristics-such as amplitude and frequency-can vary with fatigue level, exercise intensity, or body posture. For instance, signal amplitude may decrease as muscle fatigue increases, necessitating real-time dynamic adjustment of algorithm thresholds. In certain populations, such as individuals with neurological impairments, the success rate of sEMG-based intent recognition remains relatively low.

In summary, although sEMG-based intent recognition technology offers the potential advantage of being "neurally-driven," its practical implementation faces multiple challenges, including high costs. A promising direction to enhance the applicability and robustness of such systems may lie in multi-sensor fusion approaches-for example, by integrating electroencephalography devices and angle sensors to complement sEMG signals.

2.3. Upper Limb Exoskeleton Control and Assistance Functions

2.3.1. Research Status of Control Schemes

In Reference [4], the exoskeleton control scheme adopted the most traditional and classical PID control strategy for position control. Based on the patient's physical parameters (e.g., height, weight), the system retrieves the most suitable motion trajectory from a pre-stored database of limb movements and sets the corresponding motion cycle duration. Subsequently, a mathematical algorithm converts this trajectory into a Position-Velocity-Time (PVT) data format interpretable by the motor controller. Commands are then transmitted via the CAN bus communication protocol to the motor controller of the target joint, ultimately driving the actuator to assist the patient in completing rehabilitation exercises along the predefined trajectory.

The traditional PID control method is renowned for its simplicity and wide applicability, and is easy to implement. However, one of its main limitations is that the parameters cannot be adjusted in real time. When the dynamic characteristics of the system change, the gain parameters of the PID controller must be re-tuned. If the control parameters are not adjusted in time, it will directly affect the control quality of the system and even cause a significant deterioration in the control performance.

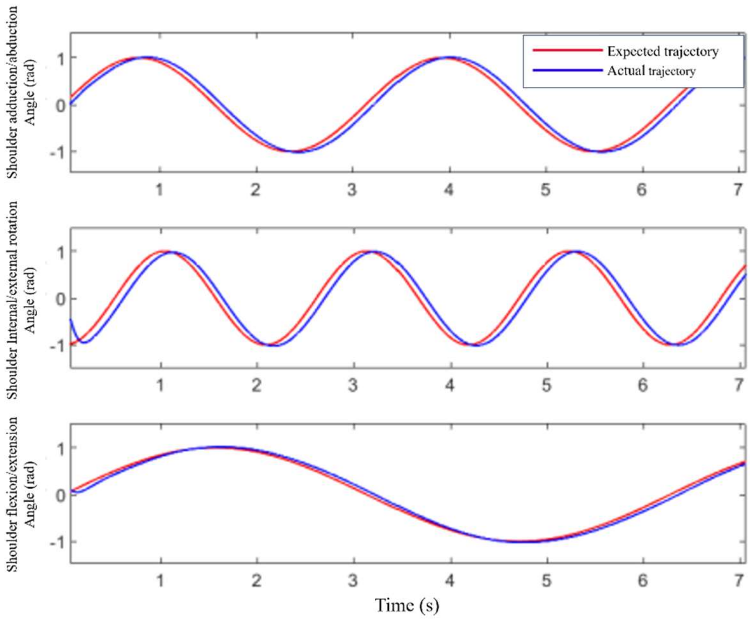

Figure 3. Tracking curves of each degree of freedom of the traditional PID

From the simulation results shown in Figure 3, it can be observed that the traditional PID control method is unable to precisely follow the expected movement angle, and fluctuations occur during the tracking process. This is mainly because the performance of the PID controller highly depends on the accuracy of the model of the controlled object; moreover, the PID controller cannot effectively utilize previous control experience, thus, when dealing with complex systems or changing trajectories, this control system often has difficulty making precise responses.

2.3.2. Optimization of PID Control

For the improvement of PID control, the control strategy can be optimized through a combination of experiments and learning to meet specific requirements and cope with complex environments (such as reinforcement learning). According to the suggestions in Reference[2], the PD-type iterative learning algorithm can be adopted. This method aims to enable the control system to more accurately track the target trajectory by repeatedly executing, accumulating experience, and gradually fine-tuning. The core concept of this control method is to use historical control strategies and error information as input parameters to dynamically optimize the output instructions of the controller. Under this mechanism, the controller achieves self-optimization through continuous accumulation of control experience, and its control performance continuously improves as the control cycle progresses, resulting in a gradual convergence of the deviation between the actual operating trajectory and the expected trajectory, ultimately achieving high-precision trajectory tracking control.

The significant advantage of the iterative learning control algorithm lies in its strong adaptive characteristic, which is particularly suitable for highly complex motion control scenarios with periodic features. Even when dealing with highly structured repetitive action tasks, this method still maintains excellent control performance. From the implementation perspective, this algorithm not only has a simple structure and is easy to implement in engineering, but also has excellent dynamic response characteristics.

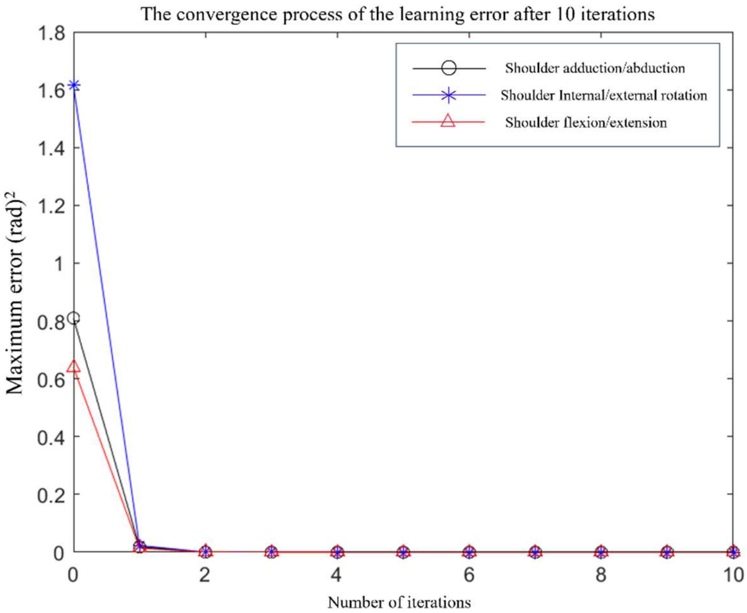

Figure 4. Convergence of PD-type iterative learning error

3. Conclusion

This study comprehensively reviews the latest advancements in the mechanical structure design and control strategies of rehabilitation-type upper limb exoskeleton robots, with a focus on addressing the core challenge of enhancing human-machine collaboration efficiency and rehabilitation outcomes. In terms of mechanical design, lightweight, flexibility, and adaptability are key factors that meet ergonomic requirements. Incorporating flexible materials into the design can enhance wear comfort while maintaining structural strength. The configuration of degrees of freedom must fully consider the complex characteristics of shoulder-elbow compound movements; however, existing solutions still have limitations in simulating multi-degree-of-freedom movements of the shoulder. Introducing flexible buffer elements and biomimetic joints might be one of the improvement paths. In the field of intent recognition technology, sEMG signals demonstrate great potential for promoting immediate interaction due to their "neural priority" feature. Although they are susceptible to external interference and have significant individual differences, these issues still need to be addressed by combining multiple sensing modalities and deep learning frameworks. From the perspective of control theory, although traditional PID controllers are simple to operate and perform well in path tracking, they struggle when facing nonlinear disturbances in multi-degree-of-freedom systems and individual differences among users. In contrast, PD-type algorithms based on iterative learning process optimization can gradually improve trajectory following accuracy through cumulative experience, thereby significantly enhancing the system's adaptability.

This paper explores the method of combining flexible structures with sensing technology, aiming to develop devices that are both stretchable and have electronic skin characteristics, as well as wireless surface electromyography systems, to reduce the burden on wearers and improve signal stability. By balancing individualized needs and universal design, using transfer learning and online adaptive algorithms, a model library that reflects individual differences has been constructed, reducing the time required for initialization settings and reducing the high dependence on professional experience. Additionally, the study emphasizes the importance of multimodal interaction interfaces and clinical validation by integrating BCI technology and biomechanical feedback mechanisms, achieving closed-loop control from the nervous system to mechanical equipment, promoting the transformation of related scientific and technological achievements from laboratory environments to household and community application domains.

The advancement of upper limb rehabilitation exoskeleton technology requires the comprehensive application of knowledge from multiple fields such as biomechanics, artificial intelligence, and materials science. In the design process, humanization should be the basic principle, and safety should always be the top priority. Through the combination and continuous innovation of multiple technologies, intelligent rehabilitation solutions that are both efficient and comfortable, and can widely benefit the public have been developed.

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