

AI-Driven Structural Design Advances in Assistive Rehabilitation Exoskeleton Robots

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Abstract. Limb dysfunction is widespread among rehabilitation populations, such as chronic stroke patients. Confronted with substantial global rehabilitation needs, requirements for exoskeletons—including comfort and functionality—have been further elevated. The recent rapid advancement of artificial intelligence technology offers new opportunities for optimizing traditional exoskeleton structural design. Given the current lack of review studies on how AI can inform exoskeleton structural design, this article focuses on recent advances in AI-driven structural design for assistive rehabilitation exoskeletons. The author conducted a literature review to summarize and analyze recent studies. This paper systematically compares three traditional design methods with three AI-driven design approaches. The traditional methods include model-based design, iterative experiments based on user feedback, and experience- or bio-inspired structural design. The AI-driven approaches include data-driven surrogate modeling, generative design and topology optimization, and personalized human data-driven intelligent structural design. Finally, this study concludes that the introduction of AI has led to improvements in computational efficiency and iteration cycles in structural design. However, further research is warranted to deepen the validation of structural design implementations.

Keywords: Rehabilitation Exoskeleton Robots; Exoskeleton Structural Design; AI-Driven Design Methods; Generative Design and Topology Optimization; Biomimetic Structural Inspiration.

1. Introduction

Currently, upper limb dysfunction is widely present in chronic stroke patients, hand function patients, and the elderly rehabilitation population. Symptoms such as arthritis seriously affect the daily life of patients, and their rehabilitation needs urgently need to be met. Meanwhile, exoskeleton rehabilitation devices are currently developing rapidly and have the potential to enhance upper limb stroke rehabilitation. However, researchers have found that there was no significant effect between the robot group and the conventional rehabilitation group in terms of activities of daily living (ADL) during the follow-up of the randomized controlled trial (RCT) [1]. As the wearable rehabilitation equipment still faces great challenges in personalized rehabilitation and comfort, the structural design has become a key bottleneck restricting the clinical application of exoskeletons.

In recent years, artificial intelligence and machine learning have been rapidly applied to multiple key aspects of human-machine integration in rehabilitation robots. The integration of the three will provide important assistance for the design of personalized treatment and rehabilitation programs for patients [2]. Based on this, this paper focuses on the AI-driven auxiliary exoskeleton structure design, summarizes the current structural design strategies of exoskeleton robots, and the research progress of AI in structural design. Besides, this article also evaluates the gains of artificial intelligence on structural design and clinical effects, aiming to provide new ideas for subsequent research on exoskeleton structural design and improve design efficiency.

2. Traditional Bionic Exoskeleton Structure Design Methods and Progress

2.1. Modeling-based Design Approach

The solid modeling-driven design method by using 3D software is one of the most systematic approaches in the traditional exoskeleton structure design. As shown in Fig. 1, this design method is

to realize the design of exoskeleton structure parameters by establishing a multi-body dynamic model of the human-machine system. By combining differential algebraic equations and simulation, and optimization algorithms, it can realize the design of exoskeleton structural parameters. In a further step, the prediction and evaluation of joint torque, power, and comfort of the exoskeleton can be realized [3].

Among them, Pérez-Soto M et al. proposed the L-GABS parametric modeling framework. This design method can capture human motion and conduct ergonomic evaluation. And it can map the patient's rehabilitation tasks and needs to the structural design parameters of the exoskeleton robot, with a modeling accuracy of 95% [4]. In addition, D'hondt et al. proposed a method for rapid prediction simulation. They achieve real-time and customized simulation through relevant equation algorithms and setting user files. This method can more efficiently evaluate the impact of different structural parameters on joint torque and metabolic consumption, allowing iterative design to provide faster feedback.[5]. However, the current modeling-based design method leads to large errors due to reasons such as manual parameter adjustment.

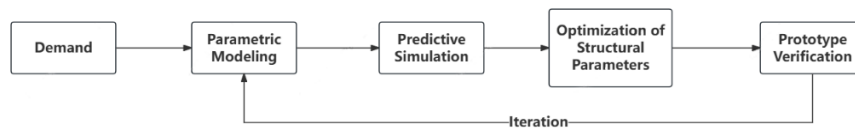


Fig. 1 Flowchart of structural design methods based on modeling (Picture credit: Original)

2.2. Iterative Approach Based on Experiments and User Feedback

Compared with the design method based on modeling, the iterative method based on experimentation and user feedback emphasizes the actual response of the human body as the basis for design optimization. Its core HILO (Human-in-the-loop Optimization) collects the user's metabolic consumption, electromechanical signals, and other human indicators in real time. And then it can iteratively optimize the structural parameters of the exoskeleton and continuously approach the optimal design solution [6].

This design method first performs parametric modeling based on laboratory data. Then it performs real-time optimization based on the natural scene of the user wearing it. Finally, it combines a user feedback survey to achieve an optimized closed loop. The entire process enables real-time monitoring of user movements and exoskeleton optimization. Slade P et al. conducted an experiment on personalized optimization of a lower limb exoskeleton, using the HILO method to compress the traditional 128-minute laboratory optimization to a 32-minute user walk. The results of this experiment demonstrate the superiority of this method [6].

In the face of a more complex and changing environment, the advantages of HILO will become more obvious. In an experiment using cadence as the optimization parameter, Park D et al. successfully found the cadence that minimizes EC (Energetic Cost), and the optimization process converged stably. Compared with the traditional baseline method based on biological torque, the optimized exoskeleton torque output time course of the power-assistance mode is significantly better. This demonstrates that experimental feedback can identify details that are difficult to predict with models, driving the continuous optimization and improvement of structural design [7].

2.3. Structural Design Methods Based on Experience and Bionics

In the early structural design of medical rehabilitation exoskeletons, engineers often based their designs on their own experience or obtained bionic inspiration from natural organisms. This design method usually takes the human body's anatomical structure and movement pattern as the design basis. And then engineers develop the design of the exoskeleton structure to achieve the exoskeleton's assistance and correction of the patient's movements. Researchers often use the concept of bioinspiration in design as well. As shown in Fig. 2, Tian et al. designed an elbow exoskeleton based on the six-segmented carapace structure of the shrimp abdomen. The structure achieves multi-degree-of-freedom bending motion through the joint membrane, ensuring that the exoskeleton can be

adaptively adjusted with the human joints. Such a structure can greatly improve the human skeletal coupling interaction [8].

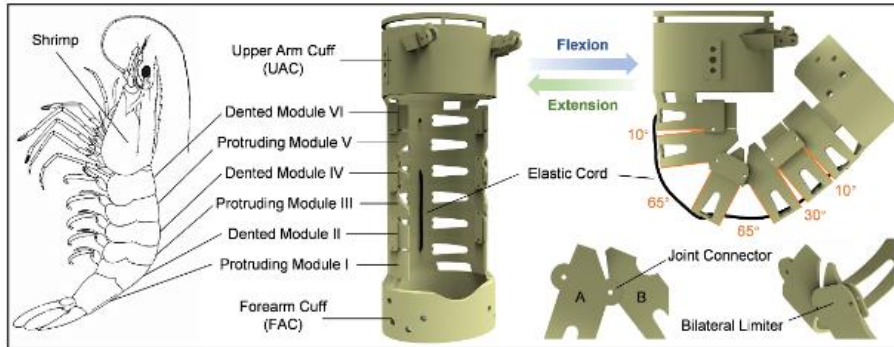


Fig. 2 A design for a bionic exoskeleton inspired by the shrimp's abdominal carapace [8]

This type of design method does not rely on complex optimization algorithms, but rather requires the designer's intuition and iterative verification through multiple rounds of experiments. Therefore, while it brings convenience, it also brings new problems. This approach has limited ability to systematize and quantify when balancing multiple objectives, such as comfort, range of motion, and usability [9]. As a result, methods based on complex optimization algorithms and models, and AI-driven, are gradually becoming the mainstream of exoskeleton structure design methods.

3. AI-assisted Application in Exoskeleton Structure Design

3.1. Data-driven agent modeling and rapid optimization

In recent years, with the rapid popularity of artificial intelligence, it has gradually begun to be used in the structural design of rehabilitation exoskeletons. AI mainly replaces or accelerates the traditional high-fidelity model simulation and experimental process through machine learning or statistical learning models. The design problem is then transformed into a prediction and optimization problem based on existing experimental data [10-11]. As one of the important application branches in the field of artificial intelligence and machine learning, data-driven agent modeling has gradually begun to play an auxiliary role in the design of exoskeleton structures in recent years. The general design process is shown in Fig. 3.

Among them, Asghar Mahmoudi et al. proposed a dual-loop optimization framework for predictive simulation and design optimization in their research this year [12]. They performed predictive simulations of motion in the inner loop and used Bayesian optimization in the outer loop to obtain the optimal parameter design. Compared with traditional design and brute force search methods, this will significantly reduce the number of iterations and improve design reliability. Meanwhile, the peak negative work of the knee joint damping exoskeleton assisted by the framework is reduced by about 92% compared to flat ground, demonstrating the advantages of the framework [12].

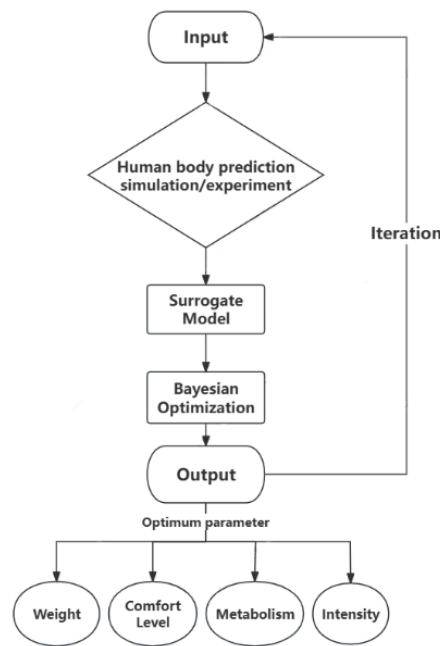


Fig. 3 Data-driven agent modeling and optimization method framework (Picture credit: Original)

3.2. Intelligent Extension of Generative Design and Topology Optimization

Recent studies have shown that generative design (GD) and topology optimization (TO), as important means to improve structural performance in the engineering field, are gradually being combined with artificial intelligence technology. For example, Manasa et al. proposed a generative design framework driven by AI. The framework can automatically output lightweight structures while ensuring manufacturability, reducing optimization calculation costs [13].

As a result, this trend is also entering the design of exoskeleton structures. A review of recent exoskeleton research by Stroppa et al. shows that complex optimization algorithms have been widely used in the structural design and control of exoskeletons [14]. Furthermore, Mariano et al.'s study highlights the advantages of AI-driven exoskeleton design methods. As shown in Fig. 4, a is the original linkage inversion lever, b is the linkage inversion lever optimized traditionally, and c is the linkage inversion lever GD optimized [15]. The three middle histograms show the differences in mass, von Mises stress, and maximum displacement between inversion lever, linkage inversion lever, and hinge support without optimization, with traditional optimization, and with GD optimization. According to the comparison results, the lever obtained by manually adjusting the parameters in CAD and verifying the stress and displacement with finite element analysis software is not as good as the lever obtained by combining GD in terms of stress reduction and stiffness. This shows that generative design optimization that combines topology optimization with artificial intelligence can not only shorten the design cycle but also ensure the quality of the generated [15].

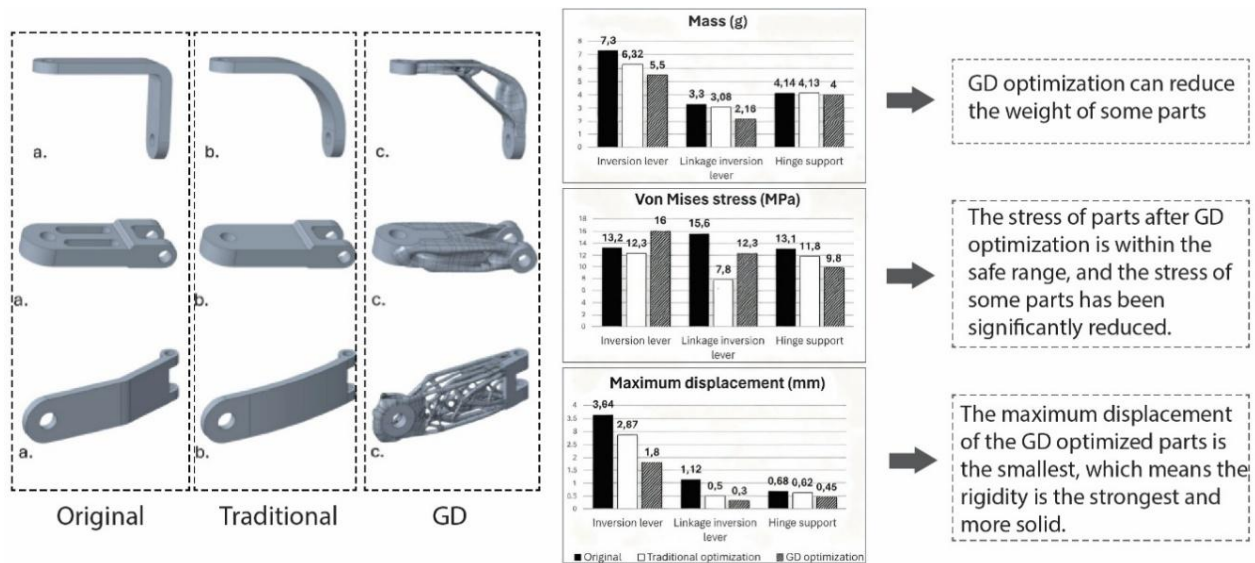


Fig. 4 Comparison chart between traditional CAD optimization and GD optimization (taking [15] as an example)

3.3. Intelligent Extension of Generative Design and Topology Optimization

In recent years, personalized design solutions have become the direction of efforts in many fields. Similarly, for the exoskeleton, the parameters of each subject's adaptation are different. Therefore, the design of important exoskeleton parameters, such as anchor point positions, needs to be determined according to the individual conditions of the subjects [16]. In recent years, researchers have proposed intelligent structural design ideas based on human body data: By collecting human body data and biomechanical characteristics and combining them with artificial intelligence technology, the exoskeleton parameters are optimized and the effectiveness and comfort of the exoskeleton are improved [16-18].

Chen et al. proposed a personalized design and optimization method for cable-driven exoskeletons. By extracting and analyzing the key features of human motion, a genetic algorithm is used to generate trajectories and control the cable-driven exoskeleton. This personalized optimized cable attachment makes the torque curve overlap of the right knee, left hip, left knee, and left ankle greater than 85%. The human body and exoskeleton adapt more naturally as well [17]. At the same time, although Wu et al.'s research is not directly related to exoskeleton design, they proposed a personalized assistance solution based on multimodal physiological signals. By grasping the research pain points of the lack of real-time monitoring cases in the past, they recorded and analyzed these physiological signals in real time. Then they got a more reasonable soft coat design [19].

The above research shows that the exoskeleton design method based on data-driven and combined with AI technology will push the product towards a more personalized and adaptable direction.

4. Conclusion

This paper systematically reviews the traditional methods of exoskeleton structure design and summarizes the auxiliary applications of generative design, agent models, and other technologies in the field of artificial intelligence in exoskeleton structure design in recent years. The article points out that AI-driven design methods can indeed solve the bottlenecks encountered by traditional exoskeleton structure design methods to a certain extent, such as computational efficiency, structural innovation, and design iteration efficiency. However, the current AI-driven structural design is still insufficient in terms of verification depth. For example, generative design remains only at the theoretical level and lacks practical engineering verification.

Therefore, in the future field of rehabilitation exoskeleton structure design, researchers can make efforts in the following aspects. The first is to combine experiments with user feedback analysis and

intelligent optimization algorithms. HILO has a great advantage in parameter optimization. The subsequent addition of intelligent algorithms such as Bayesian optimization may further accelerate the optimization process. Secondly, the practical application of the GD&TO method framework needs to be considered. In the future, we can focus on practical issues such as material performance and selection, and service life. Finally, there is the data-driven real-time monitoring direction. Currently, there is a lack of research on exoskeleton data collection and real-time monitoring. And further development can be done by drawing on research on other wearable devices.

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