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Mechanism Design and Compliant Control Method for Shoulder Joint Exoskeleton Robot

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Abstract:
This paper provides a comprehensive review of the research status of shoulder joint exoskeleton robots, focusing on analyzing their mechanism design and compliant control methods, and proposing improvement suggestions for existing shortcomings. Currently, shoulder joint exoskeletons primarily adopt three active degrees of freedom (DoFs) to mimic the motion characteristics of the human shoulder ball-and-socket joint, achieving rehabilitation or assistive functions through motor-driven or pneumatic-driven systems. Compliant control systems mainly include position-based impedance control and admittance control to ensure safe and natural human-robot interaction. However, these robots still have numerous shortcomings. Therefore, identifying current limitations and proposing optimization measures for future development by integrating cutting-edge technologies is crucial. This paper addresses the limitations in portability and non-visualized prediction, proposing optimized structural design and mechanical layout to enhance portability, as well as deep integration of multi-system compliant control with intelligent neural algorithms and the introduction of neural network or biomechanics-based predictive algorithms to improve predictability and human-robot interaction performance.

Keywords: Shoulder joint exoskeleton, mechanism design, compliant control.

1. Introduction

Stroke, also known as “cerebrovascular accident” or “brain infarction,” causes symptoms of hypoxia and ischemia in the brain, leading to impaired neurological function and disrupted nerve conduction, resulting in loss of voluntary control. It has a high likelihood of causing symptoms such as hemiplegia or partial paralysis [1]. According to data from the National Collegiate Athletic Association (NCAA) Injury Surveillance System, the risk of shoulder joint injury in post-stroke hemiplegic patients is signifi-

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cantly higher compared to the athlete population, with clinical studies indicating an incidence rate of shoulder joint injury in this group as high as 63% [2]. Traditional rehabilitation training, such as physical assistance provided by therapists, involves passive traction and repetitive exercises of the affected limb through manual techniques and treatment courses to stimulate nerve repair. While effective, this method is monotonous, time-consuming, and costly. Exoskeleton robots based on preset trajectories face issues such as fixed equipment modes, poor flexibility, low patient engagement, and inability to provide precise interventions tailored to individual differences, potentially even causing secondary injuries [1].

To enhance rehabilitation outcomes and better meet individual needs, recent years have seen the development of shoulder rehabilitation exoskeleton robots based on various structural designs, actuation methods, and compliant control strategies. These advancements have improved the robots' intelligence, safety, and adaptability. For example, in 2022, a team from the University of Wisconsin in the United States designed a shoulder rehabilitation robot equipped with three motors and two sliders. It can dynamically compensate for ICR (instant center of rotation) displacement, balancing natural movement and comfort, making it suitable for upper limb rehabilitation training [3]. In the same year, the team led by Zhanli Wang developed a fully motor-driven shoulder rehabilitation robot with three degrees of freedom. It features a compact and lightweight structure using parallel linkages and synchronous belt transmission, offering a motion range close to that of the human body and enabling precise rehabilitation training [4]. In 2020, the team led by Lucas D. L. da Silva developed an upper limb exoskeleton robot that integrates admittance-impedance control with electromyographic (EMG) signals. With two degrees of freedom and a lightweight structure, it can replicate human upper limb movements in real time with an average error of less than 4.3%, making it suitable for both rehabilitation and industrial applications [5].

However, these current robotic systems still exhibit certain limitations and offer room for further development. The primary objective of this paper is to review various classical mechanical structures of shoulder exoskeletons, compliant control systems, and recent cutting-edge shoulder exoskeleton robots. It aims to summarize the existing limitations of current shoulder exoskeleton technologies and propose suggestions for their improvement, thereby providing valuable insights and references for the future development of shoulder exoskeleton robots.

2. Mechanical Design

2.1 Pneumatic Actuation Mechanism Design

Shoulder exoskeletons based on pneumatic actuation utilize pneumatic muscle actuators (PMAs) driven by compressed air, integrating lightweight and ergonomic designs to optimize upper limb rehabilitation training. The robot adopts a serial configuration, with the shoulder joint comprising three orthogonal rotational joints—abduction/adduction, flexion/extension, and internal/external rotation—whose axes intersect at a single point, effectively simulating a ball-and-socket joint. Each joint is implemented using aluminum plate bearings, with steel cables connecting the PMAs to the ring shafts to enable unidirectional traction-driven motion. The abduction/adduction and flexion/extension motions rely on the user's arm for passive repositioning, while the internal/external rotation is assisted by a spring-based return mechanism [6].

The pneumatic muscle actuators (PMAs) are connected to the shoulder joint via steel cables. By compressing air, the PMAs contract axially, generating a unidirectional tensile force to drive joint motion. An improved Denavit-Hartenberg (D-H) method is adopted for the kinematic modeling, establishing a linear relationship between joint angles and PMA contraction lengths. Shoulder abduction, adduction, flexion, and extension are achieved by the PMAs pulling the outer or inner ring shafts, while internal and external rotation are passively restored to their initial positions with spring assistance, simplifying the design of antagonist actuators.

The high power-to-weight ratio of PMAs keeps the total system weight at only 5.6 kg. The shoulder structure is compact, portable, and low-cost, making it suitable for home-based rehabilitation. Kinematic analysis shows that the range of motion (ROM) of the shoulder joint is slightly below the normal human values (abduction/adduction: 150°/30°, flexion/extension: 110°/30°, internal/external rotation: 150°/45°), but still sufficient to support rehabilitation training for patients with high joint stiffness. Due to the nonlinear relationship between PMA contraction force and joint angle, precise design is required to meet the system's kinematic requirements. Safety is ensured by limiting the ROM of each shoulder joint [6].

Pneumatic actuation mechanisms are lightweight, offer high power density, and possess strong compliance. Their core component—the pneumatic artificial muscle (PMA)—is highly flexible and enables natural and safe motion control, making it well-suited for wearable devices by enhancing comfort and long-term usability. The mechanism features a simple structure that facilitates integration and maintenance while keeping costs low, making it ideal for rehabilitation and assistive training applications. However, the limited range of motion restricts its ability to perform complex tasks. As PMAs provide unidirectional actuation, additional components such as springs or the user's arm are required for return motion, reducing the flexibility of dynamic response. Furthermore, the compressibility of air and the relatively slow response of PMAs introduce control challenges. Long-term use also demands careful attention to air-tightness and component wear, which may impact system reliability and maintenance needs [6].

2.2 Motor-Driven Mechanism Design

Motor-driven shoulder exoskeleton robots utilize high-precision brushless motors and combine both active and passive degrees of freedom to accurately replicate the kinematic characteristics of the shoulder joint. The hybrid serial-parallel structure includes three orthogonal active rotational joints and two passive slider mechanisms, providing a total of five degrees of freedom. The sliders, implemented via linear bearings, compensate for the instantaneous center of rotation (ICR) of the shoulder, thereby enhancing the natural scapulohumeral rhythm and improving wearing comfort. However, this design also increases the system's overall weight and structural complexity [3].

An improved D-H method is used for kinematic modeling, with the axes of the three active joints defined to intersect at the instantaneous center of rotation (ICR). The passive sliders are modeled and analyzed through geometric constraints. For system dynamics, an iterative Newton-Euler approach is applied, accounting for factors such as mass, centrifugal force, gravity, and friction. This supports forward kinematics, torque modeling, and control strategies. Each active joint is equipped with a compact drive unit composed of an integrated brushless motor and harmonic reducer. Mechanical limits are implemented using shaft collars and split pins to ensure operational safety. In terms of control, the system employs computed torque control (CTC) based on the dynamic model, enabling high-precision closed-loop control that balances dynamic responsiveness and system stability. The trajectory tracking performance is exceptionally accurate, with a maximum error of just 0.02°, fully meeting the precision requirements of upper limb rehabilitation training. The system demonstrates excellent human-machine interaction capabilities and holds strong potential for practical engineering applications [3].

Compared to pneumatic actuation, motor-driven systems offer faster response, lower energy consumption, reduced noise, and greater control flexibility. They are also easier to maintain, and their modular design facilitates component replacement and system upgrades. However, these advantages come with certain trade-offs. Motor-driven systems tend to be more expensive, may suffer from inadequate heat dissipation, and often have limited torque output. Long-term use requires careful attention to the wear of reducers and sliding components. Computed torque control (CTC), while enabling high-precision performance, demands high modeling accuracy and real-time computational capability, which increases development complexity. To ensure a practical and scalable application, it is essential to optimize factors such as cost, thermal management, and maintenance accessibility [3].

3. Compliant Control System

3.1 Position-Based Impedance Control System

The position-based impedance control system is a core component of compliant control in shoulder exoskeleton robots. It aims to enhance joint compliance through force-position feedback, ensuring movement safety during rehabilitation training. This system integrates kinematic modeling, a force-position feedback mechanism, and a single-neuron adaptive PID controller to achieve precise and flexible control. Using the D-H method, a mapping is established between joint angles, limb weight, and human-robot interaction forces, providing a theoretical foundation for control. Force sensors capture real-time interaction forces, enabling the system to dynamically adjust the robot's motion trajectory to align with the patient's movement intent, while simultaneously preventing discomfort or injury. The single-neuron adaptive PID controller addresses the limitations of conventional impedance control, where fixed closed-loop parameters often lead to position errors. By adaptively adjusting parameters in real time, it enhances both control accuracy and system stability. The impedance control strategy is driven by joint interaction forces, modulating joint impedance characteristics. Its effectiveness has been verified through simulation experiments involving linear and circular movements in the sagittal plane [7].

Experimental results demonstrate that the system significantly enhances joint compliance and motion accuracy, supporting personalized rehabilitation for the shoulder, elbow, and wrist. However, force sensors may introduce measurement errors that affect control precision. The increased system complexity adds computational burden, requiring high-performance hardware to maintain real-time responsiveness. Additionally, the robustness of the adaptive parameter tuning still requires further optimization. Despite these challenges, the system's real-time

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responsiveness and its ability to ensure comfort and safety make it well-suited for clinical applications in upper limb rehabilitation robotics [7].

3.2 Admittance Control System

For shoulder exoskeleton robots, a hybrid impedance-admittance control system based on electromyographic (EMG) signals is an effective approach to achieving compliant control, with the admittance control playing a central role in shoulder joint regulation. The admittance system collects surface EMG signals from relevant shoulder muscle groups, such as the anterior deltoid and latissimus dorsi, combined with joint posture data obtained from gyroscopes. It calculates the target joint angles corresponding to the user's intended movements, driving the exoskeleton to perform the desired motions. The system assesses posture based on EMG signal intensity, employing the "Contraction for Maximum Angle (CMA)" method to normalize signals, thereby enhancing adaptability across different users. The admittance control module is implemented on a wearable microcontroller, offering fast response times and the ability to simulate user-initiated movements in real time. This makes it well-suited for assisting rehabilitation exercises involving shoulder flexion and extension [5].

Experimental results demonstrate that during unloaded shoulder joint movements, the system achieves an average error below 4.5%, exhibiting high stability and natural human-machine interaction. However, its drawback lies in relatively weak resistance to external disturbances; under varying loads or environmental interferences, position deviations tend to occur. Therefore, impedance control is introduced as a compensation mechanism to correct angle errors caused by load variations under admittance control, enhancing the overall system stability and compliance [5].

4. Discussion

4.1 Limitation

For shoulder exoskeleton robots, the ultimate development goal should focus on achieving everyday usability and portability, allowing patients to integrate rehabilitation with daily life activities, thereby improving rehabilitation continuity and quality of life. However, most shoulder exoskeleton devices currently deployed in practical applications still rely on fixed mechanical structures, lacking portability and mobility, which makes them unsuitable for home rehabilitation or daily assistive use.

Although various wearable shoulder exoskeleton prototypes have emerged in recent years, effectively addressing the overall system weight remains a challenge for performance enhancement. For example, the state-of-the-art AE4W shoulder exoskeleton robot weighs approximately 10 kg. Through its active control system, AE4W can dynamically adjust the level and mode of assistance according to different tasks, adapting to complex and variable industrial environments. Its highly biomimetic structure imposes almost no restriction on the natural range of shoulder motion. The system integrates multi-level safety mechanisms and torque sensors to ensure high-precision assistance while guaranteeing safe human-machine interaction, thus establishing a high-performance framework. However, its excessive weight still leads to user fatigue and decreased comfort during prolonged wear [8].

Furthermore, in compliant control systems, damping compensation serves as a core module that can alleviate impacts and errors during human-machine interaction to some extent. However, existing control strategies generally lack real-time predictive visualization capabilities for user behavior and external disturbances. This non-feedforward passive response mechanism may cause control delays or cumulative errors in complex environments, thereby increasing the risk of secondary injuries to patients. Therefore, developing lightweight, intelligent shoulder exoskeleton systems with advanced predictive capabilities is a critical direction for future research breakthroughs.

4.2 Outlook and Improvements

First, the future development of shoulder exoskeletons should focus on achieving a balance between lightweight design and portability to meet the demands of daily rehabilitation and diverse application scenarios. In terms of structural design, integrating modular and foldable mechanisms can effectively simplify the mechanical system, reduce redundant structures and drive components, and thereby control the overall device weight to under 5 kilograms, enhancing wearability and user comfort. At the same time, priority should be given to positioning motors and drive units close to the human body's center of mass. Coupling this with flexible transmission methods, such as flexible shafts, can reduce the system's dynamic inertia load, improving stability and coordination during movement [8]. Moreover, an exoskeleton structure with high adjustability, lightweight characteristics, and ease of operation will better accommodate users of various body types and complex working environments, thereby increasing its practicality and adaptability.

Second, regarding control strategies, future research will focus on the deep integration of multi-system compliant control and intelligent neural algorithms. This involves combining various compliant control methods, such as impedance control, admittance control, and torque tracking, along with the fusion of multimodal sensor data inputs. For example, the NuExo shoulder exoskeleton robot utilizes a six-degree-of-freedom force sensor to capture real-time human-machine interaction forces. It adapts stiffness and damping parameters dynamically, achieving a natural "human-leading, machine-following" collaboration. Additionally, NuExo integrates multiple sensors, such as joint encoders and inertial measurement units (IMUs), to simultaneously collect environmental and interaction data, constructing a high-precision heterogeneous dataset that significantly outperforms traditional motion capture systems. Furthermore, its control intuition is enhanced through augmented reality (AR) headsets, improving user experience and operational precision [9].

Furthermore, exoskeleton systems can dynamically adjust control modes and response sensitivities according to different task scenarios, significantly enhancing the naturalness of human-machine interaction and control accuracy. Moreover, by incorporating neural networks or biomechanics-based predictive algorithms, real-time decoding of user movement intentions and trajectory prediction can be achieved. These models can be trained to learn the relationships among electromyographic signals, posture changes, and external force feedback, enabling anticipatory planning and adaptive control of complex motions. This ensures stable and precise control performance even in the face of environmental disturbances and task variations. The development of such control architectures is expected to greatly advance the intelligence level of exoskeleton devices, providing both theoretical and technical support for personalized rehabilitation training and complex assistive operations.

5. Conclusion

This study integrates classic shoulder exoskeleton robotic mechanism designs with compliant control systems. Starting with the classic three-active-degree-of-freedom spherical structure that mimics the shoulder joint, it analyzes the advantages of two typical drive modes: motor-driven and pneumatic-driven systems. Next, it introduces and evaluates the classic position-based impedance control and admittance control systems, highlighting their respective strengths. Finally, based on the analysis of traditional mechanisms, compliant control systems, and cutting-edge technologies, the study identifies the primary current limitations as poor portability and a lack of visual predictive capabilities. It proposes further optimization of structural design by incorporating advanced technologies, introducing neural network-based predictive algorithms, and integrating multiple compliant control strategies. These improvements aim to enhance both the portability and intelligence level of shoulder exoskeleton structures, thereby making more significant contributions to shoulder joint rehabilitation.

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