Modular Design and Control System Optimisation of an Upper Limb Rehabilitation Robot

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Abstract. Stroke is one of the leading causes of disability and death worldwide, and upper limb dysfunction in particular seriously affects patients' daily life and self-care ability. Therefore, designing efficient and economical upper limb rehabilitation robots has become an urgent problem. In this paper, a modular and lightweight upper limb rehabilitation robot is proposed. The robot employs adaptive impedance control, model predictive control (MPC) and electromyogram (EMG)-based closed-loop control strategies to achieve personalized rehabilitation training support. Through simulation and experimentation, this paper verifies the significant effect of the robotic system in enhancing the upper limb function of stroke patients, especially in improving locomotor ability, enhancing the sense of active participation, and promoting the recovery of voluntary movement. The results show that the system has the ability of efficient and personalized rehabilitation training, and is expected to be widely applied in home and community rehabilitation to promote the popularity and development of upper limb rehabilitation technology. The analyses in this position can provide a reference for the development of upper limb rehabilitation robots.

Keywords: Upper limb rehabilitation robot, modular design, adaptive impedance control, model predictive control, EMG, personalized training.

1. Introduction

Stroke is one of the leading causes of disability and death worldwide. The number of stroke patients, deaths, or disabilities has almost doubled globally over the past 30 years, and the cost of stroke treatment and rehabilitation and indirect costs may more than double, with expenditures of $891 billion in 2020 and could be as high as $2.3 trillion by 2050 [1]. In particular, upper limb dysfunction due to stroke affects patients' daily life and self-care. Finding innovative and efficient upper limb rehabilitation methods to reduce rehabilitation costs has become a critical issue that needs to be addressed urgently.

In recent years, with the rapid development of robotics, upper limb rehabilitation robots have been gradually used in clinical rehabilitation. These devices promote neuroplasticity and help patients recover their motor abilities by providing targeted training. Upper limb rehabilitation robots with different design concepts and control strategies are now available on the market, supporting active or passive training modalities. For example, Onfiani et al. proposed a collaborative robot (cobot)-based upper limb rehabilitation system using an optimized design approach and a virtual fixture control architecture to enable effective robot interaction in both passive and active modes [2], and Islam et al. proposed a 7-degree-of-freedom upper limb robotic exoskeleton design with a wider range of motion [3]. However, existing devices still face high costs due to the inability to customize, complex manufacturing processes, and poor operability due to a lack of control system optimization, limiting their popularity in home and community environments. For example, a bedside upper limb rehabilitation training robot designed by Du Yanchen et al. to help hemiplegic patients in the flaccid stage to perform ambulatory training still suffers from deficiencies in cost and degrees of freedom [4].

This study aims to design a modular, lightweight, wearable, and highly efficient upper limb robot that can effectively support patients' rehabilitation training. Through the combination of biomechanical analysis and kinematic parameters, an ergonomic robotic system will be developed to improve the efficiency and comfort of training. At the same time, the research will focus on the use of more advanced control algorithms to improve the interaction experience between the patient and the robot. The ultimate goal is to provide a convenient, cost-effective and efficient rehabilitation solution for stroke patients and to promote the development of upper limb rehabilitation technology.

2. Design proposal

2.1. Design requirements

Shoulder and elbow movements are the focus of the design of upper limb rehabilitation robots. It is necessary to ensure that they can simulate the natural movement trajectory of the human body while providing effective rehabilitation assistance support. First, the shoulder joint has the highest degree of freedom such as flexion, extension, adduction, abduction, rotation, which is the most complex joint in the upper limb with largest range of motions. Therefore, a flexible multi-degree-of-freedom mechanical structure should be used in the design to ensure a wide range of motion coverage. In addition, the motion of the elbow joint requires a high-precision power transmission system to realise the flexion, extension and rotation functions. To achieve precise control, these joints should be equipped with lightweight motors and gearing systems to ensure stability and fluidity during rehabilitation training. To avoid joint injuries during patient training, viscoelastic dampers or other underdrive mechanisms should be introduced into the design of the drive system for the shoulder and elbow joints to ensure flexible adjustment of the robot to adapt to different patient body types and rehabilitation needs [5]. Finally, to enhance wearing comfort and safety, the mechanical structure of the robot should be made of lightweight materials, and adjustable shoulder width, upper arm and forearm length adjustment mechanisms should be designed to ensure that the device can be adapted to different patient body types. Fig. 1 illustrates the flowchart of the overall system design.

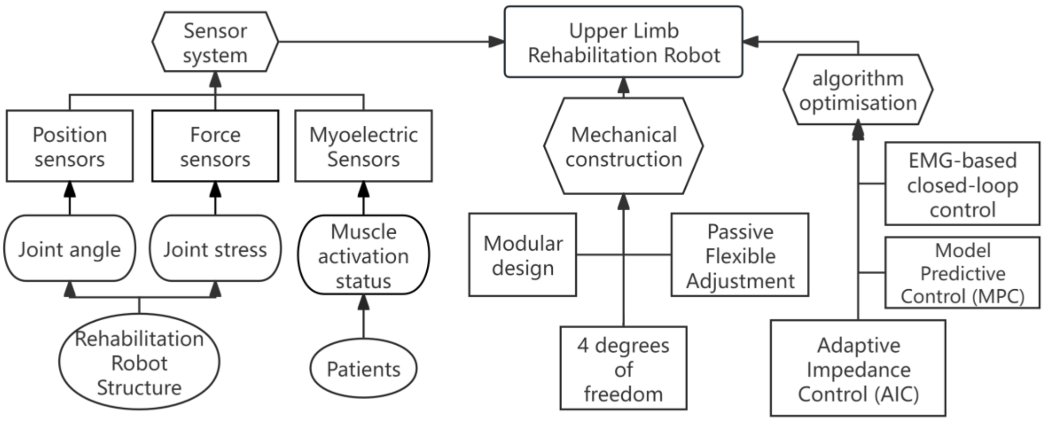

Figure 1. System flow chart

2.2. Modular structure design

To ensure that patients with different upper limb lengths and body sizes can use the same robot for rehabilitation, this paper adopts a modular structural design, dividing the robot into several independently adjustable and replaceable modules, such as shoulder, elbow, wrist, upper arm and forearm. These modules can cover a wide range of different patient physical characteristics, and each module can be altered in length and diameter or replaced with a parametric actuator through a simple mechanism to ensure its suitability for different patient body types and rehabilitation progress [6].

Through the use of standardized interfaces, modules can be quickly connected or removed from each other, facilitating maintenance and replacement of the device.

In addition, the modular design supports the expansion of functions at different stages of rehabilitation. For example, in early rehabilitation, patients may need more external assistance. In later stages of rehabilitation, the module can gradually reduce the reliance on strength and increase active movement training according to the patient's progress. This flexibility ensures that the robot can be adapted to different needs from early to late rehabilitation, thus improving rehabilitation outcomes and comfort of use.

The modular design also offers the possibility of upgrading and customizing the device. Depending on different patient or clinical needs, certain functional modules, such as high-precision sensors, intelligent control units or joint modules with higher degrees of freedom, can be added or improved to cope with more complex exercise training needs. This design approach lays the foundation for future advances in rehabilitation technology and the longevity of the device.

2.3. Mechanical design

In this paper, a four-degree-of-freedom rehabilitation robot is designed to cover the kinematic characteristics of the shoulder and elbow joints to ensure maximum functional recovery while mimicking natural motion.

The shoulder joint design contains two active degrees of freedom (flexion-extension, internal and external rotation), and the use of gears and toothed rings realises the selective internal and external movement of the shoulder to ensure smooth rotation and precise positioning of the joint; the use of pulleys and belt drives to realise shoulder flexion and extension reduces operating noise and vibration while the transmission ratio can be easily adjusted by changing the size of the pulleys. The elbow module is designed with two active degrees of freedom (flexion, extension and rotation) and uses a toothed ring for forward and backward rotation; a helical gear is used for flexion and extension to ensure smooth operation of the joint. To ensure adaptability during the different stages of rehabilitation, the joint module is equipped with an adjustable limiter to limit the maximum range of motion of the joint, thus protecting the patient from excessive movement during the early stages of rehabilitation. At the same time, the transparent shield is designed to allow easy observation of the joints and provide safety protection. To enhance safety, viscoelastic dampers are introduced in the design for passive flexibility adjustment [5] to absorb impact forces caused by patient movement and ensure the flexibility and safety of the device under a variety of operating conditions, thus reducing the stress concentration on the joints and minimizing the risk of secondary injuries.

2.4. Powertrain and Sensor Design

The shoulder and elbow joints of upper limb rehabilitation robots need efficient and stable driving force, so the power system design is one of the core parts of the rehabilitation robot. In this paper, brushless DC motors with the advantages of high-power density, long life and low maintenance requirements are used as the main driving force source. Each joint module is connected to the motor through a harmonic gear reducer or planetary gear reducer to ensure high efficiency of power transmission and low backlash characteristics for precise motion control. In the power system, the shoulder joint, with more degrees of freedom, has flexion-extension and internal-external rotation motion requirements, so a higher power brushless DC motor is used to ensure sufficient power output in all motion directions. In contrast, the elbow joint has a smaller range of motion and fewer flexibility needs, so a low-power motor is sufficient, while optimizing the torque output through a harmonic gear reducer to maintain a higher torque output capacity to support the patient's flexion-extension motion.

The sensor system is mainly used for real-time monitoring of the patient's movement status and muscle force output. The system integrates several types of sensors, including position sensors, force sensors, and electromyography (EMG) sensors. Position sensors are used to detect changes in the angle and position of the joints to ensure the accuracy of the movement trajectory; force sensors are used to measure the force applied to the joints and to obtain feedback from the patient, which guarantees the rehabilitation effect as well as the safety of the rehabilitation process; EMG sensors are used to monitor the activation status of the patient's muscles, which helps to determine the degree of the patient's participation in the active movement. When the EMG sensors detect increased muscle activity in the patient, the control system reduces the assistive force provided by the robot to motivate the patient to generate force on his/her own, thus facilitating the neuromuscular remodeling process.

Conversely, when a patient's lack of strength is detected, the system increases the assistive force to ensure smooth and safe exercise.

The combination of the power system and the sensor system enables the rehabilitation robot to achieve highly personalized rehabilitation training programs, providing precise rehabilitation support to patients through real-time feedback and adjustment. This design not only improves the effectiveness of rehabilitation training but also enhances the patient's sense of participation and autonomy, helping to shorten the rehabilitation cycle and improve outcomes.

2.5. Control algorithm optimisation

In the design of rehabilitation robots, optimisation of control algorithms is important to increase the responsiveness of the device, the precision of the movement, and the interaction experience between the patient and the robot. In order to achieve personalized rehabilitation training support for patients, this design employs a variety of advanced control algorithms, including adaptive impedance control, model predictive control (MPC), and EMG-based closed-loop control strategies.

2.5.1. Adaptive impedance control

The stiffness and damping of the robot joints are adjusted by adaptive impedance control to adapt to the different states of the patient during rehabilitation training. When the patient has strong active movement ability, the system will reduce the damping and stiffness so that the patient can rely more on his/her own strength to perform the movement, thus promoting the recovery of autonomous movement. When it detects that the patient has insufficient strength, the system automatically increases the damping and stiffness to provide additional assistive force to help the patient complete the specified movement. This adaptive strategy enables the robotic system to adjust the level of assistive force in real time, improving the effectiveness of training and patient comfort [7]. The specific implementation of Eq:

$$\mathrm{F(t)} = \mathrm{M} \cdot \ddot{\mathrm{x}}(\mathrm{t}) + \mathrm{B} \cdot \dot{\mathrm{x}}(\mathrm{t}) + \mathrm{K} \cdot \mathrm{x(t)} \tag{1}$$

Where: $\mathrm{F(t)}$ denotes the applied force or moment, M is the mass coefficient (for adjusting the sense of mass), B is the damping coefficient (for adjusting the sense of damping), K is the stiffness coefficient (for adjusting the sense of stiffness), $\mathrm{x(t)}$ is the positional variable, and $\dot{\mathrm{x}}(\mathrm{t})$ and $\ddot{\mathrm{x}}(\mathrm{t})$ are the velocity and acceleration, respectively.

2.5.2. Model Predictive Control (MPC)

MPC is an advanced control method based on a dynamic model of the system for predicting and optimizing the motion of a robotic system uses the data fed back from the sensors in conjunction with a kinematic and dynamic model of the system to predict the behaviour of the system in real time over a period of time in the future, thus calculating the optimal control inputs. This control method can effectively deal with the complexity of multi-degree-of-freedom robotic systems, ensure coordinated movement of the joints, reduce errors and improve the accuracy of the motion. The introduction of MPC enables rehabilitation robots to maintain stable and accurate motion performance during complex training tasks [8]. Its core equation is:

$$\min_{u} \sum_{k=0}^{N} \left(\left\| x_{k+1} - x_{ref} \right\|_Q^2 + \| u_k \|_R^2 \right) \tag{2}$$

Where u is a sequence of control inputs. $\mathrm{x_{k+1}}$ is the state of the system at moment $\mathrm{k+1}$ (predicted by the dynamics model). $\mathrm{x_{ref}}$ is the goal state (e.g., the patient's desired motion trajectory). The state error weight matrix Q determines the priority of the target state (e.g., the patient's desired motion trajectory) in the control optimisation. R is the weight matrix of the control inputs, which is used to constrain the magnitude or rate of change of the control signal. N is the length of the prediction time domain. MPC usually describes the system dynamics using a discrete-time model: $\mathrm{x_{k+1}} = \mathrm{A} \cdot \mathrm{x_k} + \mathrm{B} \cdot \mathrm{u_k}$. where A is the system state transfer matrix; B is the control input matrix.

2.5.3. EMG-based closed-loop control

In order to improve the interaction experience between the patient and the robot, this design integrates a closed-loop control strategy based on EMG signals. By monitoring the patient's muscle activity in real time through EMG sensors, the system is able to recognize the patient's movement intention and adjust the robot's movement assistance accordingly. For example, when the EMG signal indicates that the patient is actively attempting a certain movement, the robot reduces the assisting force to motivate the patient to complete the movement autonomously, while when the EMG signal is weakened, the system increases the assisting force to help the patient complete the task successfully [9]. The core formula is:

$$F_{assist} = F_{max} \cdot \left(1 - \alpha \cdot \frac{E(t)}{E_{threshold}}\right) \tag{3}$$

The parameter F_{assist} is the auxiliary force provided by the system; F_{max} is the maximum auxiliary force that the system can provide; $E(t)$ is the amplitude of the EMG signal at the current moment; $E_{threshold}$ is the threshold of the EMG signal, which is used to define the reference intensity of the patient's active participation; and α is the adjusting factor, which can be adjusted according to the patient's rehabilitation stage to adjust the sensitivity and enhance the robustness of control. This strategy can improve the active participation of patients in rehabilitation training and enhance the effect of neuromuscular remodeling.

2.5.4. Integrated application of control algorithms

In practice, adaptive impedance control, model predictive control and EMG-based closed-loop control work together in the rehabilitation robotic system. Adaptive impedance control ensures personalized support for patients at different stages of rehabilitation, model predictive control ensures the overall motion accuracy and coordination of the system, and EMG-based control enhances the active participation of patients. Through the combined application of these control algorithms, the rehabilitation robot can provide stable and efficient assistance in complex and changing training environments, maximizing the rehabilitation effect.

This integration of multiple control strategies allows the system to flexibly adjust to the real-time state of the patient, thus providing a personalized rehabilitation plan for each patient, enhancing the effectiveness and efficiency of rehabilitation training, promoting functional recovery and shortening rehabilitation time.

3. Results and analyses

3.1. Mechanical Structure Simulation

The key mechanical components of the rehabilitation robot were simulated and verified using the Motion and Simulation plug-ins in SOLIDWORKS. The force and deformation behaviours of each joint module under different motion conditions were analysed through simulation to ensure that the structural design has sufficient strength and stiffness during the rehabilitation process. In addition, the simulation also verifies the stability and reliability of the modular design interface to ensure the precise docking and functional stability of the joint modules during frequent disassembly and adjustment. As shown in Fig. 2, the structure can realise the bending action during the rehabilitation process.

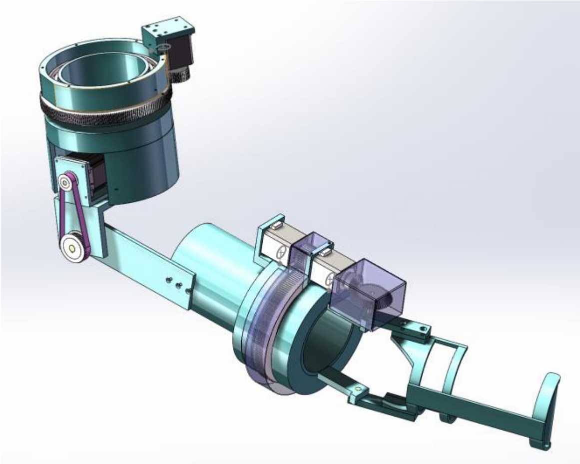

Figure 2. Motion Simulation of Mechanical Structures

The simulation results show that the robotic system has good flexibility and structural stability in the range of motion of each joint of shoulder, elbow and wrist. The maximum stresses of each joint during the simulated rehabilitation manoeuvres are lower than the yield strength of the material, verifying the safety and durability of the design.

3.2. Algorithm validation

To ensure that the algorithm can effectively regulate the dynamics of the rehabilitation robot, the algorithm needs to be computationally analysed. Assuming that the patient's EMG strength can represent the current patient's strength level, then when the patient's muscle activation is enhanced, as the EMG signal (E) increases, the stiffness (K) and damping (B) gradually decrease to help the patient to better control the movement; on the contrary, when the patient's muscle activity is weaker, as the EMG signal (E) decreases, the stiffness (K) and damping (B) gradually increase to provide more external assistance. Fig. 3 illustrates the graphs of stiffness, damping, and assist force overtime and EMG signal.

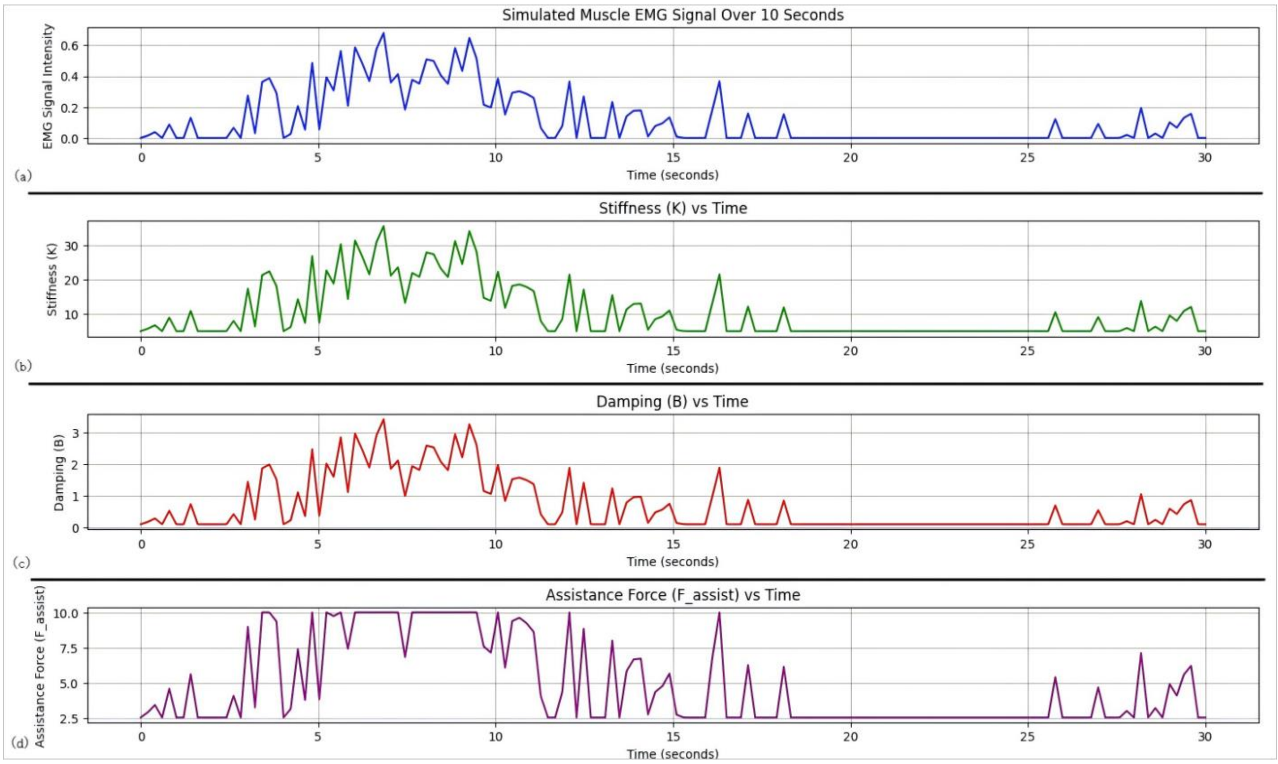

Figure 3. Algorithmic simulation data plot

It can be observed that: with the change of the patient's strength, the system is able to dynamically adjust the auxiliary force according to the EMG signal, stiffness and damping, and gradually reduce the external assistance to promote the recovery of the patient's voluntary movement ability. At the same time, the size of the auxiliary force has a certain limit to prevent secondary injury to the patient.

3.3. Experimental design

Position sensors are installed in the joints of a 4-degree-of-freedom upper limb rehabilitation robot, and EMG sensors are installed in the patient's large and small arms to obtain the patient's motor intentions. Multiple algorithms are used to optimize the control inputs and ensure dynamic adjustment of the robot's assistive force. The goal of the experiment is to optimise the control inputs through the MPC algorithm and the EMG control algorithm to enable the patient to gradually regain active locomotor ability, and at the same time to verify the effectiveness of the dynamic adjustment of stiffness and damping.

The stud assume that the patient is in the early stage of rehabilitation, with weak muscle strength, and the robot provides strong auxiliary force. The robot position and velocity are set to the initial state x_0, and the target state is set to x_{ref}, i.e., the patient is expected to reach the target position and stabilise at the target velocity. Before the formal experiment, the patient's EMG signals and motion trajectory data need to be collected through pre-experimentation, and the stiffness and damping parameters need to be adjusted individually.

Using the MPC control algorithm, the control inputs for each time step are derived through optimisation calculations. The control inputs are calculated based on the patient's current state (position, velocity, EMG signals) as well as the target state, with the goal of minimizing the positional error and the cost of the control inputs. The position and velocity are brought progressively closer to the target by adjusting the control inputs step by step for each calculation. The adjustment of stiffness and damping as well as the support of the patient's movements are observed during this process.

The results of the experiment should have the following phenomenon: the control inputs should be adjusted gradually over time, initially larger and gradually decreasing. As the patient's motor ability increases, the magnitude of the control inputs gradually decreases, indicating that the system successfully reduces the assisting force to the patient; the system is able to gradually guide the position and velocity to the target state x_{ref}, and the state error gradually decreases over time; as the patient's myoelectric signals increase, the assisting force (stiffness and damping) should gradually decrease, demonstrating that the system gradually reduces the support to the patient's movement to help them to recover their voluntary movement ability.

This experimental design has certain limitations, such as the performance of the motor and friction have multiple influencing factors [10]; EMG signals may be affected by noise and external factors, which may lead to the MPC control algorithm misjudging the patient's movement intention and affecting the control effect; there are individual differences in the patients, and the parameters of the algorithm may need to be adjusted individually according to the characteristics of different patients; the analysis of the EMG signal reading and MPC algorithms may face a high computational burden and require strong hardware support.

4. Conclusion

In this paper, an upper limb rehabilitation robot based on the concepts of modularity and lightweight is designed to enhance the rehabilitation effect of stroke patients. The strength and stiffness of the device were verified through mechanical structure simulation, the effectiveness of the algorithm was verified through testing, and experiments that can verify the sensor data with the training effect were designed. This study aims to ensure that personalized support is provided to patients at different stages of rehabilitation, which is superior in terms of safety, effectiveness and comfort.

This upper limb rehabilitation robotic system is expected to be widely used in home rehabilitation and community healthcare in the future, which will relieve the burden of healthcare providers and reduce the cost of rehabilitation for patients. Further improvement of the modular design and intelligent control unit will further increase the flexibility and adaptability of the device to better meet the individual needs of different patients.

On top of that, the robotic system uses machine learning algorithms, combined with virtual reality technology to enable it to offer a more immersive and tailored rehabilitation training experience, further improving the efficiency of rehabilitation. Future work will also seek to optimise the device weight and design, making it easier to wear and more comfortable for extended use. The upper limb rehabilitation robot has overall great potential to become a popular home rehabilitation device, which will contribute to the development of rehabilitation medicine.

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