

Flexible Robot Protection Materials and Technologies

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Abstract. Flexible robots, as a new type of robotics technology, have received extensive attention and research in recent years. In practical applications, flexible robots face a variety of challenges, with the protection of their soft and delicate structures being a critical concern. Therefore, the research of soft robot protection materials and technologies is particularly important. This literature review offers a comprehensive overview of relevant research advances in the field of materials and protection technologies for adaptive robots. It commences by introducing the development background of flexible robots, their application scenarios, and the significance of protection technologies. Subsequently, it systematically organizes, compares, and analyzes the existing protection materials and corresponding technologies through illustrative examples. The review concludes that current flexible robots face technical limitations, such as the trade - off between material performance, stability, and lightweight design. To address these issues, future research should focus on reducing material weight, alleviating the conflict between material performance and stability, enhancing technical efficiency, and improving system integration and reliability.

Keywords: flexible robots, protective materials, protective technologies, literature review

1. Introduction

In recent years, soft robotics, a new type of robotics, has attracted much attention due to its breakthroughs in the fields of healthcare, aerospace, and daily life assistance. With the continuous expansion of application scenarios, the importance of soft robots has become increasingly prominent. However, its soft and fragile structure faces numerous challenges in practical applications, especially in complex or extreme environments. Ensuring their stability and durability has thus emerged as a crucial issue that demands immediate resolution. Therefore, the research on protective materials and technologies for soft robots is not only of great scientific significance but also an important guarantee to promote their wide application.

The development of soft robots can be traced back to the beginning of the 21st century, when scientists began to explore new forms of robots that are different from traditional rigid robots. With its unique flexibility and adaptability, soft robots have shown significant advantages in complex environments. However, it is precisely their soft nature that renders them vulnerable to damage during operation, especially when they come into contact with hard objects or experience external impacts. This limitation has restricted the application of soft robots in more fields and has created an urgent need for protective materials and technologies.

Existing research on protective materials has focused on improving the durability and impact resistance of soft robots. Currently, a variety of materials have been applied to the protection of soft robots, such as elastomers, gels and flexible composites. These materials not only exhibit good elasticity and flexibility but also can absorb and disperse the external impact force to a certain extent, thus reducing the damage to the soft robot body. In addition, researchers are also exploring materials with self-healing ability, which can automatically repair after damage to further improve the service life of soft robots [1-3].

In addition to the research on protection materials, investigations on protection technologies are also indispensable, including the development of intelligent control systems to improve the adaptability of soft robots in complex environments, reasonable mechanical structure design to enhance the stability and durability of soft robots, and new drive methods to reduce the mechanical stress of soft robots during the movement process. The research and application of these technologies are of great significance to enhance the overall performance and service life of soft robots [4-6]. However, current research on soft robot protection materials and technologies still faces many challenges, such as improving the strength and abrasion resistance while ensuring the flexibility of the materials, protecting the soft robots effectively without affecting their operational flexibility, and balancing the protection performance and cost in practical applications.

Therefore, this review is structured around soft robot protection materials and technologies. Through a systematic analysis of the performance characteristics of elastomers, gels, foams, and other protective materials, as well as their current application status, the underlying mechanisms of sensor, control, and energy management technologies aimed at enhancing soft robot performance are explored [7].

Additionally, by comparing the innovation, practicality, and scene - adaptability of these materials and technologies, their durability, stability, and cost - effectiveness are assessed. Based on these analyses, directions for optimizing material design and integrating technologies are proposed, thereby providing theoretical support for improving soft robot performance and facilitating their cross - field applications.

2. Main theoretical and research results

2.1. Material properties

As a research hotspot in the field of engineering in recent years, the theory and modeling of soft robot protection materials and technology have been deepened, providing important support for the application and development of soft robots.

2.1.1. Theoretical models

In terms of theoretical models, the current soft robot protection materials are mainly categorized into intrinsic models and failure models. The intrinsic model is used to describe the stress-strain relationship, viscoelastic behavior, and nonlinear deformation properties of materials, which provides a theoretical basis for the design and optimization of soft robots. According to Zhang et al., the highly sensitive flexible strain sensing material (CB/PDMS) with nano conductive carbon black has typical elastomeric stress-strain properties, which eliminates the effect of creep on the electrical properties and guarantees the stable output of the sensor signal. Meanwhile, the body resistance change indicates that the overdiffusion threshold of the silicone rubber substrate is 12% of the carbon black mass fraction, and the conductive carbon black particles are uniformly distributed in

the substrate. In addition, the material responds quickly to the pressure sensing signal (response time of about 80 ms and recovery time of about 65 ms), and has good monitoring precision and accuracy for different frequencies and compressive stress signals [8].

Failure models, on the other hand, focus on the damage behavior and lifetime prediction of materials under extreme conditions, which helps to assess the safety and reliability of protective materials. The graph neural network (GNN)-based framework for predicting the mechanical behavior of materials and structures proposed by Maurizi et al. is capable of accurately predicting the complex nonlinearities in a variety of material systems (e.g., fibrous and layered composites as well as lattice metamaterials) by using only a few hundred data mechanical phenomena (including plasticity, buckling instability, and interfacial folds, etc.) with a mean absolute error (MAE) ranging from about 0.02 to 0.39 for different scenarios. Compared to conventional finite element simulations, well-trained GNN models can reduce computation times from minutes, hours, or even days to fractions of a second [9].

2.1.2. Classification of protective materials

Soft robot protection materials can be categorized into elastomer materials, gel materials and composite materials according to their composition and properties. These materials have good flexibility, malleability and adaptability, and can effectively protect the stable operation of soft robots in complex environments.

Elastomer materials, with their excellent elasticity and resilience, have become an vital part of the protective structure of soft robots [10,11]. Tang et al. demonstrated that shear thickening gel (SSG) is an ideal cushioning material for bulletproof vests. In the field of personal protective equipment, shear-thickening gel (SSG) demonstrates outstanding cushioning properties. Body armor made from this material reduces impact force from 0.73 kN to 0.40 kN and impact pressure from 2861.61 kPa to 1571.08 kPa upon impact. and back-flip marks (BFS) reduced from 1.07 cm to 0.56 cm. Each reduction exceeds 45%, significantly enhancing protective efficacy and wear comfort [12].

In thermal protection and insulation, nanoporous aerogel materials offer ultra-low density (3 mg/cm^3), extremely low thermal conductivity ($0.022 \text{ W/(m}\cdot\text{K)}$), and exceptional temperature resistance (up to 2800°C), making them ideal lightweight insulating materials [13]. The novel sandwich-structured flexible composite phase change material (PEE@EBF) reduces peak heat release rate (PHRR) and peak smoke production rate (PSPR) by 67.8% and 81.8%, respectively, while delaying battery thermal runaway for up to 633 seconds [14].

Zhang et al. found that the C/SiC ceramic matrix composite lightweight dot structure is ideal for the thermal protection system of hypersonic vehicles through the properties of high temperature resistance (1600°C), high specific strength ($160 \text{ MPa}\cdot\text{g}^{-1}\cdot\text{cm}^3$), and low thermal conductivity ($0.03 \text{ W/(m}\cdot\text{K)}$) when combined with multifunctional integrated design [15]. In addition, gel materials have been widely used in biomedicine as well as in soft robotics in their aerospace applications due to their unique rheological properties and biocompatibility [16,17].

2.1.3. Characterization of protective materials

The characteristics of soft robot protection materials also include wear resistance, corrosion resistance, and impact resistance, etc. These characteristics enable the protection materials to maintain stable performance in various harsh environments, thus ensuring the long-term reliable operation of soft robots. In addition, with the continuous development of new material technology,

some protective materials with special functions have gradually emerged, such as self-repairing materials and shape memory materials, etc [18-21].

Zhang et al. demonstrated the excellent self-repairing performance of the one-component polyurea material polyurea, which was prepared by inserting urea groups, for example, the repairing efficiency of PIB-1.5 was 92.4% after 9 hours at 60°C. The repairing efficiency of the polyurea material was as high as 1.5% after 9 hours of repairing, and the repairing efficiency of the polyurea material was as high as 2% after 9 hours of repairing, and the repairing efficiency of the polyurea material was as high as 2.5% after 9 hours of repairing. The efficiency after repair was as high as 92.1%. In addition, polyurea also exhibits good impact resistance, and PIB-1.5 exhibits significant strain rate sensitivity at high strain rates, and PIB-1.5 with a thickness of 3 mm significantly reduces the impact force at different heights of impact in the falling ball impact test [22].

Rokaya et al. identified numerous advantages of SMP in biomedical applications. SMP has good biocompatibility and can be used in the manufacture of implants, drug delivery systems, and tissue engineering scaffolds. Their mechanical properties can be adjusted by changing the composition and cross-linking density to meet different needs. SMPs respond to external stimuli; for example, light-responsive SMPs trigger the shape memory effect upon light exposure, while water-responsive SMPs restore their shape in a wet environment. Some SMPs are biodegradable and can be gradually degraded in the body after completion of function, eliminating the need for secondary surgical removal. In addition, SMPs can be compounded with other materials to form multifunctional composites, such as combining with drugs to realize controlled drug release. In the biomedical field, SMPs are widely used in drug delivery, tissue engineering, neuromedicine, dentistry, cancer therapy and orthopedics, etc. For example, temperature-sensitive polystyrene and polyurethane-based SMPs can achieve self-anchoring and controlled release of drugs, STPU-based SMPs maintain thermo-mechanical, chemical, and shape-memory properties in tissue engineering, thermosetting polyurethanes are used in stroke treatment, SMPs are used as nerve probe materials Reducing tissue damage, avoiding biofilm formation in dentistry and replacing metal wires in orthodontic treatment [23].

2.1.4. Mechanisms of interaction between soft robots and protective materials

The interaction mechanisms between soft robots and protective materials mainly involve the mechanical response, energy transfer and dissipation, and interfacial interactions of the materials, etc., which together determine the actual protective effect of the protective materials in soft robots. For example, in terms of mechanical response, protective materials need to be able to effectively absorb and dissipate external impact forces to mitigate damage to the soft robot body. Zhang et al. Compared with polyurea without inserted urea groups, the strength of one-component polyurea materials prepared by inserting urea groups was increased by 500%, the energy storage modulus was increased by 532%, and the toughness was increased by 281% [22]. In terms of energy transfer and dissipation, the protective material should be able to dissipate the absorbed energy in the form of heat or other forms to avoid the accumulation of energy leading to material destruction.

In terms of interfacial interaction, the bond strength and interfacial stability between the protective material and the soft robot body are also key factors affecting the protection effect. For example, Zhang, Zhipeng et al. found that polyurea also has high transparency (light transmission >92%) and high dielectric constant (≈ 4.5), which are superior to many traditional polymer materials. At the same time, polyurea also shows good flexibility and processability, and can be made into protective films and flexible substrates for electronic devices, such as PIB-1.5 protective film can effectively protect the screen of a cell phone when the screen is impacted. Moreover, polyurea has

good adhesion with a variety of substrates and can form composite materials with excellent impact resistance. For example, PIB-1.5 and alumina ceramic sheet composite impact composite materials show excellent impact resistance and energy dissipation capacity

2.1.5. Limitations

Current theoretical modeling research on soft robot protection materials and technologies has several notable limitations. Most of the existing models are derived based on simplified assumptions and ideal conditions, which are difficult to fully reflect the behavior of materials in actual complex environments. Based on Mona et al. the shielding properties against gamma rays of nano-SnO₂/SR composites are more effective than micro SnO₂/SR composites. the buildup factor increases with the increase of SnO₂ content, which suggests that the effectiveness of the In terms of radiation protection efficiency (RPE), 50% nano-SnO₂/SR has the highest RPE. This is followed by 50% micro-SnO₂/SR, indicating that nanocomposites are more advantageous in radiation protection. However, in terms of mechanical properties, the maximum tensile stress of the composites decreased from 0.06 MPa to 0.05 MPa as the SnO₂ content increased from 20% to 50%, and the tensile properties such as elongation at break and maximum tensile strain also decreased, which was attributed to the weakening of interfacial and cross-linking bonding due to the agglomeration of SnO₂ particles. In terms of shielding properties, the shielding enhancement is limited for high-energy gamma rays (e.g., above 1.022 MeV). The current study did not address long-term stability studies, insufficient comparisons with existing shielding materials, and an in-depth analysis of cost-effectiveness [24].

Futhermore, with the continuous emergence of new materials and technologies, the existing theoretical models may need to be further revised and improved to adapt to new application scenarios

2.2. Protective device requirements

In recent years, soft robot technology has received extensive attention and research, in which protective materials and technology are the key to ensure the stability of soft robot performance and extend its service life.

In the field of soft robotics protection technology, novel highly elastic materials and smart composite materials demonstrate significant advantages. A new type of highly elastic protective material can rapidly absorb energy upon impact and return to its original state, but it faces limitations such as high cost and diminished performance in extreme environments [25,26]. The polyurethane-closed-cell foam aluminum composite developed by the Stręk team effectively overcomes these issues, achieving energy absorption efficiency improvements of 34% under quasi-static conditions and 49% under dynamic conditions. It can release 35%-44% of absorbed energy over 10 loading-unloading cycles, with energy dissipation in subsequent cycles increasing by 1-3 times compared to the first cycle [27].

Another category of noteworthy protective materials are smart materials with self-repairing function, which are capable of automatically repairing cracks or breakages after damage, significantly improving the reliability and service life of soft robots [28]. However, based on the research of higher man, the preparation process of self-repairing superhydrophobic materials is complicated and some raw materials are expensive, in most of them are difficult to repair quickly at room temperature, often need to be heated, light and other auxiliary means to accelerate the repair, and is not applicable to the field of high requirements for work stability. Therefore, the self-repair

efficiency tends to decrease when improving the mechanical properties, and it remains a challenge to construct materials with both excellent mechanical properties and self-repair capability [29].

The polyurethane-closed-cell foam aluminum composite developed by the Stręk team effectively overcomes these issues, achieving energy absorption efficiency improvements of 34% under quasi-static conditions and 49% under dynamic conditions. It can release 35%-44% of absorbed energy over 10 loading-unloading cycles, with energy dissipation in subsequent cycles increasing by 1-3 times compared to the first cycle [30]. In structural design, biomimetic protective structures overcome the weight and flexibility limitations of traditional rigid shielding. Research indicates: thin-walled structures inspired by bamboo vascular bundles achieve energy absorption of 35.03 J/g per unit mass; nested honeycomb tubular structures exhibit specific energy absorption as high as 51.7 J/g; biomimetic honeycomb structures demonstrate a 43.8% increase in compressive strength compared to conventional designs; and spider web hierarchical porous structures achieve a specific strength increase of 62.1%–82.4%. These structures significantly enhance impact resistance while preserving robotic flexibility [31]. This design improves the impact resistance of the robot while maintaining its flexibility and adaptability.

In summary, research on soft robot protection technology has made significant progress, but still faces many challenges. Future research should focus on reducing the manufacturing cost of protection materials, improving the repair speed and efficiency of self-healing materials, and further optimizing the design of bionic protection structures. At the same time, the development of targeted protective materials and structures for different application scenarios is also an important direction for future research.

2.3. Sources of materials

In the field of research on protective materials and technologies for soft robots, a variety of methods and techniques have been widely used. One common approach is to design and optimize protective materials for soft robots based on the design concept of bionics by imitating the structure and function of living organisms in nature [31-33]. In the realm of biomimetic design, hydrogel microfibers inspired by spider silk exhibit exceptional mechanical properties: tensile strength reaching 525 MPa, toughness of 385 MJ/m³, damping capacity as high as 99%, and long-term stability maintained at room temperature and atmospheric pressure [34]. The material also offers outstanding recyclability, with the entire production and recycling process utilizing only water as a solvent, demonstrating excellent environmental friendliness. However, such biomimetic materials still face challenges of high manufacturing costs and complex production processes.

Another approach is to utilize advanced manufacturing technologies, such as 3D printing and micro-nano-machining, to prepare soft robotic protection materials with specific structures and properties [35]. 3D printing technology allows precise control of the shape and internal structure of the material, which enables customization of the material's properties. Research indicates that 3D-printed variable stiffness structures achieve a 70% increase in flexural modulus and a 65% improvement in impact strength compared to homogeneous structures, reaching a maximum of 213.7 kJ/m². By mimicking the distribution pattern of chitin fibers in crab shells, point-by-point control over fiber content is achieved, significantly enhancing the material's mechanical properties. Functionally, the biomimetic pressure sensor achieves a sensitivity of 1.005 kPa⁻¹ (0–1 kPa) with a detection range up to 200 kPa. The hybrid rigid-flexible drive structure enables highly efficient motion control [36]. However, the printing speed and material selection of 3D printing technology are still subject to certain limitations, and its application in mass production is yet to be further explored.

In addition, smart materials occupy an important position in soft robot protection technology. These materials are able to respond to changes in the external environment, such as temperature, humidity, or electric field, and thus change their shape, hardness, or adhesion. Research on shape memory alloy actuators has shown that shape memory alloy actuators (SMAA) have many advantages, with the highest actuation stress, and the higher actuation stress of magnetic or electrostrictive materials and piezoelectric materials commonly used in engineering, which are usually applied in micro-displacement actuators. SMAA has high power-to-weight ratio, high strain stress, high actuation frequency and high design freedom, and is used in aerospace, robotics, biomedical, automotive automation, and information electronics fields, where relevant theoretical research and application design work has been carried out, and it has the advantages of high power density, high precision, and low cost in certain fields and application scenarios compared with the traditional technologies based on electromagnetic, pneumatic, and hydraulic principles [37].

In practical research, method selection depends on specific objectives and conditions. Bionic design is suitable for high-performance specialized functional scenarios (e.g., thin-walled structural units absorb 35.03 J/g, nested honeycombs reach 51.7 J/g); 3D printing excels at rapid prototyping and customization; smart materials enhance system intelligence. Bionic honeycomb structures achieve a 43.8% increase in compressive strength compared to conventional designs. These breakthroughs lay the foundation for soft robotics protection technologies, yet ongoing exploration remains essential in cost, reliability, and scalable application.

3. Status and challenges

3.1. Status of research

Currently, research on protective materials and technologies for soft robots focuses on developing new materials and optimizing their performance. Researchers are dedicated to creating novel composite materials that combine flexibility, wear resistance, corrosion resistance, and self-healing capabilities. Through nanotechnology-based modifications, the mechanical properties and environmental stability of these materials are significantly enhanced. Simultaneously, the incorporation of smart materials like shape memory alloys enables rapid response and adaptive adjustment to external stimuli, greatly improving the environmental adaptability of soft robots.

In application domains, this technology has demonstrated immense potential in medical diagnostics, minimally invasive surgery, and operations in specialized environments. High-performance protective materials ensure stable operation of soft robots within complex human physiological environments or under extreme conditions, providing critical technological support for fields including healthcare, military, and aerospace. Future research will continue to concentrate on enhancing material properties and fostering cross-disciplinary application innovations, driving the diversified advancement of soft robotics technology.

3.2. Challenges

In the field of soft robot protection materials and technologies, there are a series of challenges and problems, which are not only related to the improvement of material performance, but also involve the lightweight design of the protection structure and other aspects.

First of all, as far as material performance is concerned, soft robot protection materials need to have a high degree of flexibility, abrasion resistance and corrosion resistance to ensure that the robot can work properly in various complex environments. However, many materials currently on the

market still have significant deficiencies in these areas, which undoubtedly restricts the range of applications and service life of soft robots. Materials must balance flexibility, abrasion resistance, and corrosion resistance, yet existing materials still exhibit significant shortcomings [38].

Secondly, the lightweight design of the protection structure is also one of the current urgent problems [39]. Due to the inherent need for high flexibility and mobility in soft robots, lightweight design must reduce weight while ensuring structural integrity, yet it is significantly constrained by material properties. PI-PDMS copolymers offer a tunable modulus range of 2–1500 MPa, exceed 400% elongation at break (compared to 103% for commercial PDMS), and withstand temperatures up to 400°C. However, they carry risks of thermal expansion delamination and present high processing challenges. The field also faces systemic challenges including high R&D costs, difficulties in mass production, and the challenge of balancing performance with stability. Breakthroughs require innovation in materials, process optimization, and interdisciplinary collaboration [40].

Lightweight design aims to reduce weight while maintaining structural integrity, yet remains constrained by material properties and manufacturing processes. This field also faces systemic challenges including high R&D costs, difficulties in mass production, and the challenge of balancing performance with stability. Addressing these issues requires interdisciplinary collaboration through material innovation (such as developing low-cost synthesis processes), technological optimization (enhancing energy efficiency), and whole-life-cycle assessments. In summary, the challenges in the field of soft robotics protective materials and technologies are interconnected and multifaceted.

3.3. Directions and trends

In order to solve these problems, researchers need to continuously innovate their thinking and methods, strengthen interdisciplinary cooperation and communication, and jointly promote the development and progress of this field. At the same time, the government and enterprises should also increase their investment and support for this field to provide strong protection and impetus for related research and innovation activities. Only in this way can we ensure that soft robots can play a greater role and value in the future.

In terms of protective materials, future research may pay more attention to the flexibility, durability and biocompatibility of materials. Currently, many soft robots are used in the medical, rehabilitation, and service industries, so the protective materials need to have good flexibility and durability to ensure the stability and safety of the robots in complex environments. In addition, as the demand for soft robots in the biomedical field continues to increase, biocompatibility has become an important research direction. In the future, scientists may explore new biocompatible materials to reduce the body's rejection of implants and improve therapeutic effects. At the technical level, intelligence and autonomy will be the future trend of soft robot protection technology. By integrating advanced sensors, control systems and artificial intelligence technologies, soft robots will be able to better adapt to a variety of complex environments and realize higher levels of autonomous movement and decision-making capabilities. This will greatly expand the application scope of soft robots and increase their value in practical applications.

Another noteworthy trend is the modular design of soft robot protection technology. Modular design not only improves the maintainability and scalability of the robot, but also reduces the production cost and helps the commercialization of soft robots. By designing a universal protection module, the protection system of the robot can be easily replaced and upgraded, thus extending the service life of the robot. In terms of practical applications, with the continuous progress of soft robot protection materials and technologies, we can foresee that soft robots will play an important role in

more fields. For example, in the medical field, soft robots with excellent biocompatibility and flexibility can be used for precise drug delivery, minimally invasive surgery, etc.; in the field of rehabilitation, soft robots can assist patients to carry out rehabilitation training and improve their quality of life; in the field of services, soft robots can perform a variety of complex tasks, such as domestic helpers, elderly care [41].

4. Conclusion

This review explores recent advancements in protective materials and technologies for soft robots. Current research primarily focuses on two directions: first, developing novel flexible materials with self-healing, environmentally responsive, and impact-resistant properties; second, enhancing the environmental adaptability of soft robots through sensing algorithms and biomimetic mechanisms (such as shape memory alloys). These innovations significantly improve the durability and safety of soft robots in complex environments.

However, the field still faces challenges such as high fabrication costs and complex system integration, with insufficient research on material economics and recyclability. Future studies should focus on scaling up material production processes, optimizing system energy efficiency, and strengthening fundamental research on the interaction between soft materials and their environments. Overcoming these technical bottlenecks will enable soft robots to deliver greater value in fields like healthcare and exploration.

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