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Research and Challenges on the Mechanical Structure of Bionic Lower Limb Exoskeleton Robots

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Abstract

Lower-limb exoskeleton is a device, which increases human power and helps movement, whose mechanics influence mechanical design directly in wearing comfort and energy efficiency, yet current exoskeleton generally has issues such as machine matching with human motion and lack of individual adaptability. This paper summarizes the demerits of the mechanical design of exoskeleton robot, analyzes 3 case instances of bio-inspired mechanical structures, and proposes optimization scheme of joint and skeleton design of exoskeleton robot in consideration of bio-inspired. The work concludes that biomimicry can benefit the mechanical structure design of exoskeleton robot. With the advent of embodied intelligence and other new technologies, exoskeleton will inevitably exhibit more intelligent capabilities, be a part of the human's body, and their mechanical structure concepts would gradually integrate into human motion. By further combining biomimetic concept and adaptive mechanism, future exoskeleton designs will continue to be forward-looking, flexible, lightweight and comfortable, to achieve high fidelity of kinematic and dynamic harmony between humans and machines.

Keywords

biomimicry, exoskeleton, mechanical structure, robot joint, mechanical simulation

1. Introduction

The lower limb exoskeleton robot is a wearable mechatronic system, which provides motion assistance and strength enhancement to the human body with external energy, and it greatly changes the boundary of human movement capabilities. In recent years, the rapid aging of the population, the increasing demand for rehabilitation medicine, and the urgent need to enhance physical strength in industry and the military have brought unprecedented development opportunities to lower limb exoskeleton technology.

The existing systems still have many challenges regarding the wearability, the naturalness of the motion and the energy efficiency. A root cause of these problems is whether the mechanical configuration, which serves as the basic structure of the exoskeleton, truly respects the inherent laws of human movement.

From the perspective of degree of freedom configuration, most existing exoskeleton robot systems adopt serial mechanisms. In terms of configuration design, the mismatch between human and machine movements is an important reason for wearing discomfort and abnormal gait. The research by scholars Shui Weiwei and Leingjing pointed out that exoskeleton robots still have the problem that the joint axes of the human body cannot be aligned [1]. The lower limb joints of the human body have complex instantaneous rotation centers and multi-axis movement characteristics, while the existing exoskeleton joints are mostly simple rotating pairs. When the kinematics of the two do not match, harmful internal forces will be generated between the human and machine, not only affecting the assistance efficiency, but also possibly causing skin abrasion and abnormal joint load.

This paper reviews the bionic design ideas in existing research, summarizes the degree of imitation and design strategies of different configurations on the human movement system, identifies the common challenges and future directions of current research, and has important theoretical value and practical significance for promoting the development of lower limb exoskeleton robot technology towards a more natural, more comfortable, and more efficient direction. The research by scholars He Yumin, Luo Ting, and Guo Siyu indicates that the human-machine coupling dynamics modeling and bionic optimization design are the key scientific issues that current research urgently needs to break through [2]. How to fundamentally break through the performance bottlenecks of the existing design requires a deep understanding and reference of the design principles of the human movement system. This paper will start from the current limitations of exoskeleton robots, bionic optimization cases, and future feasible optimization strategies, and review the bionic optimization issues of exoskeleton robots.

2. Current Limitations of Lower Limb Exoskeleton Robots

2.1 Human-Machine Kinematic Mismatch and Ergonomic Bottleneck

The human-machine kinematic mismatch is the core technical bottleneck currently faced by lower limb exoskeletons. Its essence lies in the kinematic conflict between the rigid mechanical system and the flexible biological system. The human lower limb joints are not ideal single-axis hinges, and their motion axes change with the variation of joint angles, showing the characteristic of a migrating instantaneous rotation center. The mismatch of human joints, that is, the alignment of the mechanical joint axes of the exoskeleton and the biological joints of the human body not being aligned, is always an important factor causing mechanical constraints and limiting the wearability of the exoskeleton [3]. Most of the current rigid exoskeletons adopt a fixed-axis rotating joint design, and there is a deviation between the mechanical joint axes and the human joint axes. In addition, the human lower limb structure is very complex, and during design, the positions and orientations of the human joint rotation axes can only be roughly estimated. This axis deviation has two levels of negative impacts in actual movement: Firstly, at the kinematic level, it leads to internal redundant constraints in the human-machine motion chain, forcing the wearer's joints to move in non-physiological trajectories, resulting in abnormal resistance; Secondly, at the dynamic level, when the inertia load of the exoskeleton is applied to the human body, due to the deviation of the force transmission path from the human body axis, undesirable parasitic forces and torques are generated, increasing the metabolic energy consumption of the wearer. Studies have shown that when the human-machine axes have a horizontal deviation in the sagittal plane, the average internal force of the knee joint increases by 23.48% [4].

2.2 Optimization of the Wearable Interface Biocompatibility

The mechanical configuration design of the current mainstream exoskeletons often relies on statistical averages or limited sizes, essentially ignoring the individual differences in the morphology of the lower limb bones. Data shows that the inner and outer diameters of the femoral distal end and the inner and outer diameters of the tibial proximal end of males are significantly larger than those of females, and the average values of the inner and outer diameters of the tibial plateau of males are approximately 6.5mm larger than those of females [5]. This mismatch caused by ignoring individual differences not only reduces the comfort of wearing but may also bring long-term biomechanical risks. In scenarios such as rehabilitation training and weight-bearing, the comfort of wearing is particularly important.

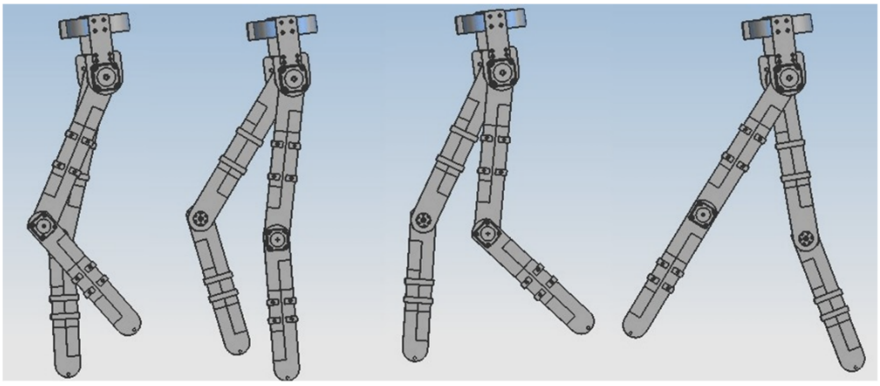
The abnormal movement guidance path of the exoskeleton may possibly interfere with the process of reshaping the normal gait pattern by the central nervous system, and even cause the fixation of the movement, which is against the original purpose of rehabilitation training, especially in the neuro-rehabilitation training scenario. For users who rely on the exoskeleton robots for weight-bearing or daily walking assistance, long-term wearing could lead to abnormal wear of joint cartilage, induce or accelerate osteoarthritis, or cause excessive pressure concentration on the exoskeleton-belt interface, leading to soft tissue discomfort and affecting the user's wearing compliance.

3. Case Study of Exoskeleton Robot Design Driven by Bionic Principles

3.1 Case Study of a Rigid Structure Bionic Exoskeleton

To solve the problem of kinematic mismatch between human and machine, the bionic exoskeleton-based lower limb rehabilitation robot developed by Hebei University of Technology integrates the technologies of ergonomics, bionics and mechatronics. It is equipped with an 8-DOF bionic exoskeleton mechanical leg, which simulates biological motion patterns by engineering models to provide the theoretical basis for mechanism design and control algorithms. Torque motors and harmonic reducers actuate the exoskeleton, allowing active flexion and extension movements of the hip and knee joints. A four-bar rigid-body model of human lower limb was established for kinematic and dynamic analysis (see Figure 1). Finally, the simulation analysis of gait coordination shows that the partial gait phase diagrams generated by the UG motion simulation show a striking resemblance to human walking patterns [6].

Figure 1: The Different Gait States



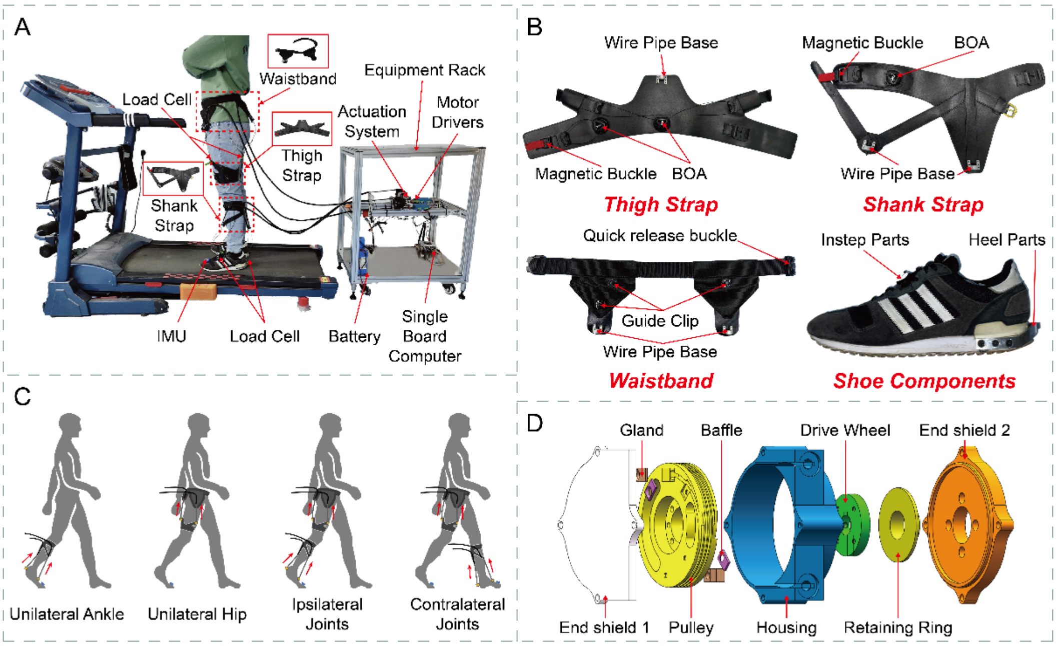
3.2 Case Study of a Flexible Bionic Exoskeleton

With the aging of society and the need for rehabilitation, the Shenyang Institute of Automation, Chinese Academy of Sciences has developed a modular flexible lower limb exoskeleton. The wearable body of this exoskeleton is constructed from flexible materials such as leather and fabric and features easy-wear and tension regulation mechanisms such as magnetic fasteners and BOA knobs. This design philosophy removes the rigid framework of traditional exoskeletons, instead mimicking the wrapping and supporting mechanisms of human soft tissues to provide assistance while maximizing the natural range of motion of human joints. Additionally, bidirectional pulley actuators are used, where motors drive movements in opposite directions of the same joint (imitating the antagonistic action of muscles), allowing for bidirectional assistance for flexion/extension (hip) or plantar/dorsiflexion (ankle). Experimental results on 10 healthy subjects showed that the exoskeleton has reliable assistive effects in assisting the hip and ankle joints either individually or synergistically. Fig 2 illustrates that the root mean square surface electromyographic activity of the rectus femoris and iliopsoas muscles were reduced by approximately 25–35% under the hip flexion assistance condition, and the root mean square surface electromyographic activity of the tibialis anterior muscle was reduced by approximately 30% under the ankle dorsiflexion assistance condition [7].

3.3 Case Study on Joint Bionic Design

Zhejiang University's hydraulically driven lower limb assistive exoskeleton robot adopts a quasi-humanoid design, that is, the exoskeleton resembles the human lower limb but is not necessarily anatomically matched, in an effort to improve human weight-bearing capacity while effectively reducing the load burden and minimizing stress on the knee joint. The biophysical bases of the design of the knee joint were built on the basis of bionic analysis of the normal human gait data (CGA data). The experiments showed that when the user's load increased from 10 kg to 20 kg (100% increase), the average tracking error of the knee joint trajectory decreased by 0.05%, while the maximum error increased by 20.7%, which is only 1.2% of the total range of motion, highlighting the structural effectiveness of this mechanism [8].

Figure 2: Exoskeleton Design Framework Diagram



3.4 Summarize

The application of bionic principles endows the mechanical structure of lower limb exoskeleton robots with biological rationality from the beginning of design. These approaches, whether they are exact reproductions of joint kinematics, the clever embedding of passive degrees of freedom in rigid structures, or innovations in flexible materials and actuation methods, all aim to transform human-machine systems from a simple "mechanical-biological" superposition to a deep synergy thru "human-machine integration." The above conclusion is also reflected in the quantitative data, including the stability of trajectory tracking error, the compliance provided by passive degrees of freedom, and the 15.29% improvement in energy efficiency caused by the reduction in metabolic rate. These metrics demonstrate from multiple dimensions that bionic design significantly improves the motion compatibility, wearable comfort, and energy utilization efficiency of exoskeleton robots.

4. Exoskeleton Robots Integrate Bionic Approaches and Their Advantages

Bionics may optimize the mechanical structure of exoskeleton robots. A model can be established on the basis of the human lower limb as a prototype, and the joint and skeletal parts can be improved.

4.1 Design of Bionic Mechanical Structures for Joints

Human joints, especially the knee joint, do not function as perfect cylindrical hinges, since their axis of rotation fluctuates dynamically during motion. A four-bar or six-bar mechanism may be utilized to replicate the instantaneous axis of rotation of the knee joint. Research indicates that the four-bar knee joint can effectively mimic the instantaneous center trajectory of the human knee joint throughout the 0°–120° flexion-extension spectrum, exhibiting peak knee joint angle fluctuations under 5%, diminished knee joint torque, and markedly restricted muscle range of motion in the vastus lateralis, gastrocnemius, and long head of the biceps femoris [9]. This method provides significant benefits in augmenting the comfort of wearable exoskeleton robots, optimizing human-machine ergonomics, and minimizing energy expenditure.

4.2 Bionic Mechanical Structure Design for Bones

There are large individual differences in lower limb dimensions and joint kinematic characteristics, which put stringent requirements on the human-machine compatibility of the lower limb exoskeleton. This problem has been solved successfully by using adjustable mechanical structures. More specifically, conventional fixed-length leg rods can be replaced by screw mechanisms, which allow a continuous and stepless adjustment of the length of the thigh and lower leg rods to cater for wearers of different genders, heights, leg lengths and joint positions. Studies have shown that such adjustable designs may substantially decrease relative displacement and interface interaction forces between the exoskeleton and human body when wearing, thus improving system comfort and motion compliance [10].

5. Challenges and Prospects of Bionic Exoskeletons

5.1 Challenges Faced by Exoskeleton Robots in Mechanical Structure

The human musculoskeletal system is very complex and difficult to model. The highly nonlinear mechanical behaviors of tissues like bones, muscles, ligaments and cartilage, resulting from their coordinated action, impose stringent requirements on the current engineering simulation capabilities. Moreover, the individual differences bring great difficulties. The perfect way is to design the exoskeletons according to individuals. However, there are practical limitations such as the high cost, long development cycle, and the difficulty in large-scale application, which is a dilemma. The adjustable structure has some defects in the structural strength. The ability to handle customized design and adjustable configurations continues to be a major challenge in the development of exoskeletons.

5.2 Further Expectations for Bionic Exoskeleton Robots

With the deep integration of artificial intelligence and robotics technologies, the embodied intelligence will turn exoskeletons from passive mechanical followers to active intelligent collaborators. For the exoskeleton robots, the embodied intelligence is introduced to generate intelligent behaviors by the interaction of the system and environment, which achieves the closed-loop coupling of “perception-cognition-action.” Especially, it enables the system to perceive the terrain, tasks and user status in real-time thru multimodal sensing and dynamically adjust the assistance strategy, while optimizing the model thru long-term interaction with specific users for tailored adaptation.

6. Conclusion

This document comprehensively evaluates the existing research landscape and constraints of lower limb exoskeleton robots concerning their mechanical structure, while examining the efficacy of bionic optimization approaches thru the lenses of joint and skeletal design, illustrated by three representative examples. From the preceding analysis, the subsequent conclusions may be inferred: Lower limb exoskeleton robots are presently at a pivotal juncture of evolving from “mechanical mimicry” to “human-machine synergy. Bionic design, thru the imitation of human joint movement patterns and the integration of flexible structures and adjustable mechanisms, has markedly improved the system's motion compatibility, comfort during wear, and energy efficiency. However the complexity of the human musculoskeletal system, individual variability and engineering implementation are still a major challenge. In the future, exoskeletons are expected to produce more natural and intelligent interactions, thanks to the integration of technologies such as embodied intelligence. They are not seen as external devices away from the human body, but as an extension of the physical structure of the user, with their mechanical structures being deeply integrated into the human motion.

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Conflicts of Interest

The authors declare no conflict of interest.

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