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Review Article

Nanomaterial-Based Prosthetic Limbs for Disability Mobility Assistance: A Review of Recent Advances

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The emergence of new hybrid nanomaterial has enabled prosthetic devices to have more performance and significantly improved the quality of life of the disabled. Due to the biosensing properties of prosthetic limbs made of nanomaterials, a large number of nanocomposites have been designed, developed, and evaluated for various prosthetic limbs, such as e-skin, e-skin's neurotactility sensing, human prosthetic interface tissue engineering, bones, and biosensors. Nano-based materials are also considered to be the new generation of scientific and technological materials for the preparation of various prosthetic devices for the disabled, which can effectively improve the sense of use of the disabled and achieve functional diversity. The study described various nanomaterials for prosthetic devices, and introduced some basic components of nanocomposites; their applications are in three areas, such as bone, skin, and nerve, and evaluated and summarized the advantages of these applications. The results show that (1) carbon-based nanomaterials as neural materials have been studied most deeply. Due to that strong stability of the carbon-based material and the simple transmission mechanism, the cost can be controlled in manufacturing the artificial limb. Materials with human-computer interaction function are the research focus in the future. (2) Skin nanomaterials are mainly composite materials, generally containing metal- and carbon-based materials. Ionic gels, ionic liquids, hydrogels, and elastomers have become the focus of attention due to the sensitivity, multimodal, and memory properties of their materials. (3) Outstanding nanomaterials for bone are fibrous materials, metallic synthetic materials, and composite materials, with extremely high hardness, weight, and toughness. Of the skeletal materials, the choice of prosthetic socket material is the most important and is typically based on fiber laminate composites. Some of these materials make sensors for durability and performance that can be used for large-scale clinical testing.

1. Introduction

Since the emergence of nanotechnology, the application of nanomaterials in wearing aids and sports prosthetic limbs has been the focus of attention of researchers in the field of disability sports. As nanomaterials have different electrical, magnetic, thermal, mechanical, and other properties from common materials, they are currently used by a large number of scholars in the field of prosthesis manufacturing [1]. Prosthetic limbs used by persons with disabilities to assist movement include mechanical prosthetic limbs (ordinary materials), electric prosthetic limbs (nanomaterials), and myoelectric prosthetic limbs (nanomaterials). According to research, artificial limbs made of traditional materials are stiff, expensive, and not easy to handle [2]. The users of artificial limbs made of traditional materials can only rely on the uncomfortable tactile information between the residual limb and the ground. As a result, the risk of falling is increased, and the activity ability is limited. Artificial limbs are considered to increase cognitive burden of the brain caused by foreign objects in the movement. As a result, many psychological troubles and problems of giving up artificial

Table 1: The generation and use of neural material.

Material name	Generation method	Function	Advantage	Reference
Graphene	3D structure making (1) Template orientation (2) Self-assembly (3) Electrospinning and 3D printing	The piezoresistive sensor made of 3D graphene shows good potential in electronic skin and other aspects	(1) Simple Preparation (2) Simple readout mechanism (3) Low power consumption (4) Convenient signal acquisition	[14]
Carbon-based materials, inorganic nanomaterials	NM	Detectable index (1) Body movements (2) Body temperature (3) Respiratory rate (4) Heart rate and blood pressure (5) Electrophysiological signals	(1) Stretchability (2) Ultrathin and conformal (3) Biocompatibility (4) Biodegradability	[12]
Carbon nanoparticle material	Integrate nano-additive from 0 to 3.5%	Experimental, artificial neural network techniques were used to calculate the strain-time relationships of prosthetic and orthotic composites of carbon nanoparticle materials	For the nanoparticle-reinforced composite, the mechanical properties and creep properties can be up to 5 times	[9]
Carbon nanotube polyester wire	A bionic electronic nerve sensor with high tensile and deformation insensitivity is made of a composite material of polyester wires coated with carbon nanotubes	Bionic electronic exogenous nerve sensor has great potential in some fields, such as human-computer interaction	(1) High stretchability (2) Deformation insensitive (3) Excellent stability (4) Rapid response (5) High robustness (6) Geometric layered sensing (7) Cutability	[13]
Metal polymer carbon material (metal-polymer mixture)	Implantable device	(1) Prosthetic limbs for pain relief (2) Sports prosthesis (3) Cognitive nerve prosthesis	By reducing the difference between the soft tissue and the electrode, the polymer portion can adjust the metal modulus	[8]
NiCo (nickel-cobalt) nanoparticles	Obtaining nickel-cobalt nanoparticles by chemical reduction on multiwalled carbon nanotubes	(1) Make sensor (2) Realize automatic detection (3) Automatic control	(1) High stability (2) High sensitivity (3) Reproducibility (4) Low detection limit	[15]
Proanthocyanidins/reduced graphene oxide (PC/rGO), glycerol-plasticized polyvinyl alcohol-borax (PVA-borax) hydrogel	The proanthocyanidin/reduced graphene oxide (PC/rGO) composite was introduced into glycerol-plasticized polyvinyl alcohol-borax (PVA-borax) hydrogel, and the bionic tactile PC/rGO/PVA hydrogel was obtained	(1) It can imitate and detect skin epidermal movements, such as facial expression changes and finger bending (2) Simulate the tactile ability of natural skin through hydrogel	(1) Stretchability (2) Immediate and complete self-healing (3) High strain sensitivity	[17]
Hydrogel	NM	(1) The human body movement monitoring (2) Artificial tissues or artificial limbs	(1) Biocompatibility and degradability, antibacterial (2) Heat protection and antifreeze (3) Stretchability and compressibility (4) Dynamic durability	[16]
Ion gel gated organic synaptic transistor (IGOST)	Crossbar array simulation Sensor integration	Artificial auditory nerve with short-term attenuation and artificial neural network with long-term memory	Synaptic attenuation of IGOST is relatively easy to regulate	[18]

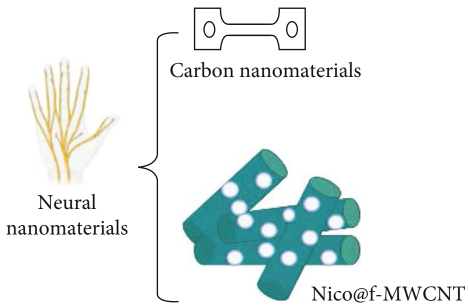

Figure 1

limbs have become the major causes of burden [3]. The combination of biomedicine and material science has led to the emergence of new hybrid nanomaterials that meet the needs of ideal prosthetic limbs. Prosthetic limbs made of nanomaterials can significantly improve the quality of life of the disabled due to their unique and more capabilities.

Due to the biosensing nature of prosthetic limbs made of nanomaterials, there are different components based on the use of polymer nanocomposites in prosthetic limbs. In these components, the functional stretchable composite structures are mainly manufactured by using conductive nanofillers in an insulating or conductive polymer matrix [4]. Conductive polymers such as carbon-based composites and structures include carbon black (CB), carbon nanotubes (CNT), carbon fibers, graphene sheets, and graphene oxides. Other conductive fillers such as metal nanowires, nanoparticles, ionic liquids, and Mxenes are also quite common. In addition, polymers such as polydimethylsiloxane (PDMS), polyurethane (PU), thermoplastic polyurethane (TPU), ecoflex, polyimide (PI), natural rubber, polypropylene, polypyrrole, and polyethylene terephthalate can be used as materials in the flexible matrix to maintain the nanofiller interface. Conductive polymers, such as poly (3, 4-ethylenedioxythiophene):-poly (styrene sulfonate) (PEDOT:PSS) and polyaniline, are also used in functional nanocomposite to support conductive networks [5]. In summary, in functional nanocomposites, the nanofillers impart functional sensing properties, while the polymer matrix supports a conductive network configuration. Some of these materials make sensors for durability and performance that can be used for large-scale clinical testing [6].

In recent years, a large number of nanocomposites have been designed, developed, and evaluated for various prosthetic prostheses, such as e-skin, e-skin's neurotactility sensing, human prosthetic interface tissue engineering, bones, and biosensors. Nano-based materials are also considered to be the new generation of scientific and technological materials for the preparation of various prosthetic devices for the disabled, which can effectively improve the sense of use of the disabled and achieve functional diversity. Prosthetic limbs made of nanocomposites enable patients to engage in more demanding recreational activities such as running [7]. Today, the use of most nanomaterials holds promise for a variety of prosthetic applications. The study described various nanomaterials for prosthetic devices and introduced some basic components of nanocomposites; their applications are in three areas, such as bone, skin, and nerve, and evaluated and summarized the advantages of these applications.

2. Classification and Application of Tissue Material

2.1. Neural Material. As shown in Table 1, nanomaterials used to manufacture prosthetic nerve sensors are carbon-based materials, metal nanomaterials, metal-polymer mixtures, hydrogels, and the like [8]. As shown in Table 1, carbon-based nanomaterials perform well in creep resistance, and nanoparticle-reinforced composites creep more easily than carbon nanoparticle materials, affecting the useful life of prosthetic limbs [9]. Bionic electronic exogenous nerve sensor can achieve monitor physiological indexes [10] and feel the body movements; the role of the transmission of electrophysiological signals [11], such as additional wearable devices, body temperature, respiratory rate, heart rate, and blood pressure, can also be tested [12]. The neural sensor can be applied to the surface layer of the skin and can also be used for nerve signal transmission inside limbs. When used for the nerve signal transmission of the skin's surface layer, the carbon nanotube polyester thread of the carbon-based material is highly stretchable and insensitive to deformation, and has excellent stability ($>$ 15,000 cycles test), rapid response ($\leq$ 15 ms), high robustness, geometric layered sensing, and personalized cuttability [13]. In addition, there are 3D graphene-based piezoresistive sensors, which show good performance in electronic skin. It comes from electrospinning and 3D printing because of its simple preparation and readout. It is considered as a promising flexible sensor due to its simple mechanism, low power consumption, and convenient signal acquisition [14].

The neural sensor can also use metal nanomaterial, such as NiCo nanoparticles (as shown in Figure 1), which are derived from that nickel-cobalt nanoparticles obtained on the functionalized multiwall carbon nanotubes by a chemical reduction method and have higher stability, high sensitivity, repeatability, and low detection limit [15]. In terms of the combination of metal polymers and carbon nanomaterials, the polymer part can adjust the metal modulus, and the material can reduce the difference between soft tissues and electrodes and improve the function of prosthetic limbs. In addition, the emerging hydrogel material is also one of the nerve manufacturing options. As an artificial tissue or artificial limb into which bioelectronics can be implanted, it possesses biocompatibility, biodegradability, and antibacterial property. It also protects against heat and freezing and takes a long time to recover. Tensile, compressive, dynamic durability, and strain sensitivity are stronger than other materials [16]. For example, the proanthocyanidin/reduced graphene oxide (PC/rGO) composite material with a neural-like nanonetwork is introduced into a glycerol-plasticized polyvinyl alcohol-borax (PVA-borax) hydrogel system to obtain a bionic tactile PC/rGO/PVA hydrogel [17]. It can simulate and control some real epidermal movements controlled by nerves, such as finger bending and facial expression changes, and can simulate the tactile ability through the layered design

Table 2: The generation and use of skin material.

Material name	Generation method	Function	Advantage	Reference
Cross-linked gold nanoparticles	Using inkjet printing and scalable microforming technology	Prosthetic artificial skin	(1) Physical flexibility (2) Sensitivity	[20]
Polydimethylsiloxane (PDMS) zinc (ZnO) nanorods	The top and bottom electrode layers are interlocked by zinc oxide (ZnO) nanorods grown vertically on top of the PDMS to improve the sensitivity of the contact force and ambient temperature measurements	(1) A tactile sensor array was successfully fabricated and will be applied to (e-skin) (2) Tactile sensors can be used for flexible interfaces, wearable devices, and bionic robot skin	(1) High sensitivity (2) Flexibility (3) Measurable temperature	[21]
Silver nanowire @ polyurethane scaffold Carbon fiber active composite material	A tactile sensor was made by combining silver nanowires @ polyurethane scaffolds with layered carbon fabrics	The actual fingertip events can be transformed into visual or auditory interactive feedback in virtual reality	(1) Mechanical feeling range can be enhanced > 100% (2) High sensitivity (3) Fast response time 4 Repeatability	[23]
Carbon nanotubes (CNT) Film and polyacrylonitrile (PAN)	Use an electrostatic spinning process	The multimodal sensing capability is developed in the electronic skin for soft robots, intelligent artificial	(1) CNT strong, flexible, stretchable (2) PAN material can withstand thousands of cycles with little effect on the output signal	[25]
Carbon materials (carbon black (CB), carbon nanotubes (CNT), carbon fibers, graphene sheets, and graphene oxide)	Made from conductive nanofillers in an insulating or conductive polymer matrix	(1) Human motion detection (2) Soft robot (3) Smart textiles	(1) This is the most widely studied nanocomposite material (2) Low cost and available volume	[5]
Thermoelectric clays made of carbon nanotubes (CNT) and nonionic surfactants	Reconfigurable thermoelectric clay made of carbon nanotubes and viscous additives create a skin-compatible thermoelectric patch for e-skin	(1) To prevent hammering or even piercing (2) Used for skin adaptive semipermanent power supply with mechanical durability	(1) Skin suitability and mechanical durability (2) Very soft, stretchable, and repairable	[26]
Vertical graphene array (VGA)	A vertical graphene array (VGA) was fabricated directly on the surface of the natural latex film	E-skin can be used in soft robot, artificial limbs, wearable equipment, etc.	The electronic skin has multifunctional tactile perception of object pressure and surface morphology and also has noncontact sensing characteristics for temperature difference between the detected object and the electronic skin, including ultrafast response, elasticity, high sensitivity, and strong cyclicity	[27]
Laser-induced graphene (LIG) on polyimide film	The honeycomb electronic skin with laser-induced graphene (LIG) was prepared by one-step carbonization of polyimide film	(1) Promote carbon-based electronic skin with a large area array pattern (2) The e-skin has great potential for artificial intelligence, the universal touch of robots, and prosthetic limbs	(2) Strain sensitivity (2) It has excellent mechanical properties and high dyeing sensitivity (3) This kind of e-skin shows the perception ability and subtle touch to a wide range of human activities	Wei, Liu [28]
HCl-doped poly (o-methylaniline) (POMANI)-Mn 3O4 thin film nanocomposites	(1) Split using OP-AMP method (2) Shunting by logarithmic amplifier method	(1) Sensing prosthesis temperature (2) For prosthetic applications (3) Manufacture of conformal temperature sensors for prosthetic gloves/hands	(1) This nanocomposite sensor has consistency and flexibility (2) Various linearization methods have been analyzed to find the best output	[31]
				[30]

Table 2: Continued.

Material name	Generation method	Function	Advantage	Reference
Carrageenan and locust bean gum (hydrogel)	Photo-crosslinking of acrylamide provides an elastomeric matrix that is functionally modified with carrageenan and locust bean gum by physical crosslinking with K2CO3	The hydrogel-based soft controller is used for potential bionic skin of artificial limb human-computer interaction control	(1) The hydrogel has high elasticity (2) Recovers immediately after stretching to 500% or compressing to 10% of its original length (3) It can still maintain its flexibility and conductivity at low temperature	
Ionic gel, ionic liquids, hydrogel, and elastomers ITS	NM	Mimics human skin, such as anisotropic structures, mechanical behavior, and tactile function, and even includes mechanically sensitive ion channels critical for human tactile sensation	It has advantages in sensitivity, response speed, and multimode sensing, especially the development of electrochromism	[29]
Silane and keratin derivatives	A percutaneous bone-integrated prosthesis (POP) consists of a metal post attached to bone that extends outwardly through the skin to connect to an external prosthesis	A coating that mimics the composition of human nails	The purified human keratin biomaterial coating is resistant to degradation	[33]
Folded nanocone cluster	Novel microstructures introduce folded nanoclusters, semi-ellipsoids, and folds in different sensors	(1) Wearable equipment (2) Robots (3) In bionic artificial limb	(1) It can provide more complete and accurate interactive information such as gesture recognition and fine tactile discrimination (2) Real-time recording and mapping of multiple mechanical stimuli can be achieved due to independence, high sensitivity, and rapid response	[32]

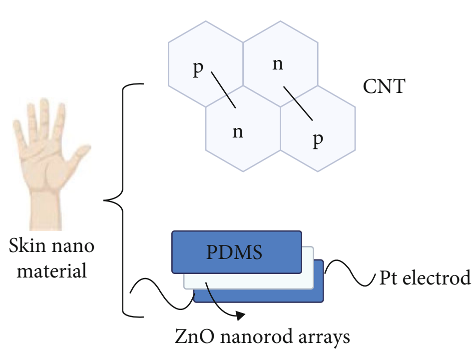

Figure 2

of hydrogel networks. There is also an ion gel gate organic synaptic transistor (IGOST) which can convert biological signals and bet regulate synaptic attenuation to generate an artificial neural network with long-term memory, thus realizing multifunctional neural mimicry application from neural mimicry calculation to neural prosthesis [18].

2.2. Skin Material. As shown in Table 2, nanomaterials for skin are metal materials, carbon-based materials, and other composite materials [5], in general, to make prosthetic limbs more realistic to the touch; air bladders are designed for each nanomaterial layer on the skin surface [19]. Metallic materials generally have advantages in terms of physical flexibility and sensitivity. Cross-linked gold nanoparticles, such as prosthetic skin and using inkjet printing and microforming techniques, can be extended to submillimeter dimensions [20]. Demonstrating high sensitivity, fast response time, and repeatability, in addition to the former, polydimethylsiloxane (PDMS) zinc oxide (ZnO) nanorods also have the ability to measure temperature [21], as shown in Figure 2. The mechanical feel range of smart sensors made of silver nanowire composites can be significantly enhanced > 100% programmatically, translating actual fingertip events into visual or auditory interactive feedback from the electronic device [22]; can be used for designing the intelligent artificial limbs with sensory disability and physical disability; and shows the feasibility and practicability of the design concept with the sense of future science fiction [23].

The research on carbon-based materials is quite extensive and advantageous. Carbon materials (carbon black (CB), carbon nanotubes (CNT), carbon fibers, graphene

Table 3: The generation and use of skeleton material.

Material name	Generation method	Function	Advantage	Reference
Polyester resin (jute, glass, carbon, pearl cotton) fiber	The laminated composite is reinforced with polyester resin as the bonding matrix and with (jute, glass, carbon, pearl cotton) fibers by vacuum bagging technology. The laminate samples were characterized by mechanical tensile tests, such as tensile strength, Young' s modulus, and elongation, and physical tests (density) to measure specific strength and specific modulus	The smoothness of the cross section increases, indicating that the brittle to semiductile transition occurs	Tensile strength reached 162 Mpa and modulus of elasticity reached 3.60 GPa. Specific strength and specific modulus up to 134 MPa. cm^3/gm–2.544 GPa. cm^3/gm	[37]
Composite material made of agave	Cantala fibers (CF) were treated with 6% NaOH and incubated for 0 h (UF), 3 h (AK3), 6 h (AK6), 9 h (AK9), and 12 h (AK12), respectively	Used as prosthetic engineering components to make prosthetic sockets	(1) The best tensile strength was obtained when Kantala fiber was treated with 1 6% NaOH solution (2) Biodegradable, with sufficient strength and power (3) Good mechanical resistance	[35]
Synthetic fibers (carbon, kevlar, and glass)	Made with a constant 5 wt% glass fiber-reinforced epoxy, vinyl ester, and polyester matrix with different jute and jute loading	Widely used as a reinforcing material in the manufacture of artificial limbs	(1) Strength and hardness increase with the increase in the proportion of natural fibers (2) Higher stretching and bending are obtained	[34]
(Carbon, jute, glass, and perlon) fiber-reinforced polyester resin	Different laminated composites, such as fiber-reinforced polymers, are used to make the prosthetic socket	It can be used in prosthetic sockets: devices that connect prosthetic limbs to amputated parts	(1) Bending strength, bending modulus, maximum shear stress, impact strength, fracture toughness (2) Manufacturing prosthetic socket makes wear more comfortable, light weight, high strength, and durable	[36]
MWCNT–(polydimethylsiloxane) PDMS	NM	(1) Development of printable nanocomposite tensile sensor system (2) Low-cost digital method for casting custom prosthetic liners (3) For growth/volume tracking (4) With embedded active cooling system	(1) Cheaper (2) Easier replacement and maintenance	[38]
EBM Ti-6Al-4V implant	The bioactivity and osteogenesis of the 3D-printed Ti-6Al-4V implant were enhanced by constructing layered micro-/nanotopography on the surface	Accelerating 3D printing in the future	NM	[41]
Ti-Ta composites	The Ti-Ta composites with layered structure were prepared by continuous discharge plasma sintering, machining, and annealing. The samples were sintered at 1200°C and then hot rolled at 60% high	Ti-Ta composites can be used in orthopedic applications	The Ti-Ta composite material with bionic structure has high strength, good ductility, low modulus, and good biocompatibility	[40]

Table 3: Continued.

Material name	Generation method	Function	Advantage	Reference
	pressure to exhibit a multiscale-layered microstructure			
Al_2O_3-CaO	It is composed of two materials (Al_2O_3-CaO) and prepared by sol-gel method	These composite materials are used in biological applications such as the manufacture of artificial limbs	(1) Compared with the polymer blend material without adding the nano powder, the mechanical property of the obtained composite material is remarkably improved (2) When different sizes of particles are added, respectively, the tensile property, flexural property and hardness are improved	[42]
High-density polyethylene (HDPE), polyamide (PA) 6 or nylon 6, polyamide (PA) 66	NM	This is the best choice for standing, walking, and running under standard loads	Various loads applied by the patient are supported	[39]

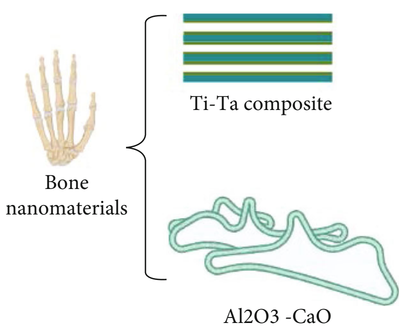

Figure 3

sheets, and graphene oxides) are generally made of conductive nanofillers. In multimode sensing, carbon-based materials have attracted much attention due to their strong sensing ability, durability, and low cost [24]. Synthetic materials such as carbon nanotube (CNT) films and polyacrylonitrile (PAN) are very strong, flexible, and stretchable when used as skin. It can withstand more than 1000 cycles with little effect on the output signal [25]. CNT can also be used with thermoelectric clay made of nonionic surfactant as viscous additive to make skin-adaptive thermoelectric patch for e-skin. It serves as a mechanically durable, skin-compatible, semipermanent power source that prevents hammering and even puncture [26].

Carbon-based nanomaterials are made with films of other materials and have different effects. For example, laser-induced graphene (LIG) was prepared by one-step carbonization of polyimide film [27]. Cellular electronic skin can be made that exhibits strain sensitivity to a wide range of tensile and compressive stimuli. Based on its excellent mechanical properties and high staining sensitivity, this e-skin well demonstrates the perception of a wide range of human activities and subtle tactile sensations. There is also a vertical graphene array (VGA), which is directly fabricated on the surface of a natural latex film using a simple method. It can realize the multifunctional tactile sensation to the pressure, air flow, and surface morphology of the object and can also sense the temperature difference sensing characteristic between the detected object and the electronic skin in a noncontact mode, including ultrafast response (6.7 ms) and elasticity (13.4 ms), wide pressure sensing range (2.5 Pa-1.1 MPa), high sensitivity, and strong cyclicity [28].

With respect to other composite materials, ionic gels, ionic liquids, hydrogels, and elastomers, ITS can mimic human skin, including not only typical anisotropic structures, mechanical behaviors, and tactile functions, but even mechanically sensitive ion channels crucial for human tactile sensation. Breakthrough element advances have been made in the sensitivity, response speed, and multimodal sensing of these materials [29], especially electrochromic breakthrough. Also improved carrageenan and locust bean gum are obtained on an elastic matrix by photo-crosslinking with acrylamide, the hydrogel having high elasticity, a stress of 0.04 MPa at 650% strain, which immediately recovers after stretching to 500%, or compression to 10% of its original length, which still maintains its flexibility and conductivity at a low temperature of -10°C [30]. Cutaneous nerve sensing: HCl-doped poly (o-toluidine) (POMANI)-Mn_3O_4 film nanocomposite material can be used for manufacturing conformal temperature sensors for upper limb hand skin or gloves [31]. In the aspect of receptor fabrication for finer functions, there are novel microstructures that introduce folded nanoclusters, semi-ellipsoids, and folds in different sensors to provide more complete and accurate interactive information to achieve finer functions, such as object manipulation and fine tactile discrimination, and real-time recording and mapping of multiple mechanical stimuli [32]. With respect to prosthetic nails, silane and keratin derivatives can mimic a coating of a human nail component, showing resistance to degradation [33].

2.3. Bone Material. As shown in Table 3, the skeletal material of the prosthetic limb is generally used for support and is therefore required to be particularly rigid. However, due to the need for user experience and the need for light weight, bone nanomaterials used for prosthetic limbs include fiber materials, metal composites, and composites. Fiber materials are generally synthesized by adding natural fibers and other fibers, which can significantly enhance their original properties. They are called reinforced materials. Such as a synthetic fiber made of carbon fiber, Kevlar fiber, and glass fiber, after adding a lot of jute fiber, strength and hardness increase with the increase in the proportion of natural fiber and also get higher tensile and bending ability [34]. This fibrous material is commonly used in prosthetic sockets, which are devices that connect prosthetic limbs to amputated parts. Among the skeletal materials, the choice of prosthetic socket material is of prime importance because it determines the user's experience. The bending strength, maximum shear stress, impact strength, and fracture toughness of the prosthetic socket can be enhanced with different laminated composites (fiber reinforced polymers). Agave fibers have biodegradability, sufficient strength and power, and good mechanical resistance [35], which are generally used as prosthetic engineering components, making prosthetic socket. Fiber-reinforced polyester resin, such as carbon, jute, glass, and perlon, can make prosthetic socket wear more comfortable, light weight, high strength, and durable [36]. Fiber laminate composites are very durable and are reinforced with polyester resin as the bonding matrix and with (jute, glass, carbon, pearl cotton) fibers by vacuum bagging. Upon mechanical stretching, the smoothness of its cross section automatically changes from brittle to semiductile [37].

Prosthetic sockets have cheaper options, such as MWCNT–(polydimethylsiloxane) PDMS, as a composite material that can be used to make prosthetic socket pads for embedded tensile sensors, active cooling systems, and at lower cost [38]. Composites for bones are high-density polyethylene (HDPE), polyamide (PA) 6 or nylon 6, and polyamide (PA) 66, which are the best choice considering standard loads for standing, walking, and running [39].

The metallic material is generally a Ti-Ta composite, sintered at 1200°C, and then hot rolled at a height of 60% reduction, which exhibits a multiscale-layered microstructure [40], as shown in Figure 3. It has a good bearing application prospect in orthopedics, such as EBM Ti-6Al-4V [41]; Ti-Ta composites with bionic structure have high strength, good ductility, low modulus, and good biocompatibility. Other high hardness bone materials include Al_2O_3-CaO composite nanoparticles, which can also significantly improve the tensile properties, flexural properties, and hardness [42].

3. Conclusion

The realization of the vast functions of the intelligent limb cannot be separated from various nanomaterials. When manufacturing an intelligent prosthetic limb, the selection of materials for each part is crucial. The results have shown that (1) carbon-based nanomaterials have been studied most deeply when they are used for neural materials. Because carbon-based material has strong stability and has simple transmission mechanism, the cost can be controlled when being use for manufacturing the artificial limb. Materials with the function of man-machine interaction are the focus of future research. (2) The nanomaterials for skin are mainly composite materials and generally contain metal- and carbon-based materials. Ionic gels, ionic liquids, hydrogels, and elastomers have been the focus of attention due to the sensitivity, multimodal, and memory properties of the materials. (3) Outstanding nanomaterials for bones are fiber materials, metal synthetic materials, and composite materials, with extremely high hardness, weight, and toughness. Of the skeletal materials, the choice of prosthetic socket material is the most important and is generally dominated by fiber laminate composites.

To date, the use of most nanomaterials in the manufacture of prosthetic limbs has been derived from limited experimentation. Due to the extraction process, manufacturing cost, stability, and other reasons, some parts have not yet been put into the actual production of prosthetic limbs. Therefore, the industry needs more relevant research, including specific material update iterations, generation of new functions (not only at the theoretical level), and disability motor function recovery data to finally verify the effectiveness and practicability of these nanomaterials. It is hoped that in the future, more materials can be applied to nanomaterials for artificial limbs, and the nanomaterials are more practical, environment-friendly, and cost-effective.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Authors' Contributions

The manuscript was written through the contributions of all authors. All authors have read and agreed to the published version of the manuscript.

References

[1] M. S. Hasnain, S. A. Ahmad, M. A. Minhaj, T. J. Ara, and A. K. Nayak, "6-Nanocomposite materials for prosthetic devices," in *Applications of Nanocomposite Materials in Orthopedics*, A. M. A. Inamuddin and A. Mohammad, Eds., pp. 127–144, Woodhead Publishing, Cambridge, England, 2019.

[2] E. Gashawtena, B. Sirahbizu, and A. Kidane, "Review on alternate materials for producing low cost lower limb prosthetic socket," *Journal of Material Sciences & Engineering*, vol. 10, no. 6, 2021.

[3] G. Valle, G. Preatoni, and S. Raspopovic, "Chapter 9-Connecting residual nervous system and prosthetic legs for sensorimotor and cognitive rehabilitation," in *Somatosensory Feedback for Neuroprosthetics*, B. Güçlü, Ed., pp. 293–320, Academic Press, Salt Lake City,Utah,USA, 2021.

[4] Y. Chen and T. J. Webster, "9-Nanostructured biomaterials for artificial tissues and organs," in *Biomaterials for Artificial*

Organs, M. Lysaght, Ed., pp. 236–269, Woodhead Publishing, Cambridge, England, 2011.

[5] M. A. U. Khalid and S. H. Chang, "Flexible strain sensors for wearable applications fabricated using novel functional nanocomposites: a review," *Composite Structures*, vol. 284, article 115214, 2022.

[6] E. J. Weathersby, J. C. Cagle, B. G. Larsen, K. M. Henrikson, and J. E. Sanders, "Development of a magnetic composite material for measurement of residual limb displacements in prosthetic sockets," *Journal of Rehabilitation and Assistive Technologies Engineering*, vol. 5, 2018.

[7] H. K. Talla, J. K. Oleiwi, and A. K. F. Hassan, "Performance of athletic prosthetic feet made of various composite materials with PMMA matrix: numerical and theoretical study," *Revue des Composites et des Matériaux Avancés*, vol. 31, no. 4, pp. 257–264, 2021.

[8] P. Zarrintaj, M. R. Saeb, S. Ramakrishna, and M. Mozafari, "Biomaterials selection for neuroprosthetics," *Current Opinion in Biomedical Engineering*, vol. 6, pp. 99–109, 2018.

[9] M. Al-Waily, M. J. Jweeg, Q. H. Jebur, and K. K. Resan, *Creep characterization of various prosthetic and orthotics composite materials with nanoparticles using an experimental program and an artificial neural network*, Materials Today: Proceedings, Amsterdam, Netherlands, 2021.

[10] F. Khoshmanesh, P. Thurgood, E. Pirogova, S. Nahavandi, and S. Baratchi, "Wearable sensors: at the frontier of personalised health monitoring, smart prosthetics and assistive technologies," *Biosensors and Bioelectronics*, vol. 176, article 112946, 2021.

[11] A. Leal-Junior and A. Frizera-Neto, "Soft wearable robots," in *Optical Fiber Sensors for the Next Generation of Rehabilitation Robotics*, A. Leal-Junior and A. Frizera-Neto, Eds., pp. 27–52, Academic Press, 2022.

[12] Z. Lou, L. Wang, K. Jiang, Z. Wei, and G. Shen, "Reviews of wearable healthcare systems: materials, devices and system integration," *Materials Science and Engineering: R: Reports*, vol. 140, article 100523, 2020.

[13] X. Liao, W. Wang, L. Wang et al., "A highly stretchable and deformation-insensitive bionic electronic exteroceptive neural sensor for human-machine interfaces," *Nano Energy*, vol. 80, article 105548, 2021.

[14] M. Cao, J. Su, S. Fan, H. Qiu, D. Su, and L. Li, "Wearable piezoresistive pressure sensors based on 3D graphene," *Chemical Engineering Journal*, vol. 406, article 126777, 2021.

[15] K. Arikan, H. Burhan, R. Bayat, and F. Sen, "Glucose nano biosensor with non-enzymatic excellent sensitivity prepared with nickel–cobalt nanocomposites on f-MWCNT," *Chemosphere*, vol. 291, Part 3, article 132720, 2022.

[16] P. Rahmani and A. Shojaei, "A review on the features, performance and potential applications of hydrogel-based wearable strain/pressure sensors," *Advances in Colloid and Interface Science*, vol. 298, article 102553, 2021.

[17] X. Pan, Q. Wang, P. He et al., "A bionic tactile plastic hydrogel-based electronic skin constructed by a nerve-like nanonetwork combining stretchable, compliant, and self-healing properties," *Chemical Engineering Journal*, vol. 379, article 122271, 2020.

[18] D.-G. Seo, Y. Lee, G. T. Go et al., "Versatile neuromorphic electronics by modulating synaptic decay of single organic synaptic transistor: from artificial neural networks to neuro-prosthetics," *Nano Energy*, vol. 65, article 104035, 2019.

[19] M. Buchanan, "Softer skin makes for more realistic touch from artificial limbs," *New Scientist*, vol. 210, no. 2807, p. 14, 2011.

[20] D. Alvares, L. Wieczorek, B. Raguse, F. Ladouceur, and N. H. Lovell, "Development of nanoparticle film-based multi-axial tactile sensors for biomedical applications," *Sensors and Actuators A: Physical*, vol. 196, pp. 38–47, 2013.

[21] M.-S. Suen, Y.-C. Lin, and R. Chen, "A flexible multifunctional tactile sensor using interlocked ZnO nanorod arrays for artificial electronic skin," *Procedia Engineering*, vol. 168, pp. 1044–1047, 2016.

[22] C. Demolder, A. Molina, F. L. Hammond III, and W. H. Yeo, "Recent advances in wearable biosensing gloves and sensory feedback biosystems for enhancing rehabilitation, prostheses, healthcare, and virtual reality," *Biosensors and Bioelectronics*, vol. 190, article 113443, 2021.

[23] X. Liao, W. Song, X. Zhang et al., "Hetero-contact microstructure to program discerning tactile interactions for virtual reality," *Nano Energy*, vol. 60, pp. 127–136, 2019.

[24] Y. Liu, R. Bao, J. Tao, J. Li, M. Dong, and C. Pan, "Recent progress in tactile sensors and their applications in intelligent systems," *Science Bulletin*, vol. 65, no. 1, pp. 70–88, 2020.

[25] J. W. Fastier-Wooller, V. T. Dau, T. Dinh, C. D. Tran, and D. V. Dao, "Pressure and temperature sensitive e-skin for in situ robotic applications," *Materials & Design*, vol. 208, article 109886, 2021.

[26] M. H. Kim, C. H. Cho, J. S. Kim et al., "Thermoelectric energy harvesting electronic skin (e-skin) patch with reconfigurable carbon nanotube clays," *Nano Energy*, vol. 87, article 106156, 2021.

[27] D. Yao, L. Wu, S. A et al., "Stretchable vertical graphene arrays for electronic skin with multifunctional sensing capabilities," *Chemical Engineering Journal*, vol. 431, article 134038, 2022.

[28] S. Wei, Y. Liu, L. Yang et al., "Flexible large e-skin array based on patterned laser-induced graphene for tactile perception," *Sensors and Actuators A: Physical*, vol. 334, article 113308, 2022.

[29] R. Scaffaro, A. Maio, and M. C. Citarrella, "Ionic tactile sensors as promising biomaterials for artificial skin: review of latest advances and future perspectives," *European Polymer Journal*, vol. 151, article 110421, 2021.

[30] Y. Miao, M. Xu, J. Yu, and L. Zhang, "Conductive cold-resistant and elastic hydrogel: a potential bionic skin for human-machine interaction control over artificial limbs," *Sensors and Actuators B: Chemical*, vol. 327, article 128916, 2021.

[31] A. Kumar, M. L. Singla, A. Kumar, and J. K. Rajput, "Fabrication and linearisation of conformable POMANI-Mn3O4 nanocomposite based thermistor for temperature monitoring applications in prosthetic gloves," *Sensors and Actuators A: Physical*, vol. 285, pp. 588–598, 2019.

[32] X. Zeng, Y. Liu, F. Liu et al., "A bioinspired three-dimensional integrated e-skin for multiple mechanical stimuli recognition," *Nano Energy*, vol. 92, article 106777, 2022.

[33] A. Trent and M. E. Van Dyke, "Development and characterization of a biomimetic coating for percutaneous devices," *Colloids and Surfaces B: Biointerfaces*, vol. 182, article 110351, 2019.

[34] J. M. Khare, S. Dahiya, B. Gangil, and L. Ranakoti, "Influence of different resins on physico-mechanical properties of hybrid fiber reinforced polymer composites used in human prosthetics," *Materials Today: Proceedings*, vol. 38, pp. 345–349, 2021.

[35] S. Sakuri, E. Surojo, D. Ariawan, and A. R. Prabowo, "Investigation of Agave cantala-based composite fibers as prosthetic socket materials accounting for a variety of alkali and microcrystalline cellulose treatments," *Theoretical and Applied Mechanics Letters*, vol. 10, no. 6, pp. 405–411, 2020.

[36] J. K. Oleiwi, Q. A. Hamad, and S. A. Abdulrahman, *Flexural, impact and max. shear stress properties of fibers composite for prosthetic socket*, Materials Today: Proceedings, Amsterdam, Netherlands, 2022.

[37] Q. A. Hamad, J. K. Oleiwi, and S. A. Abdulrahman, *Tensile properties of laminated composite prosthetic socket reinforced by different fibers*, Materials Today: Proceedings, Amsterdam, Netherlands, 2021.

[38] B. Oldfrey, A. Tchorzewska, R. Jackson et al., "Additive manufacturing techniques for smart prosthetic liners," *Medical Engineering & Physics*, vol. 87, pp. 45–55, 2021.

[39] S. Sundararaj and G. V. Subramaniyan, "Structural design and economic analysis of prosthetic leg for below and above knee amputation," *Materials Today: Proceedings*, vol. 37, pp. 3450–3460, 2021.

[40] Q. Huang, S. Xu, Z. Ouyang, Y. Yang, and Y. Liu, "Multi-scale nacre-inspired lamella-structured Ti-Ta composites with high strength and low modulus for load-bearing orthopedic and dental applications," *Materials Science and Engineering: C*, vol. 118, article 111458, 2021.

[41] B. Ren, Y. Wan, C. Liu et al., "Improved osseointegration of 3D printed Ti-6Al-4V implant with a hierarchical micro/nano surface topography: an in vitro and in vivo study," *Materials Science and Engineering: C*, vol. 118, article 111505, 2021.

[42] H. A. Sallal, A. A. Abdul-Hamead, and F. M. Othman, "Effect of nano powder (Al2O3-CaO) addition on the mechanical properties of the polymer blend matrix composite," *Defence Technology*, vol. 16, no. 2, pp. 425–431, 2020.