The Development and Prospect of Shoulder Flexible Exoskeleton Structures

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Abstract. The emergence of flexible exoskeletons has provided new ideas for the treatment and rehabilitation of various diseases. The development of shoulder flexible exoskeleton structures is a topic of great research value and potential in the field of exoskeleton research. This paper aims to analyze and prospect the development of shoulder flexible exoskeleton structures. By comparing and analyzing the representative achievements of each key technology in the structure and support system, drive and transmission system, and sensing and control system, the advantages of different achievements are derived. By reviewing the development process of shoulder flexible exoskeletons, it is proposed that flexibility, lightweight, and intelligence are the development trends of shoulder flexible exoskeletons. It is also suggested that a standardized evaluation system should be established to facilitate researchers to intuitively experience the performance of different products. By focusing on the existing problems, it is pointed out that the key points of research on the flexible exoskeleton structure of the shoulder mainly lie in improving the mechanical structure of the flexible exoskeleton, coordinating the driving mode, human-computer interaction, and motion intention recognition, as well as the comfort of use.

Keywords: Shoulder flexible exoskeleton, mechanical structure of flexible exoskeleton, flexibility.

1. Introduction

Upper limb dysfunction is a common sequela after neurological and musculoskeletal diseases, seriously affecting patients' ability to perform daily activities and their quality of life. As the most flexible and largest range joint complex in the human body, the shoulder joint plays a core role in upper limb function, and its rehabilitation and assistance needs are huge and urgent. Traditional rehabilitation therapy is highly dependent on the manual operation of therapists and has limitations such as difficulty in quantifying intensity, low efficiency, and high labor costs.

In recent years, robot-assisted technology has brought changes to rehabilitation medicine. Exoskeleton robots, especially flexible exoskeletons, have become a cutting-edge research direction in the field of rehabilitation engineering and assistive assistance due to their outstanding advantages such as light weight, good compatibility with the human body, and high intrinsic safety. Compared with the research on single-degree-of-freedom joints such as the wrist and elbow, the shoulder exoskeleton has become a bottleneck for technological breakthroughs due to its extreme complexity and the difficulty of bionic adaptation.

This article introduces various technical systems of flexible exoskeletons and the development of shoulder flexible exoskeletons. It analyzes the research trends of shoulder flexible exoskeleton structures from three research perspectives: structural design, driving methods, and human-computer interaction, and puts forward prospects to provide ideas for the development of related technologies of flexible exoskeletons.

2. Introduction to Various Technical Systems of Flexible Exoskeletons

The exoskeleton system is divided into three categories. The first one is the structural and support system, which serves as the skeleton and skin of the exoskeleton system. Then there is the drive transmission system, which consists of the muscles and tendons of the exoskeleton. The last one is the sensing and control system, which is the nervous system and brain of the exoskeleton.

The relationship between these three types of systems and the human body is shown in Fig. 1.

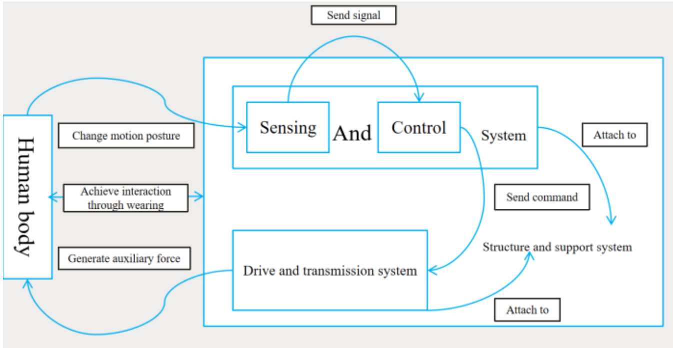

Fig. 1 The relationship between the human body and various systems (Original)

The detailed introductions of each system are shown in Table 1.

Table 1. Introduction to each system

Classification of systems	Design key/key technologies	Components/materials that can be designed	Advantage	The Challenges
Structure and support system	Material selection	Flexible substrate material	Breathable, lightweight, soft, comfortable, and anti-slip	/
		Rigid reinforcing material	It has a certain structural strength and can provide protection at key parts.	/
	Structural form design	Bionic package design	It has strong comfort and can better fit the human body	/
		Modular design or integrated design	The former is detachable and highly flexible, while the latter offers better integrity and comfort.	/
Drive and transmission system	Drive system	Motor drive	High control accuracy, fast response speed, and mature technology	Its own weight is large. If it is directly installed on a limb, it will increase inertia and affect the naturalness of movement.
		Pneumatic artificial muscle	It features an extremely high power-to-weight ratio and a flexible body that is safe.	It requires carrying a gas source, has a relatively slow response speed, and a complex control system.
		Shape memory alloy	Extremely quiet and compact in structure	Low efficiency, slow response, and thermal delay
	Transmission system	Cable drive	The transmission mode is flexible. It almost does not restrict the freedom of joints,	There are frictional losses and elastic hysteresis.

			allowing heavy drives to be placed far from the limbs, significantly reducing the load on the extremities.	
		Tendon transmission	Lighter and more flexible than metal cables	The material has creep and durability issues
		Connecting rod mechanism transmission	It has high transmission efficiency and precise control	It will increase the rigidity of the system and may reduce comfort
Sensing and control system	Sensing system	Electromyographic signal/mechanical sensor	It can capture the user's movement intention before the muscles actually generate force and the joints start to move.	/
		Inertial Measurement Unit (IMU)	It can quickly capture the click movement state	/
	Control system	Force-based control	Fast reaction speed	Not intelligent enough to recognize the user's specific actions or special intentions
		Control based on impedance or admittance	It has a wide range of application scenarios and is easy to design	
		Adaptive control	The realization of personalized assistance is often closely related to intelligent algorithms, with flexible usage methods, diverse application scenarios, and a fast response speed.	There are certain difficulties in writing the algorithm level.

3. Overview of Structural Design and Development of the Shoulder Flexible Exoskeleton

3.1. Early Shoulder Joint Exoskeleton Design and the Challenges it Faces

3.1.1 The complexity of the shoulder joint

The connection part between the human trunk and the upper limbs is usually the shoulder joint in a broad sense, which contains the clavicle and the connection area between the scapula and the sternum. The entire shoulder structure is included. In a narrow sense, the shoulder joint refers to the joint between the scapula and the upper arm bone, which is usually called the glenohumeral joint. The glenohumeral joint is mainly composed of the humerus, glenoid, and joint capsule. It has a large range of motion and high flexibility, which directly affects the motor function of the upper limb. In the design of upper limb rehabilitation exoskeletons, the shoulder joint generally refers to the narrow sense of the shoulder joint [1].

The shoulder joint is a spherical joint, featuring three degrees of rotational freedom: adduction/abduction, flexion/extension, and internal/external rotation, as well as one degree of mobility: shrugging. As shown in Fig. 2.

Fig. 2 Display of shoulder joint degrees of freedom (Original)

The movement patterns and limit ranges of each shoulder joint are shown in Table 2.

Table 2. The movement patterns and limit ranges of each shoulder joint [1]

Exercise methods	Benchmark reference	Limits of movement	
Shoulder joint adduction/abduction	Sagittal plane	(0°, 40°)	(0°, 110°)
Shoulder joint flexion/extension	Coronal plane	(0°, 50°)	(0°, 175°)
Shoulder joint internal/external	Sagittal axis	(0°, 90°)	(0°, 80°)

The table provides the movement limits of the shoulder joint in various directions on the reference surface, reflecting its relatively large range of motion. It can be said that the shoulder joint is a joint in the upper limb of the human body that is used frequently, has a rather complex movement form, a relatively large range of motion, and is very flexible.

3.1.2 Early design of shoulder joint exoskeletons

The earliest upper limb exoskeletons mostly adopted rigid connecting rod structures in series or parallel to imitate the movement of the human shoulder joint. Its structure and support system are mostly made of rigid materials, and the sensing and control systems are mostly surface-mount sensors [2]. For instance, in 2005, Arizona State University developed an upper limb rehabilitation wearable device named RUPERT. It is driven by pneumatic muscles and can help patients complete the four basic movements of the shoulder, elbow, forearm, and wrist. It is mainly used to assist patients with upper limb movement disorders in their daily activities. RUPERT can provide passive assistance during activities, which helps maintain the patient's sense of movement and promotes the recovery of brain function. The device is equipped with position and pressure sensors on the shoulders and wrists, which can automatically adjust the assistance size according to the pressure changes during limb movement. This design pursues high precision, high load capacity, and good controllability, but simple rotary joints are difficult to accurately reproduce this compound motion with multiple degrees of freedom and instantaneous changes in the rotation center [3].

Rigid exoskeletons also have many problems in human-machine matching. For instance, it is difficult for the fixed rotational center of a rigid exoskeleton to always be consistent with the instantaneous rotational center of the human shoulder joint. This will lead to motion interference and limit the user's natural range of motion. It will also generate additional forces/moments, causing force interaction between the human and the machine. In mild cases, it may lead to discomfort and fatigue; in severe cases, it may cause secondary damage.

Although it can be optimized through anthropomorphic multi-degree-of-freedom design (such as the mechanical structure of the five-degree-of-freedom multi-link shoulder rehabilitation exoskeleton) or passive compensation mechanisms (such as the parallelogram mechanism), the structure often becomes complex and bulky, and the issues of wearing comfort and safety remain prominent.

3.2. The Introduction and Development of the Concept of Flexibility

To overcome the drawbacks of rigid exoskeletons, researchers have turned their attention to flexible materials and related technologies, with the core goal of making the system lighter, more compliant, and safer [4]. At this time, flexible materials such as high-strength textile fibers gradually emerged in the selection process of the structure and support system of the mechanism, which are usually used to make the fastening layer that fits the human body parts.

In 2017, Walsh's team at Harvard University developed a flexible wearable exoskeleton for the shoulders [5]. This device employs two types of specially designed flexible pneumatic components: one is installed under the armpit to assist in shoulder abduction; Another is installed on the outer side of the chest to assist in the horizontal flexion and extension of the shoulder, thereby providing support and assistance for the movement of the upper limbs. The study evaluated the effect by measuring the muscle electrical signals of the subjects when they completed specific movements before and after wearing the device. The data show that the activity levels of all the tested muscles, including the infraspinatus, pectoralis major, and deltoid, have significantly decreased. For instance, when performing the movement of arm abduction and horizontal extension, the muscle activity of the posterior deltoid muscle is significantly reduced regardless of whether the arm is burdened or not, with the maximum reduction exceeding 65% [5]. These results prove that the exoskeleton can effectively support the arm and reduce the burden on the related muscles [5].

Meanwhile, flexible and elastic drive joints are widely selected. Designers introduce elastic elements (such as springs) at the output end of the drive or at the joint to imitate the passive elasticity of muscles and tendons, thereby better absorbing energy, reducing impact, effectively weakening the possible harm to the limbs caused by driving starts, stops, and speed fluctuations, and enhancing safety and comfort [6-8]. Professor He Fuben and his team from Dalian University of Technology, in response to the requirements of flexible movement of robot joints, combined the advantages of the SEA drive form and the muscle-tendon model, and referred to the musculoskeletal structure of human joints, designed a robot joint that mimics muscle elasticity drive. The shoulder joint is driven by the SEA actuator, and the joints are connected by passive traction springs, that is composed of a spring group with an antagonistic structural form that mimics muscles and tendons. The average position control error is approximately 1.5 °, basically achieving the design goal of the drive control system [9].

With the rapid development of flexible machinery, the application of new flexible actuators, namely soft robot technology, has been put on the agenda. Common new types of flexible actuators, such as pneumatic artificial muscles, generate tension through inflation and deflation. They have a high power-to-weight ratio and inherent flexibility, but they require an air source and have a relatively slow response speed. In 2000, the German company Festo launched a series of bionic pneumatic tendons. This marks that pneumatic artificial muscles have officially become a standard industrial actuator, ushering in their commercial era [10][11].

Based on the above introduction to flexible components, Table 3 is drawn to discuss the basic situation of each design route, such as its technical type, core principle, advantages, challenges faced, and application prospects.

Table 3. The technical features, advantages, and disadvantages, and applicable scenarios of three types of flexible components

Technology type	Core principle	Advantage	Challenges faced	Potential application scenarios
Remote line drive (Bowden line)	Power is transmitted through cables by means of motors and other drivers away from the joints.	It reduces the load on the distal limbs and has a relatively simple structure.	There will be frictional losses, elastic hysteresis will occur, and the control accuracy will be easily affected.	An upper limb-assisted exoskeleton system that requires weight reduction.
Flexible and elastic joints combined with the SEA drive	Introduce elastic components (such as series elastic drives, etc.) into the drive system to achieve shock absorption.	Buffer shock, enhance safety and comfort.	The parameter design is complex and may introduce resonance.	Rehabilitation training, scenarios that require better joint protection.
Pneumatic artificial muscle	Pneumatic artificial muscles inflate and contract to generate tension, driving various mechanisms.	High power-to-weight ratio, inherent flexibility, and relative safety.	It requires an external air source, has a relatively slow response speed, and a complex control system.	Rehabilitation training, long-term bed rest, and other occasions with high comfort requirements.

4. Problem Optimization and Outlook

Based on the above discussion, in the face of higher requirements for data accuracy, the demand for lightness and flexibility, and the need for more complex computing systems to predict user behavior, the future development of exoskeletons will present three trends: deepening the degree of perception and cognition, innovating the way of fit, and upgrading the logic of intelligent computing.

Sensors need to shift from discrete sEMG and IMU sensors to large-area, high-density flexible electronic sensing skin, continuously and globally capturing physiological and motion information. Drivers need to develop towards high-performance soft actuators. In the future, pneumatic muscles are expected to break free from the constraints of air sources. Intelligent arithmetic units can be integrated with artificial intelligence, thereby being upgraded to personalized adaptation systems driven by big data statistics. By establishing a virtual model of the user, AI can simulate the effects of different control parameters in the cloud and recommend and load the optimal auxiliary strategies for the user in real time.

Furthermore, although flexible exoskeletons have a promising future, research suggests that there is a lack of a unified and comprehensive evaluation system in this field at presentOne paper may report a "maximum reduction of 65% in muscle activity", while another emphasizes an "increase in range of motion", making it difficult to make a fair comparison between studies [5, 11]. The industry needs to establish a multi-dimensional technical level evaluation system, which should at least include: biomechanical efficacy (myoelectric reduction rate, changes in metabolic costs); Task performance (completion time, accuracy); Human factors engineering (wearing time, subjective comfort score, psychological burden) System performance (weight, battery life, noise). This approach helps guide the research in this field to move from pursuing a single indicator to balanced development.

5. Conclusion

This study focuses on the structural design of the flexible exoskeleton for the shoulder joint and systematically reviews its technological evolution from rigid configuration to flexible bionics. Research indicates that flexibility, lightweighting, and intelligence are the main development trends of shoulder flexible exoskeletons in the future. Through continuous innovation and exploration of key technical solutions such as drive transmission, structural materials, and perception control, the fundamental path to address challenges is to keep exploring. This article, by sorting out the key parts among the three critical systems, points out the challenges faced by the components of each system. With the development of multiple disciplines, issues such as material properties and human-computer interaction can be well addressed. Ultimately, the ideal system will become an imperceptible and enhanced second skin on the user's body, truly achieving the symbiotic integration of humans and machines.

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This paper provides a systematic review of the development of flexible shoulder exoskeletons, focusing on representative achievements in key technologies such as structure and support systems, drive and transmission systems, and sensing and control systems, and summarizing the advantages of different solutions. The authors point out that flexibility, lightweighting, and intelligence are the development trends of flexible shoulder exoskeletons, and propose establishing a standardized evaluation system for direct comparison of the performance of different products. The paper also identifies key research areas for addressing existing problems, including mechanical structure optimization, drive mechanism coordination, human-computer interaction and motion intention recognition, and wearing comfort. With a clear overall structure, comprehensive analysis, and significant forward-looking perspective, this paper has high reference value and is recommended for direct acceptance.