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Application of Nano Materials in Artificial Limbs: Carbon Based, Metal Based and Hydrogel Materials

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Abstract. Traditional prostheses are hard to meet demands for precise control and long-term comfort because of rigid materials and poor biocompatibility. They lack perception and neural feedback functions, which further restricts their practical application effect. Nanomaterials have large specific surface areas, excellent mechanical and electrical properties and good biocompatibility. Studies show that carbon-based nanomaterials can be used to make highly stretchable and deformation-insensitive bionic sensory sensors. These sensors can achieve the integration of multi-modal signals in intelligent prosthetic devices. Metal nanomaterials such as silver nanowires are suitable for multi-axis force detection and dynamic tactile feedback. They can obviously improve the sensing range and response speed of prosthetic sensors. Hydrogel materials have obvious advantages in Electromyography (EMG) signal collection and flexible electrode interfaces. This is due to their skin-like modulus, high electrical conductivity and anti-freezing properties. Future development directions include designing multifunctional composite nanomaterials for prosthetic applications. Researchers also combine 3D printing and artificial intelligence algorithms to optimize prosthetic performance. Another direction is to build bionic intelligent prostheses with bidirectional neural interaction functions. This paper systematically reviews structural design and working mechanisms of carbon-based, metal-based and hydrogel materials. It also summarizes their applications in tactile sensation, neural signal transmission and EMG control.

Keywords: Artificial Limbs, Nano Materials, Hydrogel Materials

1. Introduction

Physical disability is a severe global public health challenge which affects mobility and quality of life for millions of people. Amputation from trauma, birth defects or vascular diseases causes physical loss and psychological distress for affected patients. It also creates barriers which prevent patients from fully participating in social activities and daily life. Prosthetic devices are key tools which restore movement and help users rebuild confidence and social integration. The development of such devices has followed the progress of human civilization and technological innovation. Traditional prosthetic technologies have long been limited by inherent flaws in available materials. Early prosthetic parts made of plastic, metal and common polymers offer basic support and movement replacement. But they show clear weaknesses in biocompatibility, mechanical fit and dynamic response to human motion. Rigid metal connections often lead to stress shielding and bone resorption in the human body. Traditional elastomers may cause skin irritation, pressure ulcers and poor sweat release over long-term use [1]. Traditional prosthetics cannot sense or respond to neural signals which limits intuitive control for users. This lack of function reduces movement accuracy and overall comfort for people who wear prosthetic limbs.

In recent years, the rise of nanomaterials has provided new technical solutions to these existing limitations. Nanomaterials possess remarkable characteristics due to their unique size effects, such as extremely large specific surface area and easily tunable surface chemical properties. These features enable nanomaterials to exhibit excellent mechanical and electrical performance in the field of biomedical engineering, demonstrating significant application potential [1]. In prosthetics, nanomaterials can form highly biocompatible surface coatings for better tissue interaction. They strengthen composite structures and improve both mechanical strength and toughness for prosthetic components. These materials also support smart sensing and controlled drug delivery which upgrades prosthetics from passive to adaptive. Carbon-based, metal-based and functional hydrogel nanomaterials have advanced prosthetic performance significantly. They improve mechanical behavior, neural interface compatibility and skin adaptability for prosthetic users. This paper systematically reviews research progress of these three nanomaterial types in prosthetic devices. It analyzes mechanisms and applications which enhance strength, sensing, biocompatibility and user adaptability. The review also discusses current research challenges and future directions for advanced prosthetic development. It aims to offer theoretical support and technical references for high-performance prosthetic systems (see Table 1).

2. Carbon based nanomaterials

In recent years, research on carbon nanotechnology has been quite active, with various forms and shapes of nanocarbon crystals such as needle shaped, rod-shaped, barrel shaped, hollow cage shaped, etc. emerging one after another. The application of carbon-based nanomaterials in prosthetic limbs is also constantly being explored.

Biomimetic integrated sensing devices have significantly expanded human interactive control capabilities through a large number of distributed electronic components, but traditional electronic devices are often bulky and rigid, making it difficult to be perfectly compatible with soft tissues in the human body. Although bionics provides construction ideas, existing solutions require the application of a large number of electronic components, which can lead to complex structures, cumbersome interconnections, and high power consumption. At the same time, how to maintain stable and continuous operation of the device under large deformations such as stretching and bending is also a huge technical challenge. In response to the above issues, Xinqin Liao et al. (2021) proposed and prepared an integrated device called "stretchable artificial sensing and transmission neural sensor". Its construction is very clever: the functional fibers with carbon nanotube coated polyester fibers as the core are responsible for signal perception, conversion, and transmission, while the outer layer is protected by elastic bands. The core breakthrough of this system lies in its high stretchability and deformation insensitivity. A clever structural design allows it to maintain functional stability even under the extreme condition of 100% strain. This system is also highly integrated and multifunctional. It combines the sensing, transmission, and recognition of information in a unified manner. This mimics the peripheral sensory nervous system of organisms. As a result, there is no need to integrate a large number of electronic components. In addition, its performance is exceptional, which can withstand over 15,000 cycles of stable operation. Its response time is within 15 milliseconds. It also exhibits synaptic plasticity and tailorable properties, which enable flexible size adjustments according to specific requirements. Overall, this research provides major technological breakthroughs for fields such as human-computer interaction and wearable devices. At the same time, this technology can make mechanical prosthetics more lightweight, intelligent, and durable. Most importantly, it can give mechanical prosthetics the ability to perceive and interact with natural limbs [2].

Traditional sensors have limitations such as rigidity and bulkiness, while 3D graphene sensors have advantages such as easy preparation, direct signal reading, and low power consumption. Compared to traditional two-dimensional materials, three-dimensional graphene has significant advantages in piezoresistive sensing due to its porous network structure, including high sensitivity, wide response range, and mechanical flexibility. Hyunseon Seo et al. summarized three main methods for building three-dimensional graphene sensors: template method, which uses templates such as foam nickel to build regular porous frameworks. The self-assembly method enables graphene oxide sheets to spontaneously assemble into hydrogels or aerogels through hydrothermal or reduction processes. Composite material method, combining graphene with flexible substrate to enhance mechanical properties [3]. The 3D structure of 3D graphene sensors can achieve high sensitivity, an increase in detective range, and has great potential in fields such as human motion detection, health monitoring, and electronic skin. Minghui Cao et al. provided a detailed summary of the synthesis methods of graphene and highlighted four major techniques for constructing three-dimensional structures: template method, self-assembly method, electrospinning method, and 3D printing method. Using the π - π stacking characteristics between graphene sheets, graphene foam, aerogel and other multi-level structures can be assembled in a controlled manner. The core mechanism of 3D graphene sensors is the piezoresistive effect, which senses pressure through changes in resistance under strain. It has three major characteristics: high sensitivity and the ability to capture weak signals such as smiles and pulses. Wide response range, capable of covering subtle deformations to large-scale movements. Long term stability meets the durability requirements of wearable devices [4]. Al Kharusi et al. adopted an "equivalent continuous medium" simulation method, modeling at the atomic scale. In the finite element model, each carbon atom on the carbon nanotube is set as a node, and the connecting bonds between atoms are set as beam elements. Using mechanical equivalent calculations, the mechanical properties of these beam elements are derived by analyzing the total potential energy between atoms, thereby transforming the microscopic atomic structure into a macroscopic analyzable continuous model. The result verification found that the simulated data highly matched the existing experimental results in the literature, proving the reliability of the calculation method. Single walled carbon nanotubes exhibit isotropy (i.e. consistent mechanical properties in all directions), which is advantageous for manufacturing prosthetic components with uniform stress distribution. And it was found in the study that the thickness of the pipe wall has a significant impact on the stiffness calculation results, which means that in the material research of prostheses, the wall thickness control of carbon nanotubes is a key factor in controlling the final stiffness and durability of prostheses [5]. In the future, mechanical prostheses may use three-dimensional graphene sensors to construct highly sensitive electronic skin and use Stress-Applying Part Trapezoidal (SAPT) optical fibers for long-distance signal transmission, which may enable biomimetic perception of mechanical prostheses.

3. Metal nanomaterials

Traditional metal prostheses have many shortcomings, while the emergence of nano metal materials has given prostheses more possibilities. Li Yue et al. developed a biomimetic flexible capacitive sensor inspired by fingerprint structures. To achieve selective detection of static friction and sliding friction, this work proposes a novel sensor with a parallel plate capacitor structure. The electrode part adopts a spiral shaped, vertical substrate silver nanowire three-dimensional Polydimethylsiloxane (PDMS) design, with silver nanowires uniformly modified on the surface of PDMS micro columns and silicone rubber as the dielectric layer. Its outstanding advantage lies in the highly stable output of the capacitor in a changing positive pressure environment, but its response to friction modes varies significantly. Static friction causes the capacitor to rise, while sliding friction causes the capacitor to fall [6]. This new biomimetic flexible sensor, which combines directional sensitivity and dynamic tactile sensitivity, has great development and application prospects in new intelligent prostheses.

In biomedical fields such as artificial skin and minimally invasive surgery, tactile feedback requires multi axis force detection capability, simultaneous perception of normal and shear forces, and high sensitivity and reliability. However, existing sensors still have many shortcomings in this regard. Alvares, Darren, and others have developed a new type of nanoparticle thin film sensor to solve this problem. The structure of this sensor is a nano particle thin film resistive multi axis sensor, with a working range of 0-300mN. Its manufacturing process adopts inkjet printing and micro molding technology. After testing, this sensor exhibits stable dynamic characteristics at different strain rates with minimal response changes, fully demonstrating its good repeatability and reliability [7]. The multi axis detection capability, high sensitivity, manufacturing scalability, and dynamic stability of this sensor make it have great potential for development in intelligent prosthetics.

Liao Xinqin et al. proposed a heterogeneous contact microstructure sensor to achieve a wider range of mechanical perception and apply it to virtual reality interaction. This sensor uses silver nanowires @ polyurethane support as the conductive active layer, and layered carbon fabric is used to form a heterogeneous contact structure with the support. By the synergy of two materials, a heterogeneous contact microstructure is formed, significantly improving the sensing performance of this sensor. After testing, this sensor has increased its mechanical sensing range by over 100% compared to traditional sensors [8]. In addition, the high sensitivity, fast response time, and high stability of this sensor determine its great application prospects in prosthetic limbs.

4. Hydrogel nanomaterials

As a material constructed by chemical or physical crosslinking, the framework of hydrogel is derived from water-soluble or hydrophilic polymers. Polymer hydrogels based on this structure have unique environmental sensitivity, and can effectively sense the small changes of external stimuli such as temperature and pressure. According to this characteristic, polymer hydrogel can be used to make sensors, and it has good biocompatibility, and is also a kind of material with high water absorption and high-water retention.

Miao Yan et al. developed a new type of hydrogel through the photocrosslinking of acrylamide to form an elastic network skeleton, and introduced potassium carbonate, carrageenan and locust bean gum for physical crosslinking to improve mechanical properties and conductivity. After testing, it can still maintain soft and conductive properties at 10°C, overcoming the limitations of traditional hydrogels that are easy to freeze crack. It also has the characteristics of high elasticity, large deformation recovery, cold resistance, and resistance response, which solves the problem of flexible sensor failure in low-temperature environments. The bending deformation of hydrogel can directly generate control commands without using complex electronic components, providing a new solution for prosthetic control [9].

Lianjia Zhao et al. used MXene and polyvinyl alcohol (PVA) to synergistically construct a biocompatible electronic skin through strong hydrogen bonding. PVA was used as a crosslinking agent to connect two-dimensional $\mathrm{Ti} \propto \mathrm{C}_2 \mathrm{T}_x$ MXene layers into a layered network structure through strong hydrogen bonding. It will form a hierarchical structure film with high chemical stability, high voltage electrical response, and sensitivity up to $164.75\ \mathrm{kPa}^{-1}$, which can be adjusted for electrical properties and mechanical deformation ability through PVA intercalation [10]. Benefiting from the incorporation of biocompatible PVA and improved device safety, a new direction for future prosthetic research is established.

Based on the rigid structure of traditional commercial electrodes, which is difficult to fit the complex body surface, resulting in low fidelity of surface electromechanical signals, uncomfortable wearing, poor long-term stability and other problems, Lai Jinxin et al. developed a high-density surface electromyography electrode array based on 3D printed myoelectric sensitive hydrogel.

Table 1. Materials, advantages of materials and applications

Materials	Advantages	Applications
Carbon nanotube	Excellent conductivity, high mechanical strength, easy to functionalize, and good compatibility with flexible substrates	Biomimetic external sensory neural sensor, stretch sensing
Graphene	High specific surface area, excellent mechanical flexibility, uhigh conductivity, and the ability to self-assemble into three-dimensional structures	Wearable piezoresistive sensors, electronic skin
MXene	Two-dimensional layered structure, high conductivity, good hydrophilicity, easy crosslinking with polymers, strong environmental stability	Highly stable electronic skin, in vivo biological monitoring
Hydrogel	High flexibility, excellent biocompatibility, skin like modulus, can respond to various stimuli, easily loses water, and is prone to freezing at low temperatures	EMG electrode, software controller, biomimetic skin
MXene + PVA	Improved environmental stability for over 6 months and high sensitivity	Long term implantable neural interface
Carbon nanotubes+polyester fibers	Realize 100% deformation insensitivity under stretching, integrated multifunctional	Wearable tactile sensing
Silver nanowires+polyurethane/carbon fabric	Improved sensing range	Virtual reality tactile interaction
Nano particle thin film	Normal/tangential multi axis force detection with minimal hysteresis variation	Soft robot control
Conductive hydrogel	EMG sensitivity, conformal fit with the skin, achieving high fidelity surface EMG signal acquisition	Surface electromyography electrode

Its manufacturing adopts 3D printing technology, realizing customized manufacturing of electrode arrays, and has the characteristics of stretchable, flexible, high-density electrode arrays that can conform to the skin in a conformal manner. By collecting electromyographic signals from the surface of the human hand, multi-channel readout circuits, and decoding them through artificial intelligence algorithms, prosthetic limbs can be controlled [11]. Due to its conformal fit: reducing motion artifacts, high conductivity: lower contact impedance, long-term stability: can be worn for a long time, and stable signal quality, it provides a new path for the development of prosthetics.

5. Conclusions

This paper systematically reviews the research progress of carbon-based nanomaterials, metal nanomaterials and hydrogels in the field of flexible sensors in recent years and their applications in intelligent prosthetics and human-computer interaction. Research has shown that different types of functional materials have their own advantages and are suitable for differentiated application scenarios. Carbon based nanomaterials, like graphene and carbon nanotubes, have excellent conductivity, outstanding mechanical flexibility, and are easy to functionalize, making them suitable for constructing biomimetic sensing devices with high stretchability and deformation insensitivity. Metal nanomaterials such as silver nanowires exhibit unique value in multi axis force detection and rapid dynamic response due to their advantages of large mechanical sensing range, high sensitivity, short response time, and good electromechanical stability. Hydrogel materials play an important role in EMG signal acquisition and flexible electrode interface due to their high flexibility, excellent biocompatibility and adjustable electrochemical properties. By combining the above-mentioned nanomaterials, further enhancement of sensor performance can be achieved. These composite material strategies effectively overcome the limitations of single materials in terms of mechanical strength, environmental adaptability, and biocompatibility. Based on the above material advantages, flexible sensors have shown great potential in multiple key fields such as tactile perception, neural signal transduction, and electromyographic control. Compared to traditional rigid sensors, flexible devices have significant advantages in signal fidelity and long-term comfort, and are expected to gradually replace traditional rigid devices. In the future, with the deep integration of nanomaterials science, flexible electronics technology, and artificial intelligence algorithms, intelligent prostheses with skin like multimodal perception capabilities and bidirectional neural interaction functions are expected to achieve true bioelectronic fusion. This type of system not only provides prosthetic users with a more natural and reliable operating experience. Ultimately, these technologies will effectively improve the quality of life for people with disabilities and promote the development of personalized medicine and intelligent rehabilitation engineering.This paper reviews the research and application of carbon-based nanomaterials, metal nanomaterials and hydrogels in the field of flexible sensors in recent years.

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