Wearable Exoskeleton Robots Based on Human-machine Coupling Systems

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Abstract. The normal functioning of the human limbs is crucial to health, and any impairment of their function can lead to severe mobility issues. Disability of any degree significantly impacts daily life. Although assessment and treatment systems based on robotic exoskeletons have demonstrated positive results over the past two decades, there are still areas in applied research that require further exploration. In recent years, flexible exoskeleton human-machine intelligent systems have emerged as a new hotspot in interdisciplinary fields such as robotics, mechatronics, control engineering, bioengineering, and artificial intelligence. Their applications in scientific research, industrial manufacturing, deep space and deep sea exploration, entertainment, rehabilitation medicine, and daily life are continuously expanding. The core of this technology lies in human-machine integration, aiming to fuse human intelligence with machine capabilities. Through deep coupling at the perception, decision-making, and execution levels, the system's overall performance is enhanced. Among these, teleoperated and power-assisted exoskeletons constitute the two key branches of the flexible exoskeleton human-machine intelligent system. Recent technical explorations and product developments both domestically and internationally have demonstrated its profound foundational research value and vast application potential. This article centers on the human-machine coupling system of exoskeleton robots, based on human body structure analysis, and provides an overview of existing research findings, current technical challenges, and future trends both domestically and internationally.

Keywords: Wearable; Exoskeleton Robot; Human-machine Coupling System; Challenges and Prospects.

1. Introduction

Normal limb function plays a critical role in maintaining human health. Any temporary or permanent impairment of limb function can lead to severe mobility impairments. As the global population ages, older adults face increasing challenges in daily activities, and currently, diseases related to disability are experiencing rapid growth worldwide. The World Report on Disability indicates that approximately 15% of the global population experiences various types of motor function abnormalities, with 4% suffering from conditions related to motor or neuromotor function abnormalities [1]. Regardless of the severity of the disability, it impacts an individual's daily life. Additionally, certain underlying factors may increase the likelihood of disability. Traditional rehabilitation services and technology-based rehabilitation services have limited coverage, there is poor coordination between care institutions, and existing specialists are overburdened with work. From the perspective of rehabilitation therapy, the effectiveness of traditional therapies depends on the therapist's professional competence, experience in treating similar cases, and the ability to develop effective rehabilitation plans. Typically, there is a lack of timely, adequate, and objective analysis of patients and their rehabilitation progress, making it difficult to accurately assess the effectiveness of rehabilitation interventions. Although assessment and treatment systems based on robotic exoskeletons have been in use for nearly two decades and have achieved relatively positive results in the field of rehabilitation, there are still areas of application research that require further exploration. During the design process of rehabilitation technologies, complete or partial clinical trials are often not conducted, meaning that these technological achievements cannot be directly applied in medical or rehabilitation centers. This is crucial for promoting the implementation of these technologies in

clinical practice. This provides new opportunities for the development of stable and reliable systems that can restore motor control capabilities lost due to accidental injury or disease. The use of active devices in rehabilitation therapy has been proven feasible, and their direct benefits are not limited to patients with motor or neuromotor impairments. They also demonstrate value in other areas where human movement plays a significant role and in optimizing medical resources [2]. This paper reviews the biomimetic design principles of exoskeleton robots, the current state of research on human-machine coupling systems both domestically and internationally, technical challenges, and future trends, based on an analysis of human anatomy.

2. Bionic Design Principles for Exoskeletons

Wearability is a core attribute of exoskeleton systems, which rely on close physical coupling between exoskeleton joints and human limb joints to ensure that the two move as a single unit. Therefore, the structural design of flexible exoskeletons must follow the principles of human joint movement and establish bionic design criteria for the system. These principles aim to achieve lightweight, wearable convenience, and smooth movement of the exoskeleton while ensuring the wearer's comfort and operational safety.

For human limb modeling, researchers have proposed models of varying complexity to accommodate diverse analytical requirements. In simple scenarios where only joint forces or torques need to be obtained, human limbs can be simplified into multi-body open-chain or closed-chain structures. When the model needs to incorporate joint stiffness and damping characteristics, a second-order stiffness-damping system model is appropriate for representation. For more detailed analysis, such as quantifying the force states of individual muscle bundles within a joint, a high-complexity model incorporating muscle mechanical properties must be constructed [3].

3. Exoskeleton robots based on human-machine coupling systems

3.1. Human upper limbs

Among the skeletal muscle systems of the human upper limbs, the shoulder joint structure is the most complex. Early studies relied heavily on empirical conclusions, suggesting that abduction/adduction movements of the shoulder originate from the elevation and depression of the clavicle and scapula. Hoegfors et al. optimized the previously proposed passive damping joint cone model by describing the force states of muscles within the joint, thereby constructing a more comprehensive shoulder kinematic model as shown in Figure 1 [3].



Fig. 1 Multi-rigid body motion model [3]

In the model established by Van der Helm, the upper limb is described as a multi-body system comprising bones, muscles, and soft tissues, with each body connected by ideal frictionless kinematic joints. Bones are connected via ball-and-socket joints; the joint formed by the scapula and thoracic wall constitutes a three-body structure, whose movement is constrained to an ellipsoidal surface; all muscles and ligaments are simplified into linear or curved models based on their functions. The primary forms of movement at the shoulder joint include: abduction/adduction, flexion/extension,

internal/external rotation, and circumduction. Among these, circumduction can be considered a composite of abduction/adduction and flexion/extension movements.

Compared to the shoulder joint, the elbow joint only has the degree of freedom for flexion/extension and can be simplified as a hinge joint. The mechanism of its flexion/extension movement is as follows: contraction of the biceps brachii muscle and relaxation of the triceps brachii muscle cause flexion; conversely, relaxation of the biceps brachii muscle and contraction of the triceps brachii muscle drive extension movement.

The wrist joint has a unique structure. From an anatomical perspective, the wrist joint's movement units can be divided into two relatively independent parts: the upper part consists of the radius and ulna of the forearm, connected to the elbow joint. Under the action of related muscle groups, the radius and ulna rotate relative to each other, driving the wrist joint to perform internal and external rotation movements. The lower part connects to the palm and primarily performs abduction/adduction and flexion/extension functions.

The palm and finger region is the area of the human body with the densest distribution of joints. According to the model proposed by A. Morecki, this region comprises a total of 20 degrees of freedom.

Numerous research institutions worldwide have developed exoskeleton rehabilitation systems with diverse functionalities. The WristBot wrist rehabilitation device developed by the Assistive and Rehabilitation Robotics Laboratory at the Italian Institute of Technology (IIT) [4] can perform wrist joint flexion/extension, radial deviation/ulnar deviation (left/right bending), and forearm pronation/supination composite movements. The InMotion upper limb rehabilitation robot developed by BioMech Labs in Toronto features a fixed frame structure and integrated visual feedback components; its interactive gamified training enhances rehabilitation therapy outcomes. Professor Sun Lining's team at Harbin Institute of Technology designed an exoskeleton-type upper limb rehabilitation robot system to assist patients in functional training of the shoulder and elbow joints [5]. Professor Guo Chao's research team at Wuhan University proposed a flexible upper limb exoskeleton solution, which reduces system complexity by physically separating the actuators from the robot joints and employs impedance control strategies to regulate the rehabilitation training process [6]. Chen Yong et al. from Dalian Jiaotong University developed a walking exoskeleton robot for the elderly based on biomimetic principles [7]. By constructing a human-machine coupled dynamic model, they conducted an in-depth study of its gait characteristics under flat walking conditions, providing key kinematic basis for biomimetic coupled design of exoskeletons. Wang Wending et al. from Northwestern Polytechnical University proposed a biomimetic control method for exoskeleton arms based on human movement intention recognition [8], as shown in Figure 2, and designed a corresponding movement intention perception system. This scheme optimizes control signal quality and uses posture sensors to predict human movement intentions to reproduce daily activity trajectories, significantly improving the naturalness and fluidity of human-machine interaction.

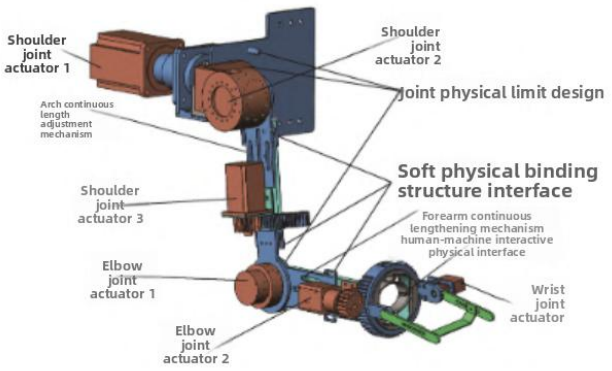


Fig2. Wang Wending et al. proposed a 6-degree-of-freedom exoskeleton structure [8]

3.2. Lower Limbs

Based on anatomical principles, an analysis of the structure of the human lower limbs reveals that their motor functions are primarily achieved through the coordinated action of the skeletal system, muscle tissue, and the joints connecting the bones. During lower limb movement, the skeleton provides support, muscle contraction generates the force to drive limb movement, and the coordinated changes in joint angles enable the lower limbs to assume various postures. The hip joint, knee joint, and ankle joint are the three most critical joints: the hip joint has the widest range of motion; the knee joint has the most complex structure, with its actual movement involving a combination of rotation and sliding components; and the ankle joint exhibits the highest flexibility [9].

The hip joint is formed by the femoral head fitting into the acetabulum of the pelvis, constituting a typical ball-and-socket joint structure. This joint centers on the femoral head and can move within three basic anatomical planes, playing a crucial role in maintaining dynamic stability and bearing the load of the upper body.

The knee joint, as a gliding joint, is composed of the distal end of the femur, the proximal end of the tibia, the patella, and the articular cartilage of the joint cavity. Typically, only flexion/extension movements within the sagittal plane are considered [10].

The ankle joint is formed by the distal ends of the tibia and fibula and the articular surface of the talus, as shown in Figure 3. This joint bears nearly the entire body weight and serves dual functions of maintaining stability and cushioning ground impact during movement. During normal gait, the ankle joint primarily performs flexion/extension movements around the coronal axis; when walking on uneven terrain to maintain balance, it generates adduction/abduction movements around the sagittal axis; and during directional adjustments, it involves internal/external rotation movements around the vertical axis. Therefore, the ankle joint is generally considered to have three degrees of freedom, as shown in Figure 3 [11].

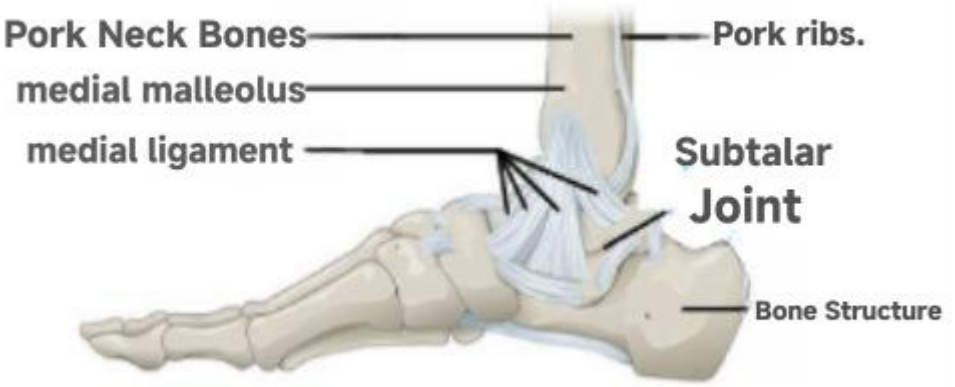


Fig. 3 Ankle joint [11]

Based on the patient's body posture during training, lower limb rehabilitation robots can be primarily categorized into two main types: standing-type and sitting/lying-type. Sitting/lying-type lower limb rehabilitation robots allow patients to undergo training in a supine or seated position. Their significant advantage lies in the fact that the lower limbs do not need to support the weight of the upper body during training, making them particularly suitable for the rehabilitation needs of patients in the early to mid-stages of stroke onset [12]. The Motion Maker device developed by the Swiss Federal Institute of Technology is equipped with bilateral exoskeleton mechanical legs, supporting lower limb rehabilitation training in supine, semi-supine, and seated positions. Its limitation lies in the fact that the length of the mechanical legs can only be adjusted manually; the COCOROE robot developed by Yaskawa Electric Corporation in Japan can simulate the techniques of professional

physical therapists, using an end-effector traction method to provide six training modes supporting unilateral lower limb training. Yanshan University's multi-joint lower limb rehabilitation robot can perform active and passive training along pre-set trajectories. It is the first product of its kind in China to obtain Class II medical device registration certification and has been deployed in the rehabilitation departments of multiple hospitals. Beijing Institute of Technology's seated mobile rehabilitation robot is designed for home and nursing home applications, integrating mobility assistance and rehabilitation training functions. It is currently in the industrialization promotion phase.

4. Technical Challenges and Development Trends

Despite significant progress in exoskeleton robot research, it still faces numerous constraints, with inadequate human-machine interaction comfort and poor collaborative control compliance constituting the two major technical bottlenecks. The key to improving human-machine interaction comfort lies in accurately characterizing the human-machine coupled motion relationship and establishing corresponding dynamic models. Traditional modeling approaches simplify the human lower limbs into rigid links and treat the human-machine system as a single entity without relative displacement [13], which fails to effectively represent real-world interaction behaviors. Other studies have attempted to construct detailed musculoskeletal models, but this process is complex and time-consuming, making it difficult to quickly adapt to patients with different body types, thereby limiting practical applications. Enhancing the flexibility of cooperative control Conventional control strategies such as PID, impedance control, and force/position hybrid control have limitations when applied to actual training scenarios. Patients may experience spasms or uncontrolled tremors, leading to rapid, nonlinear random fluctuations in human-machine interaction forces. These methods struggle to dynamically respond to and adjust for sudden changes in load, failing to meet the high-load, high-dynamic performance control requirements of robots. Introducing feedforward control strategies to dynamically compensate for system control quantities and reduce current loop control cycle deviations is an effective approach to enhancing human-machine collaborative control performance.

As modern society continues to develop, the application scope of exoskeleton robotics technology will expand into various dimensions of human production and daily life, with extremely broad prospects for development. Currently, exoskeleton robotics technology is primarily applied in three major fields: military, medical rehabilitation, and civilian assistance. Exoskeleton technology demonstrates significant potential in enhancing individual soldier combat effectiveness. For example, the next-generation individual soldier combat exoskeleton system not only integrates an independent power supply unit and human protection functions but also combines advanced weapon platforms, modern communication and sensing networks, and life support systems, thereby transforming ordinary soldiers into “highly enhanced combat units” with exceptional combat capabilities [11]. In the field of neural function reconstruction, rehabilitation robots have become a cutting-edge research hotspot at the intersection of medicine and engineering due to their high training efficiency. Breakthroughs in this technology are reflected in optimized human-machine interaction interfaces, enhanced intelligence levels, and improved precision control capabilities, making them more suitable for the rehabilitation needs of people with disabilities and the elderly. For patients requiring long-term, regular movement intervention, this marks a major innovation in rehabilitation models. Additionally, exoskeleton devices empower individuals with limb dysfunction and the elderly to achieve self-sufficiency in daily living. Against the backdrop of China's accelerating aging population, the widespread adoption of this technology will effectively alleviate the resulting pressure on care resources and social security burdens [14].

5. Conclusions

This paper reviews the biomimetic design principles of exoskeletons, summarizes their development history and current state-of-the-art, conducts an in-depth analysis of structural design

methods based on the anatomical structure of the human upper and lower limbs, identifies current technical challenges, and outlines prospects for future development. In summary, wearable exoskeleton robots based on human-machine coupling systems have made significant progress in design and implementation, but still face numerous technical challenges. Exoskeleton robot technology demonstrates immense application potential and social value across broad fields such as military enhancement, medical rehabilitation, and civilian assistance, yet its development remains constrained by critical technical bottlenecks. The core challenges lie in enhancing human-machine interaction comfort and optimizing the compliance of collaborative control. The former requires breaking through the limitations of traditional rigid models and developing more precise and practical human-machine coupling dynamics modeling methods; the latter demands transcending conventional control strategies to effectively address sudden fluctuations in human-machine interaction forces and nonlinear load changes, and exploring the introduction of dynamic compensation mechanisms such as feedforward control to enhance system response performance. Continuously overcoming these technical challenges is key to enabling exoskeleton robots to serve human production and daily life more widely and efficiently. Future research should focus on addressing the shortcomings in human-machine interaction comfort and collaborative control compliance to achieve more intelligent, personalized, and comfortable human-machine coupling systems. As technology continues to advance, wearable exoskeleton robots will play an increasingly important role in more fields, providing humans with more convenient and comfortable living experiences.

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