Proceedings of the 3rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/125/2025.21285

Structural Design and Clinical Application Research of Upper Limb Rehabilitation Robots

Xuanshuo Zhang[1,a,*]

[1]*Jiangsu University, Zhenjiang City, Jiangsu Province, 212013, China*
a. 1075976512@qq.com
**corresponding author*

Abstract: Stroke is one of the most prevalent diseases among the adult population worldwide, and robotic-assisted rehabilitation therapy has proven to be an effective treatment method. Traditional therapist-based treatments are limited by factors such as time and manpower, making it difficult to achieve ideal treatment results. Rehabilitation robots, with their precise movements, repetitive training, and timely data feedback, greatly enhance patient recovery and reduces treatment costs.This paper provides a detailed explanation of the mechanical design and application research of upper limb rehabilitation robots. In terms of mechanical design, the paper reviews the design characteristics and development history of rigid structures, flexible structures, and hybrid rigid-flexible structures for upper limb rehabilitation robots, including design improvements in the shoulder and elbow joints. The paper also discusses the research directions of upper limb rehabilitation robots from the perspectives of quantitative assessment and rehabilitation training, focusing on the technologies that analyze movement trajectories and physiological signals, which provide valuable references for the design and application of upper limb rehabilitation robots.

Keywords: Rehabilitation robot, Hybrid rigid-flexible structure, Quantitative assessment, Rehabilitation training

1. Introduction

Stroke is one of the most prevalent, disabling, and fatal diseases among cardiovascular diseases, severely affecting human health [1]. As of 2013, the global standardized mortality rate reached 110.10/100,000 [2]. The causes of stroke are numerous, including genetic factors, age and gender, hypertension, diabetes, and poor dietary habits. The clinical manifestations of stroke patients mainly include motor disorders, cognitive disorders, and swallowing disorders. Hemiplegia, one of the most common and typical symptoms of stroke, not only causes significant physical harm to patients but also brings a heavy economic burden to their families. Therefore, restoring the motor function of hemiplegic stroke patients has become one of the key concerns in stroke treatment. For stroke patients, modern rehabilitation therapies primarily focus on exercise therapy, supplemented by physical therapy, acupuncture, respiratory muscle training, and others. However, traditional exercise therapy mainly relies on the manual operations of rehabilitation therapists, which has limitations such as poor targeting, low efficiency, and high costs. Furthermore, as the assessment of patient recovery is subjective [3], it is challenging to achieve ideal therapeutic outcomes. As a product of the deep integration of robotic technology and rehabilitation medicine, rehabilitation robots offer new hope

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/125/2025.21285

for stroke treatment. First, rehabilitation robots can tailor treatment plans based on the patient's specific condition, moving along preset trajectories according to set parameters, thereby better promoting the improvement of neurological function. Rehabilitation robots can also perform repetitive tasks over long periods without being affected by fatigue, reducing treatment costs and shortening recovery time. Moreover, since rehabilitation robots are equipped with advanced sensors and feedback devices [4], they can monitor the patient's movement status and recovery level in real-time, making the next step in the rehabilitation training plan based on quantitative assessments. Thus, rehabilitation robots have significant advantages over conventional therapies [5].

Based on human anatomy, the upper limbs are more complex than the lower limbs, with more joints and degrees of freedom. Additionally, the brain's cortical region that controls the sensory-motor functions of the upper limbs has a broad distribution, making the remolding of neurons and activation of neural pathways in the corresponding brain areas more challenging than for other limbs. Therefore, studying upper limb rehabilitation robots is of more general practical significance.

The human upper limb has a complex physiological structure, so the design of upper limb rehabilitation robots must fully consider the movement characteristics of different joints and parts. During the development of upper limb rehabilitation robots, rigid structures, flexible structures, and hybrid rigid-flexible structures have emerged, and the compliance of human-robot interaction has increased, leading to better rehabilitation training outcomes for patients. This paper reviews the mechanical structure design and clinical application of upper limb rehabilitation robots in two specific scenarios: quantitative assessment and rehabilitation training, as shown in Figure 1,with the hope of providing a theoretical foundation for the clinical application of upper limb rehabilitation robots.

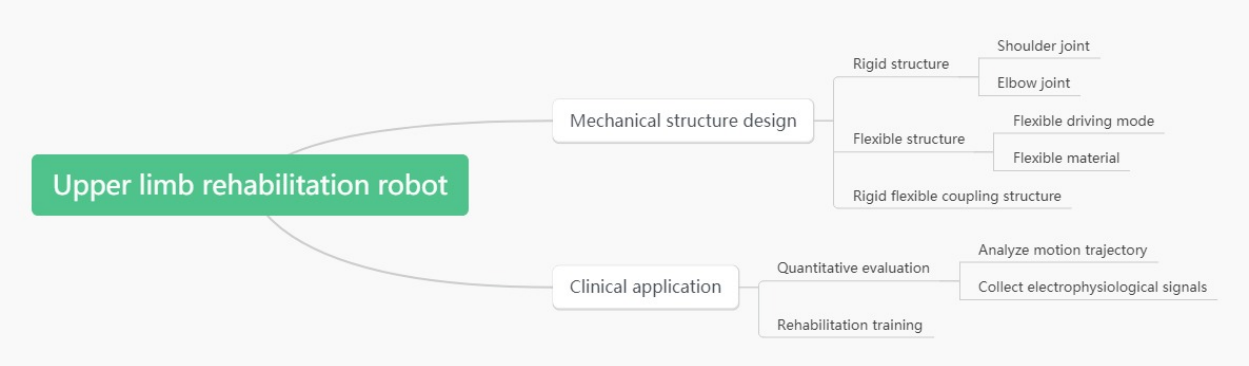

Figure 1: Upper limb rehabilitation robots'mechanical design and clinical application.

2. Mechanical Structure Design Research

Upper limb rehabilitation robots can be divided into two main types: exoskeleton-based and end-effector-based. The main structure of an end-effector-based robot includes the arm structure, end effector, and drive mechanism, while the main structure of an exoskeleton-based robot includes the drive mechanism, shoulder joint module, elbow joint module, and hand module. As shown in Figure 2,in the early stages of research, the primary structures of upper limb rehabilitation robots were mostly rigid structures. However, with the development of technology, flexible materials and flexible drive mechanisms have been introduced, significantly enhancing the compliance of human-robot interaction. The following section reviews the development history of the key structures of upper limb rehabilitation robots.

DOI: 10.54254/2755-2721/125/2025.21285

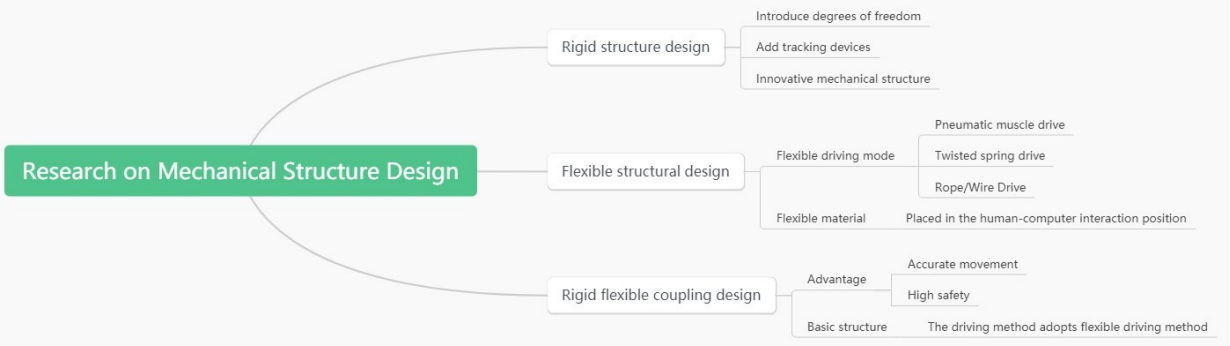

Figure 2: Mechanical structure design.

2.1. Rigid Structure Design

The shoulder joint is a complex joint composed of the sternoclavicular joint, acromioclavicular joint, and glenohumeral joint. It can perform three degrees of freedom: flexion/extension, abduction/adduction, and external/internal rotation. While the shoulder joint offers high flexibility, its stability is relatively poor. Therefore, improving the stability and compliance of the shoulder joint module in human-robot interaction has become an urgent problem. To assist with shoulder abduction/adduction, M.H. Rahman from McGill University in Montreal, Canada, designed an open semicircular ring at the interface between the human shoulder joint and the machine. Stainless steel balls were installed in the grooves of the inner and outer rings, reducing friction during internal and external rotation of the shoulder joint [6]. To achieve shoulder flexion/extension and abduction/adduction, Carin Vaida from the Technical University of Cluj-Napoca in Romania designed a 3-degree-of-freedom spherical parallel upper limb rehabilitation robot for shoulder and forearm rehabilitation training [7] (ASPIRE robotic system). The robot consists of two motion chains that perform abduction/adduction and flexion/extension movements. By introducing a rotational degree of freedom between the two motion chains to control the forearm direction, the robot achieved fine control of arm flexion/extension and abduction/adduction, while also reducing the risk of injury. In most studies, the complex movements of the shoulder joint are often simplified to the single-joint movement of the glenohumeral joint. However, during actual movement, the sternoclavicular and acromioclavicular joints are responsible for the shoulder joint's elevation/depression and forward/backward swinging, which causes the original fixed rotational center of the glenohumeral joint to shift during motion. To ensure that the rotational axis of the human glenohumeral joint coincides with that of the exoskeleton shoulder joint, Qingcong Wu from Southeast University developed an adaptive shoulder joint mobile platform [8]. This platform uses linear guide rails in both the horizontal and vertical directions, allowing for flexion/extension, abduction/adduction, and external/internal rotation, all of which are achieved through linear motion. The horizontal (X and Y) guide rails are equipped with return springs, which eliminate errors between joints by applying a horizontal force through the human upper limb on the exoskeleton. In the vertical (Z) direction, a servo motor drives the ball screw to dynamically adjust the platform's height. The combined motion in the three directions of the adaptive mobile platform resolves the problem of the shoulder joint module's shifting rotational center, while also preventing injuries caused by detachment of the human-machine interface. Additionally, this system uses a dual-lasso drive system to control the movements of the shoulder, elbow, and wrist joints. Although this design solves the misalignment issue between the human and robot axes, the increased degrees of freedom lead to a decrease in structural compactness. To address this, Jingyu Shen from China University of Petroleum made improvements in his design of a 5-degree-of-freedom upper limb robot [9]. He replaced the traditional orthogonal mechanical arms with a vertical mechanical arm adjusted to a certain angle, and used a virtual floating

DOI: 10.54254/2755-2721/125/2025.21285

pivot to replace the traditional fixed pivot structure of the shoulder joint. This design better aligns with the movement characteristics of the human upper limb, improving the human-machine system's compatibility by addressing the shoulder joint's shifting pivot problem.

The elbow joint primarily performs flexion/extension and facilitates forearm pronation/supination. Cuiyao Fu from Nanchang University utilized two motor-driven bevel gears in the elbow joint mechanism [10], enabling the forearm assistive device to perform flexion/extension and pronation/supination. Patients can also switch between their left and right hands as needed. To assist patients in performing elbow flexion/extension and glenohumeral joint abduction/adduction during upper limb rehabilitation, Juan C. Freire from the University of Valladolid in Spain designed an end-effector-based rehabilitation robot [11]. This robot has two degrees of freedom in the X/Y directions, allowing patients to move the end effector to perform elbow flexion/extension and glenohumeral joint abduction/adduction therapies. The end effector is equipped with an anti-spasm orthotic to ensure the limb remains in the correct position even during spasms. Chengke Zhou from University of Electronic Science and Technology of China designed a curved mechanical structure for human-robot interaction [12]. The robot uses a motor-driven synchronous belt to move the exoskeleton's forearm along the curved structure for pronation/supination, ensuring that the elbow joint module's axis of motion aligns with the human upper arm's central axis.

2.2. Flexible Structure Design

The design of flexible structures in upper limb rehabilitation robots is mainly aimed at ensuring the safety of the affected limb and enhancing the compliance of human-robot interaction. The application of flexible structures focuses primarily on the driving mechanism and the use of flexible materials. Ge Lili from Huazhong University of Science and Technology employed pneumatic muscles as actuators in the design of a 7-degree-of-freedom serial-link robot [13]. When the internal air pressure of the pneumatic muscles changes, the muscle length also changes, producing force and displacement. This design mimics natural muscle movements, making it more closely aligned with the movement of the affected limb and reducing the risk of strain injuries that could be caused by rigid mechanical structures. Liu Yifan from Harbin Institute of Technology, in his design of an end-effector-based rehabilitation robot [14], used a flexible joint based on a dual-torsion spring drive system. The actuator undergoes elastic deformation when subjected to the joint transmission forces, generating an elastic torque that transmits motion. This flexible joint design ensures the user’s safety in case of robot malfunction or loss of control, as it allows the joint to deform elastically rather than causing injury. Irfan Hussein from the University of Siena, Italy, designed a soft redundant robotic finger [15], where the extension and flexion of the finger are achieved by pulling tendon lines. Each joint of the finger is made from 3D-printed thermoplastic polyurethane components and elastic lines. This flexible structure allows the joints to deform adaptively when the tendons pull on the finger joints, making the movement of the entire finger more compliant. This allows the patient to perform exercises with the robot's finger providing minimal assistance but enabling maximum effort from the patient.

2.3. Rigid-Flexible Hybrid Design

As mentioned earlier, the rigid structure of upper limb rehabilitation robots offers high accuracy, allowing precise control of the robotic arm’s motion trajectory and force according to a predefined pattern, thereby providing reliable support for the patient. However, due to its inherent rigidity, it may pose a risk of injury to the patient. In contrast, the flexible structure can offer cushioning in case of robot malfunction, better matching the human body's motion curve, and reducing the overall weight of the robot. However, it does not provide the same level of motion control accuracy and stability as

DOI: 10.54254/2755-2721/125/2025.21285

the rigid structure. Therefore, combining rigid and flexible structures, known as the rigid-flexible hybrid design, has become one of the popular research directions in modern upper limb rehabilitation robots.

The elbow joint is a more complex joint in the human body, where flexion/extension involves both sliding and rolling motions. To accommodate the changes in the axis of motion during elbow flexion/extension and reduce human-robot mismatch, Guodong Lang from Harbin Institute of Technology designed a rigid-flexible hybrid elbow rehabilitation robot [16]. The robot uses a parallelogram hexagonal compensating structure, which compensates for the misalignment of the elbow joint. To reduce the weight of the robot body, the developer employed a relatively simple flexible cable drive mechanism for elbow flexion/extension. This design efficiently utilizes the limited space in the human upper limb while ensuring better coordination between the robot's components.

In addition to reducing the robot's weight, Wu Weifeng from South China University of Technology proposed a "mechanical arm + exoskeleton" integrated structure to ensure the accuracy of the exoskeleton's motion trajectory and improve human-robot compatibility [17]. In this design, the elbow joint employs a lasso transmission scheme to reduce the weight of the exoskeleton. Furthermore, a six-degree-of-freedom robotic arm is introduced at the shoulder joint, improving human-robot coupling during movement. At the elbow joint, a parallelogram mechanism is used to adaptively compensate for forearm displacement caused by mismatched flexion/extension axes.

3. Rehabilitation Robot Application Research

In clinical treatments, upper limb rehabilitation robots are mainly applied in two fields: quantitative assessment and rehabilitation training, as shown in Figure 3.

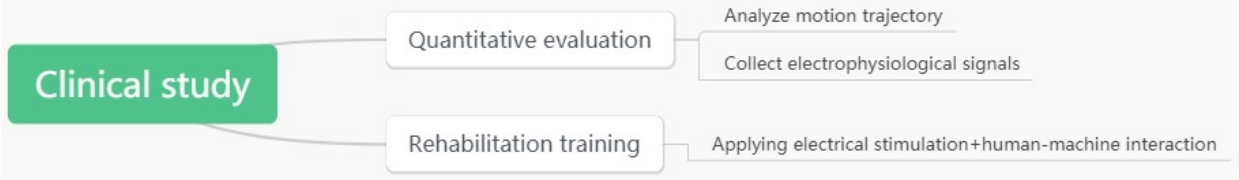

Figure 3: Clinical application.

In quantitative assessment, therapists typically conduct scientific evaluations and diagnoses through the analysis of motion trajectories or by collecting physiological signals. During this process, therapists often propose their own quantitative evaluation standards based on the collected information and its characteristics. Zhang Shuo from Shandong University proposed the concept of "joint active participation" [18] as an evaluation metric for joints with weak motor abilities, which targets specific training for those joints. He developed an experimental platform for a single-arm upper limb rehabilitation robot system, where subjects are fixed to the robot’s end flange using a connector. In the experiment, the subject’s upper limb undergoes three sets of experiments: fully active, fully passive, and partially active. The mean position of the robot’s end effector during three repetitions of the fully active trial is taken as the expected motion trajectory. For the other two groups, specific motion paths are defined for each subject based on the experimental requirements. By calculating the deviation between the actual and expected motion paths, the active joint torque in each experiment can be determined, from which the joint's active participation level is calculated. The results of assessment experiments on different subjects' same-side upper limb joints, as well as experiments on the bilateral upper limb joints of the same subject, demonstrate that using a single-arm upper limb rehabilitation robot system allows for a comprehensive and integrated evaluation of the subject’s upper limb motor function. To achieve both active training and motion assessment

DOI: 10.54254/2755-2721/125/2025.21285

simultaneously, Gao Lin from China Medical University designed an upper limb rehabilitation robot active training system [19]. The developer proposed four evaluation standards: training range, training accuracy, training stability, and training participation. In the experiment, the rehabilitation therapist sets different motion trajectories for the patient based on their condition. By collecting interaction force information from the ROS-subscribed sensors and the robot's end effector position, the subject's motion characteristics during training are calculated. Based on the four evaluation standards, the system provides evaluation results, allowing the patient and therapist to monitor the subject's upper limb movements in real-time and make necessary adjustments. Ismail Ben Abdallah from the University of Sfax, Tunisia, developed an optimized stimulation control system (OSCS) [20], aimed at accurately assessing and responding to the patient's pain threshold, thereby dynamically adjusting the exoskeleton's stimulation level and control parameters. The basic kinematic structure of the exoskeleton consists of two rotary joints: one for elbow movement and the other for forearm rotation. Electrodes are placed on specific muscles to collect EMG signals, which are input into a fuzzy logic system for assessment, estimating the patient's pain level. Based on this estimate, the stimulator adjusts the stimulation parameters to provide personalized rehabilitation stimuli. In the field of rehabilitation training, S. Dalla Gasperina from Politecnico di Milano, Italy, proposed a hybrid rehabilitation system combining functional electrical stimulation (FES) with robotics [21]. In an experiment involving 12 healthy volunteers, the system achieved precise trajectory tracking and reduced motor torque by 51%. Compared to using FES alone, no signs of muscle fatigue were observed in 100 repetitions of elbow flexion/extension experiments, suggesting that the hybrid system can delay the onset of muscle fatigue. As a result, this technology offers significant advantages in improving motion accuracy, reducing motor energy consumption, and extending training durations.

4. Conclusion

In the extensive clinical application of stroke treatment, patients using upper limb rehabilitation robots have shown significantly better recovery outcomes compared to traditional treatments. Therefore, upper limb rehabilitation robots hold great potential in stroke rehabilitation. To achieve better recovery results, researchers worldwide have continually optimized the mechanical structures of upper limb rehabilitation robots, leading to the development of rigid, flexible, and rigid-flexible hybrid structures, with an ongoing improvement in the compliance of human-robot interaction. The main goal of upper limb rehabilitation robots is to enhance the rehabilitation effect of the affected limb. Recently, a new rehabilitation method has emerged that combines motion training with functional electrical stimulation (FES), which has been proven to be an efficient approach. Additionally, upper limb rehabilitation robots can use technologies like motion trajectory analysis or neural electrical signal feedback to quantitatively assess the training and recovery status of the affected limb. Although upper limb rehabilitation robots still face challenges such as excessive weight and the lack of clinical safety standards, they have become an indispensable part of clinical stroke treatment. In the future, upper limb rehabilitation robots will continue to evolve towards greater lightness, standardization, and intelligence.

References

[1] *Shi, Z. W. (2021). A retrospective look at the global and Chinese cardiovascular disease burden and its risk factors over the past 30 years: An interpretation of the 1990-2019 global cardiovascular disease burden and risk factors report. Diagnostic Theory and Practice, 20(04), 349-355. https://doi.org/10.16150/j.1671-2870.2021.04.004*

[2] *Gan, Y., Yang, T. T., Liu, J. X., et al. (2019). Research progress on the trends and influencing factors of stroke prevalence at home and abroad. Chinese Journal of Preventive Medicine, 20(02), 139-144. https://doi.org/10.16506/j.1009-6639.2019.02.013*

[3] *T B V , I H K , N H .Is robot-aided sensorimotor training in stroke rehabilitation a realistic option?[J].Current opinion in neurology, 2001, 14(6):745-52.*

DOI: 10.54254/2755-2721/125/2025.21285

[4] Kiyono K , Tanabe S , Hirano S , et al.Effectiveness of Robotic Devices for Medical Rehabilitation: An Umbrella Review[J].Journal of Clinical Medicine, 2024, 13(21):6616-6616.
[5] Telerehabilitation using a 2-D planar arm rehabilitation robotfor hemiparetic stroke: a feasibility study of clinic-to-home exergaming therapy.
[6] Rahman H M , Rahman J M , Cristobal L O , et al.Development of a whole arm wearable robotic exoskeleton for rehabilitation and to assist upper limb movements[J].Robotica, 2014, 33(1):19-39.
[7] Vaida C , Plitea N, Carbone G, et al.Innovative development of a spherical parallel robot for upper limb rehabilitation[J].Int. J. of Mechanisms and Robotic Systems, 2018, 4(4):256-276.
[8] Wu, Q. C. (2016). Research on the gravity-driven balance of upper limb rehabilitation exoskeleton with a lasso mechanism (Doctoral dissertation, Southeast University).
[9] Shen, J. Y. (2020). Design and research of an upper limb rehabilitation robot (Doctoral dissertation, China University of Petroleum (Beijing)). https://doi.org/10.27643/d.cnki.gsybu.2020.000607
[10] Fu, C. Y. (2022). Design and research of an upper limb exoskeleton rehabilitation system (Doctoral dissertation, Nanchang University). https://doi.org/10.27232/d.cnki.gnchu.2022.002974
[11] Fraile C J , Pérez-Turiel J , Baeyens E , et al.E2Rebot: A robotic platform for upper limb rehabilitation in patients with neuromotor disability[J].Advances in Mechanical Engineering, 2016, 8(8):61-64.
[12] Zhou, C. K. (2019). Design and preliminary realization of an upper limb hemiplegia rehabilitation exoskeleton robot (Doctoral dissertation, University of Electronic Science and Technology of China).
[13] Ge, L. L. (2009). Kinematic and dynamic analysis of upper limb rehabilitation medical robots (Doctoral dissertation, Huazhong University of Science and Technology).
[14] Liu, Y. F. (2021). Design and safety control research of an upper limb rehabilitation robot based on flexible joints (Doctoral dissertation, Harbin Institute of Technology). https://doi.org/10.27061/d.cnki.ghgdu.2021.000883
[15] Hussain I , Salvietti G , Spagnoletti G , et al.A soft supernumerary robotic finger and mobile arm support for grasping compensation and hemiparetic upper limb rehabilitation[J].Robotics and Autonomous Systems, 2017, 931-12.
[16] Lang, G. D. (2022). Research on an elbow joint rehabilitation exoskeleton robot system based on active-passive control (Doctoral dissertation, Harbin Institute of Technology). https://doi.org/10.27061/d.cnki.ghgdu.2022.003239
[17] Wu, W. F. (2022). Design and force interaction technology research of upper limb rehabilitation robots (Doctoral dissertation, South China University of Technology). https://doi.org/10.27151/d.cnki.ghnlu.2022.002058
[18] Zhang, S. (2023). Research on upper limb functional assessment and rehabilitation control methods based on joint active participation (Doctoral dissertation, Shandong University). https://doi.org/10.27272/d.cnki.gshdu.2023.005656
[19] Lin, G. (2023). Research on intelligent interaction-rehabilitation-assessment strategy for upper limb rehabilitation robots with end traction (Doctoral dissertation, China Medical University). https://doi.org/10.27652/d.cnki.gzyku.2023.000724
[20] Abdallah B I , Bouteraa Y .An Optimized Stimulation Control System for Upper Limb Exoskeleton Robot-Assisted Rehabilitation Using a Fuzzy Logic-Based Pain Detection Approach[J].Sensors, 2024, 24(4):
[21] Gasperina D S , Ferrari F , Gandolla M , et al.Hybrid Cooperative Control of Functional Electrical Stimulation and Robot Assistance for Upper Extremity Rehabilitation.[J].IEEE transactions on bio-medical engineering, 2024, 71(9):2642-2650.