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Analysis on Characteristics of Implants and Surface Bionic Prosthetic Materials

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Abstract. According to the 1990–2020 Internet for literature on materials commonly used in prosthetics and their compatibility with skin tribology and biology, it found that with the large number of amputees affected by the disease, traffic accidents, work-related injuries, and natural disasters, the relatively high manufacturing costs of prostheses could place a financial burden on patients. In addition, the choice of prosthetic material itself affects the comfort and ease of use for the patient. Whether it is an osseointegrated prosthesis or a cavity-receiving prosthesis, the use of appropriate materials is an important issue in prosthetic engineering. This paper analyses the research conducted over the last 20 years on materials for implantable prostheses and receptive cavity materials and presents some of the findings on the preferred material selection for each type of material, as well as the associated biomechanical effects and skin tribology. Through the analysis, the paper concludes that for implantable materials, biocompatible materials such as metallic materials, bioceramics, and composites are preferred. For receptive cavity materials, polymeric materials such as thermoplastic sheets, resin-based composites, and low-temperature thermoplastics are preferred.

Keywords: Prosthetic materials, Implants, Biomechanics, Osseointegration

1. Introduction

According to the results of the second national sample survey of people with disabilities published in 2006–12, the total number of people with various types of disabilities in China is 82.96 million (6.34%), of which 24.12 million (29.07%) are physically disabled [1].

From 2012 to 2018, the number of amputations of both upper and lower limbs has increased year-by-year due to factors such as the disease, traffic accidents, work-related injuries, and natural disasters. Due to daily wear and tear and other factors, most prostheses need to be replaced with new parts after an average of 3 to 4 years, and the higher manufacturing cost of prostheses puts a financial strain on families in countries that lack comprehensive health insurance. The issue of prosthetics is one of the most important aspects of rehabilitation engineering research. It is now generally accepted that prosthetic materials should meet biocompatibility, which consists of two major principles: firstly, the principle of biosafety; and secondly, the principle of biofunctionality [2]. For implantable osseointegrated prosthetic materials, the biocompatibility of the material with the bone needs to prevent inflammation and infection.

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This paper analyses the research on implantable prosthetic materials and cavity-receiving materials over the last 20 years and presents the problems faced by each type of material, as well as the preferred material selection and the related biomechanical effects and some of the findings of skin tribology studies.

For implantable materials, biocompatible materials such as metallic materials, bioceramics, and composites are preferred. For receptive cavity materials, polymeric materials such as thermoplastic sheets, resin-based composites, and low temperature thermoplastic materials are preferred.

2. Intrinsic propertiesof implantable materials

2.1. Biomechanical properties

The concept of implantable osseointegrated prostheses was first introduced by Professor Branemark in Sweden. Drawing on the techniques of dental implants and artificial joint implantation [3], he implanted one end of the osseointegrated prosthesis into the bone marrow cavity of the residual limb to bind to the internal femur of the residual limb, and the other end penetrates the soft tissue of the skin to integrate with the external prosthetic component, generally consisting of a mechanical device responsible for movement [4,5], which is sealed percutaneously employing a bioactive material.

This technology not only allows the technical advantages of direct integration of the prosthesis with the bone to be exploited but also avoids the defects of the traditional prosthesis, which must rely on the receiving cavity to be connected to the residual limb [6].

The implant is directly implanted in the human body, and if ordinary materials are used to make the implant, the human body will reject the implant and the implant will fail, which may endanger the life of the patient.

The most commonly used biocompatible materials include metal, bioceramic, and composite materials. Although titanium is an active metal, it can be oxidized spontaneously in air, water, or other electrolytes, producing a very stable oxide film that does not dissolve or release any ions in general electrolyte solutions[7,8]. Titanium has excellent mechanical properties and its toughness and ductility ensure that the implant is not easily fractured; it is biocompatible and can be well integrated with bone tissue in the bone.

The main ceramic implant materials are hydroxyapatite ceramic, bioglass ceramic, tricalcium phosphate ceramic, and alumina ceramic. These implants are biocompatible, easy to integrate with the bone, and have good corrosion resistance and stable physicochemical properties, but their mechanical properties are poor, brittle, and prone to fracture under external forces.

Recent studies have found that composites combining the advantages of bioceramics and metals are widely recognized as osseointegration materials for implants because of their good mechanical properties and biocompatibility [9].

A metallic material with good mechanical properties as the main body of the implant and a thin layer of bioactive material is sprayed on the surface of the main body, while hydroxyapatite (HA) coating is one of the more common methods [10]. The surface osseointegration rate is significantly higher than that of pure titanium implants [11,12].

2.2. Biomechanical properties

The results of biomechanical plucking experiments show that the plucking force and plucking shear strength of the implant increase with the time of implantation. The effect of different loading effects on the formation and development of osseointegration is significant. The results of this study suggest that the effect of load-induced peri-implant stress on osseointegration should be considered in the design of implantable lower limb prosthesis configurations.

Of the many structural types of implants currently available, the most commonly used in the field of implantable osseointegrated prostheses is the threaded intraosseous implant. Threaded intraosseous implants not only increase the contact area with the bone but also provide maximum mechanical locking to increase initial stability on a macroscopic scale, provide a stronger interface bond than cylindrical or

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stepped implants with smooth surfaces, and reduce shear forces at the implant interface, making the implant less likely to slip or rupture [13,14].

More than 100 years ago, Wolff pointed out that there is a physiological dynamic equilibrium between mechanical stress and bone tissue, i.e., a dynamic equilibrium between resorption and an increase in bone mass within a certain stress range [15]. Current theories on the influence of biomechanical factors on bone reconstruction and reconstruction include the bone bioelectricity theory and the bone fiber cracking theory, and the design of compressive endoprosthetic implants is no exception. To achieve "osseointegration," the prosthesis must be stable after implantation. It has been found that to ensure the stability of a pressurized intraosseous implant after implantation, the pre-compression load given at the time of fitting must be greater than 1750 N. Also, according to the bone stress-strain curve, under loads less than the yield point of the bone compressive stress, the bone will only undergo elastic deformation and will not cause structural damage or bone destruction [16,17]. It is thus clear that the minimum amount of pre-compression load required to ensure implant stability creates compressive stress on the femoral cross-section that is not damaging to the bone tissue but instead is within the physiological range of mechanical stresses that can stimulate the bone tissue at the interface and promote its reconstruction and remodeling, eventually osseointegration of the implant.

3. Surface prosthetic material properties

With the development of industry, modern prostheses mainly use high-strength and lightweight materials to manufacture prosthetic parts, and traditional materials are increasingly widely replaced by modern polymeric materials. Among them, thermoplastic sheets, resin-based composite materials, and low-temperature thermoplastic materials are the most widely used in contemporary prosthetic production.

The main thermoplastic sheet prosthetic materials are polyethylene, polypropylene, and modified polyester.Polyethylene has a very low friction factor, but relatively low hardness and wear resistance, so it is used in artificial joints for long periods under large loads and with stainless steel, titanium, ceramics, and other hard materials to form reciprocal movements, which can easily cause many problems due to wear. Abrasive debris from wear tends to accumulate and induce a range of adverse biological reactions in the soft tissues and is therefore often modified by cross-linking and physical modification to improve its wear resistance properties.

Polyethylene can be used to make a variety of orthoses, such as spinal orthoses, upper limb orthoses, lower limb orthoses, and temporary acceptor cavities for prostheses, etc. Low-density polyethylene is mainly used in prostheses as a flexible acceptor cavity. It is translucent, low temperature resistant, corrosion resistant, easy to process, harder, and better than ordinary polyethylene sheets. The biocompatibility of polyethylene hydrogels has been recognized [18].

Polypropylene is a semi-crystalline material and due to its high crystallinity, this material has good surface stiffness and scratch resistance properties, good thermal deformation properties, and good mechanical properties. It can be used as a thermoplastic polypropylene load-bearing acceptance cavity and has good flexibility. Polypropylene is usually modified by adding glass fibers, metal additives, or thermoplastic rubber. Homopolymer and copolymer polypropylene materials have excellent resistance to moisture absorption, acid and alkali corrosion, and solubility, and can be used to make prosthetic acceptor cavities and various orthopedic devices, especially lower limb orthopedic devices for long-term wear and walking. Numerous animal experiments have proved that polyacrylamide hydrogel is non-toxic, non-carcinogenic, and non-allergic to rejection. The relatively mild inflammatory changes and the rapid formation of a thin connective tissue film after polyacrylamide implantation also indicate that polyacrylamide is biologically inert to a certain extent and has good histocompatibility.

Resin-based composites are fiber-reinforced materials with an organic polymer matrix. The main reinforcing fibers are glass, carbon, and aramid fibers. The main characteristics of this type of material are its high strength and lightweight. The graphite layer structure of the carbon fiber itself has self-lubricating properties, which can reduce the friction factor of the coating. Because of the good energy storage and release properties of the carbon fiber composite material, all sports prosthetic feet are made of carbon fiber composites. Carbon fiber reinforced resin composites have no systemic toxicity and no

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hemolytic activity [19]. Carbon fiber reinforced polyether ether ketone composite materials are biocompatible with in vitro cell culture, in vivo soft tissue, and with bone tissue [20].

Low-temperature thermoplastics are plastics that have a low softening temperature and can be shaped within the temperature range of human skin, with a plasticity temperature of 55 to 75 °C. The application of low-temperature thermoplastic materials can be shaped directly on the patient and can be put into use immediately after making adjustments. The material can be heated twice to facilitate re-shaping or local re-shaping and is mostly used as a material for the production of orthopedic external fixation, orthoses, and supports.

4. Research on the frictional properties of prosthetic materials and skin

The appropriate amount of friction between the skin and external materials is beneficial, while too much friction can cause damage to the skin or external materials. However, due to the design of the prosthetic limb or the unsatisfactory condition of the limb, excessive friction in some places will cause damage to the skin of the limb and also increase the wear and tear of the prosthetic material, thus shortening its service life [21].

Many factors influence the frictional properties of human skin, such as race, age, gender, the type of skin itself (oil content, wetness and dryness, etc.), and skin texture. Age-related skin tribology studies have yielded relatively different findings. The majority of scholars have confirmed that there are no significant differences in the effects of gender, body mass, and height on the frictional properties of the skin [22].

Tribological tests showed that the coefficient of friction between the skin and the material decreases with increasing load; at a load of 0.3N-0.7N, the coefficient of friction between the silicone rubber material and the disabled person's skin is greater than that of the normal person due to the special properties of the material and the differences in roughness, dryness, and elasticity of the skin between the normal person and the disabled person. The surface roughness and hydrophilicity/hydrophobicity of the other materials had a significant effect on the coefficient of friction, while differences in the surface properties of different groups of skin had a smaller effect on the coefficient of friction.

At 8N, all materials were in a state of adhesion to the skin, and the influencing factors had shifted from the surface properties of the skin and materials to the coordination ability of the subcutaneous tissues and muscles, and there was no significant difference in the coefficient of friction between human skin and all materials. The ratio of shear force to normal force between the skin and the material of the residual limb was slightly less than that of the normal person [23, 24].

5. Conclusion

This paper analyses the research conducted over the last 20 years on implantable prosthetic materials and recipient cavity materials, and describes the superior material selection for each of the two types of materials and the associated biomechanical effects, as well as some of the findings from skin tribology studies.

The paper concludes that for implantable materials, biocompatible materials such as metallic materials, bioceramics, and composites are preferred. For receptive cavity materials, polymeric materials such as thermoplastic sheets, resin-based composites, and low-temperature thermoplastics are preferred. As for the shortcomings of this paper, the experimental results cited in the paper are not validated due to the objective conditions, and the study is not robust enough, which can be polished in future studies.

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