Research Progress on Low-Cost Soft Robotics Technology for Rehabilitation Medicine

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Abstract. With the rapid aging of the global population and the rising incidence of cardiovascular and cerebrovascular diseases, the demand for rehabilitation medicine has grown dramatically. Rehabilitation training plays a vital role in helping patients restore motor function and improve their quality of life. However, most existing rehabilitation robots rely on rigid structures and servo motor drives, resulting in high costs, bulky equipment, and limited portability—factors that restrict their use in community and home-based rehabilitation. In contrast, soft robotics, built from flexible materials and inspired by biological movement, offers an intrinsically safe and adaptable alternative. Advances in 3D printing, flexible sensing, and intelligent materials have made soft robots increasingly feasible for low-cost, personalized manufacturing. This research reviews the research progress and technical development of low-cost soft robotics for rehabilitation medicine, focusing on safety mechanisms, applicable technologies, cost-reduction strategies, and future trends. The aim is to provide a systematic overview that supports the development of inclusive and accessible rehabilitation technologies.

Keywords: Soft Robotics, Rehabilitation medicine, 3D printing manufacturing, motion intent recognition, Wearable devices.

1 Introduction

As society ages at a faster pace and the prevalence of cardiovascular and cerebrovascular diseases increases all over the world, the demand for rehabilitation medicine has been increasing. Rehabilitation training plays an important role in the recovery of motor function and enhancement of the quality of life for patients. It is an important constituent of contemporary medicine. However, the current rehabilitation robot applied in clinical practice are mostly made of rigid metal materials and driven by servo motors, which can be vulnerable to problems including high purchase and maintenance costs and large equipment with poor portability that are hard to popularize. In the vast rural areas and distant regions in our country, the rehabilitation medical care is obviously lacking, and it has created an enormous contradiction between supply and demand. The high cost and technical difficulty have seriously restricted the popularization of emerging high-end rehabilitation technologies into societies and families. The essence of the

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problem is the inherent contradiction between the technical paradigm of the original rigid robot and the application environment of inclusive healthcare. In such a situation, soft robotics provides an innovative solution for the problem. Soft robots are flexible materials and mimic the behavior of living organisms, and their intrinsic flexibility already supplies a natural physical safety and eliminates injury risk inherently existing in rigid robots. More importantly, accompanied by the development of technologies like 3D printing, flexible sensing, smart materials, and soft robots has demonstrated great potential in low-cost manufacturing and personalized customization, and is an ideal technical carrier for realizing inclusive rehabilitation medicine. This research tries to make a systematic review and summary of the current research progress and development road of low-cost soft robotics technology in rehabilitation medicine. First, this research will review the status quo of application of soft robots in rehabilitation training, aiming at analyzing the technical advantages from two aspects, safety realization mechanism and applicable technical solutions; Second, it is objectively analyze the challenges encountered by this technology in terms of reliability, energy savings and professional support; Third, we look forward to the future development trends of his integration with the telemedicine and intelligent evaluation, some interesting and useful tools and relations that facilitate working in this direction are referred as it is already the case in studies and results throughout the following text, in order to give a reference for further study and development in this direction.

2 Application status and technical analysis of soft robots in rehabilitation training

2.1 Technical basis for achieving safety

Safety is the primary consideration for rehabilitation robots, especially for rehabilitation medicine. Soft robots, through a technical approach that combines the inherent flexibility of their materials with active sensing control, fundamentally address the safety risks associated with the physical interaction between traditional rigid robots and humans, laying a solid foundation for human-machine integrated rehabilitation training. Its safety primarily stems from passive safety mechanisms. Soft robots are mainly made of high elastic modulus polymer materials such as silicone and rubber, and their low mechanical impedance means that they can absorb energy through their own deformation even if they collide with the human body in an out-of-control state, greatly reducing the risk of injury such as hitting, squeezing and jamming, which is a design philosophy of "intrinsic safety". However, passive safety alone is not enough to deal with complex rehabilitation tasks, so active safety technology needs to be introduced. Scholars are monitoring human-machine interaction in real time by embedding flexible sensor networks within them. In terms of active perception, Professor Jamie Paik's team has developed soft actuators integrated with capacitive flexible sensors that can measure their own deformation and contact force in real time, providing critical data for closed-loop control [1]. The interaction safety was greatly enhanced. In summary, the safety of the soft rehabilitation robot is not guaranteed by a single technology, but is achieved through a deep technical system consisting of "material passive safety - multimodal active perception - intelligent intent recognition". These technological advancements, led by top international teams, enable it to safely engage in long, close-range physical interactions with vulnerable patients with varying mobility abilities, which is one of its core advantages over rigid robots.

2.2 Research on applicable technologies

Rehabilitation training requires distinct methods for each dysfunctional part, which would call for very high requirements on the specification and plasticity of rehabilitation equipment. Soft robotics, enabled by the capacity of materials customizability and structure designability, could break through the requirements of rehabilitation training. Using bionic design, researchers can "design" structural shapes and drive methods suitable for each part of the body and to satisfy diverse rehabilitation needs in biomechanics, from fine movement of the upper limbs to load-supporting load-bearing of lower limbs, which is a rationality that cannot be realized by traditional rigid robots. The idea of separated design according to part characteristics has been verified in a number of advanced studies. In a rehabilitation system of the upper limb, especially reconstruction of hand function, the fundamental problem is imitating the intricate, multi-joint coordinated movements of the human hand. Based on the above research, the question we need to solve is how to design a patient-adaptive force feedback controller for the robotic hand. Team Wood has used the pneumatic network architecture creatively to develop a soft actuator that simulates the biological tendon's distribution and action by generating multiple fingers' joint motion driven by the same pneumatic unit can achieve human-like bending motion [2]. it offers a safe, efficient choice for hand rehabilitation treatment. However, the solution varies from the lower leg rehabilitation scenario in terms of larger support torque requirements. Professor Conor J. Walsh and his group were concerned with the power and timing of the aid for gait assistance. They developed the ankle-foot soft exoskeleton with a hybrid of textile materials and tendon-driven design with flexibility and high power-to-weight ratio [3]; At the same time integrated an IMU as a real-time gait phase detector to apply assist torque to the user walking, which is the most demanding phase in the gait cycle, hence decreased energy consumption of user walking. The two cases make it clear that researchers use different technical paths to promote soft robots to adapt intelligently to the rehabilitation needs of a certain part. To sum up, the application of soft robots in rehabilitation is not a morphological change of the technology design itself but a deep adaptation of the functional requirements to the technology design. In combination, these studies have proved that by considering appropriate structural design and integration with sensor control, soft robots can effectively be tailored for various rehabilitation domains as a "tailor-made" technical means. This superior technical feature and rational premise are the fundamental reasons why it can overcome the bottleneck of traditional robots and become the next generation of universal rehabilitation platforms.

3 Low-cost and easy-to-use technical solutions

3.1 Low-cost design and rapid manufacturing technology

Digital fabrication, driven by its affordability, is one of the dominating paradigms in the popularization of these compliant robotic devices, as they mainly use 3D printing as a manufacturing method, which exploits digital, layer-by-layer features for a significant reduction of the processing barrier and time expenses involved in manufacturing complex and curved components. In particular, lowcost Fused Deposition Modeling (FDM) can be used for transiently producing stiff supports/shell, while PolyJet and Digital Light Processing (DLP) technologies or other inkjet printing techniques can be used for direct, monolithic integration of actuatable, compliant objects with prescribed stiffness and internal pockets— as demonstrated with plug-and-play pneumatic network structures enabled by Prof. Jennifer A. Lewis and her group [4]. A comparison of different prototyping methods is summarized in Table 1. This on-demand and rapid production decreases development time and allows personal tailoring and quick repair of soft robots in remote locations, offering critical technical assistance to the applications of soft robots in resource-challenged locations. Recent work on pneumatic-network design and control has improved response repeatability and closed-loop stability in soft actuators [5].

Table 1. Comparison of Manufacturing Methods for Prototyping

Comparison metric	Traditional molding and casting	3D printing
Prototyping Cycle Time	Several days to weeks	Several hours to days
Cost for Small-Batch Production	High	Low
Tolerance for Design Complexity	Low	Very high
Capability for Personalization	Weak	Strong
Required Professional Skill Level	High	Relatively Lower

3.2 Lightweight and low-cost drive control systems

The development of drive control systems is a vital route towards cost-effectiveness. Conventional servo-driven systems are too pricey and huge to satisfy the demand for widespread acceptance. Thus, work has been done trying to design lighter-weight and cheaper modules. DC diaphragm minipumps with cheaper solenoid valves are commonly implemented instead of the costly servo motor to actuate the system, which constitutes the main components of the pneumatic system [4]. As for the control hardware, it has become the open source platform (e.g., Arduino, RaspberryPi) that is an ideal choice for controlling the key control logic due to its low price and plentiful ecosystems. Besides, unified technologies are another tendency, for instance, a customized lightweight multi-channel valve board developed by Professor Conor J. The soft exosuits developed by Walsh's team at Harvard University consolidate multiple pneumatic circuits and therefore reduce the volume, weight, and part numbers. To conclude, the application of open-source hardware, commercial off-the-shelf components, and modular design can, to a large degree, scale down the cost, mass, and complexity of drive control solutions while preserving requisite capabilities, as an important proof of concept step towards actual applicability. Contemporary surveys in assistive wearable robotics emphasize modularity and standardization to reduce maintenance burden in community deployments [7].

3.3 Simple deployment and maintenance schemes

Ensuring long-term usability in resource-limited settings necessitates embedding ease of deployment and maintenance into the initial design philosophy. The absence of professional technical support in remote areas demands systems with high robustness and user-maintainability. To this end, modular design serves as a core strategy, segmenting the system into independent functional modules (e.g., drive, actuator, sensing). This approach facilitates rapid assembly, fault diagnosis, and part replacement, significantly lowering the barrier to maintenance. Concurrently, incorporating Internet of Things (IoT)-enabled remote diagnostics and firmware update capabilities is vital, allowing technical personnel to perform troubleshooting and software maintenance over the network, thereby reducing reliance on on-site expertise. For instance, the soft rehabilitation glove prototype from Professor Raymond Zhang's team successfully demonstrates remote monitoring and training parameter adjustment via a mobile application [6]. These technological innovations collectively forge a robust solution tailored for remote deployments. By integrating modular architecture with intelligent maintenance technologies, the barriers to operation and upkeep are substantially lowered, ensuring the sustainable and stable provision of rehabilitation services.

4 Challenges and difficulties

Although soft robots have a huge potential in rehabilitation medicine, their actual utility and spread in practical applications still require several improvements. To start with, the ever-present conflict between cost and performance always exists. For example, at the low price, driving methods such as pneumatic drive systems are easy to get slow response and low control accuracy, while high-performance driving materials such as shape memory alloy driving materials are easy to have a high price, so it is hard to have excellent results under the universal application scene. The second is that the reliability of the long-term system is difficult to ensure. The soft materials are vulnerable to fatigue damage and aging during the repetitive deformation process, and the signal drift of embedded flexible sensors will directly limit the stability and service cycle of the equipment. The prominent conflict of energy-efficient portability is obvious. High energy consumption of continuous work of air pumps or motors is restricted by the limited battery lifespan and the real wearability of the devices. A professional support system has not been built. Tough, rural places have limited interdisciplinary specialists equipped with both knowledge of robotics technology and of rehabilitation medicine for equipment tuning and personalized program training, as well as on-site servicing. Taken together, these complementary technical and non-technical challenges impede low-cost soft rehabilitation robots transitioning from benchtop labs into a mass market.

5 Future trends and prospects

Based on the in-depth technology research and continuous scenario applications, three typical development trends are foreseen for the future soft rehabilitation robotics, including deep integration with telemedicine as a promising technology route, wherein 5G/6G would enable therapists to remotely observe patients' rehabilitation situations and conduct personalized treatments in time, thus overcoming the professional resource lack of remote areas. Second, the combination of an intelligent assessment system will drive rehabilitation training mode shift to the data-driven model, according to the multimodal sensor and machine learning algorithm to achieve rehabilitation effect evaluation of objective quantitative evaluation, adaptive adjustment of training parameters. Last but not least, interdisciplinary cooperative innovation accelerates technology maturity. Recent actuator-focused overviews report gains in force density and efficiency for textile and fiber-reinforced soft actuators, supporting clinic-to-home translation [8].

6 Conclusion

Soft robotics represents a transformative technological pathway in the field of rehabilitation medicine, offering unique advantages in safety, flexibility, and accessibility compared with traditional rigid robotic systems. By utilizing soft and deformable materials, 3D printing, open-source control systems, and modular designs, researchers have demonstrated the feasibility of producing cost-effective, lightweight, and customizable rehabilitation devices that better accommodate patient needs. Despite its significant progress, the field still faces challenges such as balancing cost and performance, improving long-term material durability, and enhancing system energy efficiency. Furthermore, the lack of technical support in remote areas continues to limit large-scale implementation. Looking ahead, deeper integration with telemedicine, the adoption of intelligent data-driven assessment systems, and cross-disciplinary collaboration across materials science, artificial intelligence, and medicine will be key to advancing this technology. Ultimately, the continued evolution of soft rehabilitation robots will enable the creation of inclusive, intelligent, and affordable rehabilitation solutions that benefit patients worldwide.

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