Research

Polymer Materials in Orthotics and Prosthetics

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Abstract:
Polymer materials play a crucial role in the design and fabrication of orthotic and prosthetic devices, enhancing functionality, comfort, and aesthetics and thus significantly impacting patient mobility and quality of life. Their versatility, characterized by lightweight properties, biocompatibility, and customization potential, has transformed the field, particularly with the introduction of advanced manufacturing techniques such as 3D printing. Polymer materials are classified into thermoplastics, thermosetting plastics, specialty polymers, composites, and foams, each serving specific mechanical and structural functions. Thermoplastics enable reshaping during fittings, while thermosetting plastics provide necessary rigidity. High-performance materials like polyether ether ketone (PEEK) and carbon fiber composites offer superior strength and lightweight benefits, making them ideal for advanced applications. The integration of smart technologies further enhances prosthetic functionality, allowing for adaptive and responsive designs. However, challenges remain, including material durability, manufacturing waste, and economic barriers to adopting novel technologies. Research efforts focus on developing biodegradable and smart materials to improve sustainability and performance. The continued evolution of polymer materials in orthotics and prosthetics is poised to drive innovation, offering more effective and patient-centered solutions for individuals with mobility impairments.

Keywords: Polymer materials; orthotics, prosthetics; biocompatibility; smart materials; 3D printing

1. Polymer materials

1.1. Thermoplastics

Thermoplastics are a significant category of polymers used in orthotics and prosthetics due to their formability when heated. These materials become mouldable at specific temperatures and can be reheated multiple times, allowing for adjustments during fittings. Thermoplastics are categorized into low-temperature and high-temperature materials based on their melting points. Low-temperature thermoplastics, which can be moulded at temperatures less than 149°C, are often used for orthotic devices that provide temporary support and protection, such as Kydex, Orthoplast, and Polysar (Kogler et al., 2020). High-temperature thermoplastics require heating to higher temperatures and are typically moulded over a positive model of the patient’s limb. Common examples include polyethylene, polypropylene, and acrylic (Kogler et al., 2020; Professional Plastic, 2024).

1.1.1 Low-Temperature Thermoplastics

Low-temperature thermoplastics can be molded directly onto a patient's limb without the need for casting, significantly reducing the time from measurement to the finished product. These materials are particularly suited for spinal and upper extremity orthoses, where flexibility and quick adjustments are necessary. Basic tools, such as an electric frying pan or a heat gun, are sufficient for their application, making them convenient for practitioners (Kogler et al., 2020).

1.1.2 High-Temperature Thermoplastics

High-temperature thermoplastics, including polycarbonate and acrylonitrile butadiene styrene, are utilized in scenarios requiring greater structural strength and durability. Unlike low-temperature variants, these materials cannot be reshaped once cooled, making them suitable for applications where permanent shapes are needed, such as in prosthetic sockets and components (Kogler et al., 2020).

1.2. Thermosetting Plastics

Thermosetting plastics are another essential category in orthotics and prosthetics. These materials are applied in a liquid state over a positive model and are chemically cured to maintain their shape. Common thermosets include acrylic, polyester, and epoxy, which are often laminated with various fabrics to enhance structural properties. Unlike thermoplastics, thermosetting plastics cannot be reheated for reshaping, which makes them less flexible but advantageous for producing rigid orthoses and prostheses (Kogler et al., 2020; Professional Plastic, 2024).

1.3. Specialty Polymers

Advanced polymers like PEEK (polyether ether ketone) and PEKK (polyether ketone ketone) are gaining traction in the field of orthotics and prosthetics due to their biocompatibility and mechanical strength. These materials are particularly useful for implantable devices and structural components requiring enhanced durability. Their ability to be processed through techniques like CAD/CAM milling and 3D printing opens new avenues for customization in prosthetic design (Ardelean et al., 2023; Huber et al., 2023; Thibodeau et al., 2022).

1.4. Composites

Composites combine two or more materials to produce a substance with enhanced performance characteristics. In orthotics and prosthetics, composites often involve reinforcing fibers such as fiberglass, carbon fiber, or Kevlar embedded in a matrix material like thermosetting plastics. These combinations provide superior strength, lightweight properties, and resilience against stresses compared to the individual components alone. Carbon fiber, in particular, is known for its high strength-to-weight ratio, making it a popular choice for high-performance orthotic and prosthetic devices (Kogler et al., 2020).

1.5. Polyurethane Foams

Polyurethane open-cell foams serve as alternative materials for top covers in foot orthoses. They are favored for their excellent shock absorption and heat dissipation properties, contributing to enhanced comfort for users. Some commercially available options include Poron, PPT, and Vylite (Kogler et al., 2020).

2. Properties of Polymer materials

Polymer materials play a critical role in the design and fabrication of orthotic and prosthetic devices, owing to their diverse properties that influence functionality, comfort, and durability.

2.1. Durability and Fatigue Resistance

Durability, particularly fatigue resistance, is essential for polymer materials used in orthotics and prosthetics. This property determines the material's ability to withstand repeated cycles of loading and unloading during typical activities, which can compromise strength and increase the risk of failure or fracture (Kogler et al., 2020). The interface between materials with differing characteristics can exacerbate fatigue resistance challenges, making it crucial to select compatible materials.

2.2. Density and Weight Considerations

The density of a polymer material significantly impacts the overall weight of an orthotic or prosthetic device. Lighter materials are generally preferred to minimize energy costs during functional activities; however, achieving optimal strength, durability, and fatigue resistance may necessitate using denser materials. For example, some advanced polymers, such as Kevlar, provide tensile strength properties that are significantly greater than those of steel, allowing for lighter designs without sacrificing strength (Kogler et al., 2020).

2.3. Corrosion Resistance and Moisture Imperviousness

Corrosion resistance is another vital characteristic of polymers in orthotic and prosthetic applications. Many materials used retain heat, which can exacerbate issues related to perspiration and moisture retention. Materials that are impervious to moisture are easier to clean and maintain compared to porous options, making them more suitable for devices used in potentially wet environments or by patients with incontinence concerns (Kogler et al., 2020).

2.4. Stiffness and Flexibility

The stiffness of polymer materials is crucial in determining their suitability for various applications within orthotics and prosthetics. Stiff materials provide stability and support, making them ideal for devices like fracture braces and rigid prosthetic frames. Conversely, flexible materials are necessary for components that must conform to body segments, such as in a posterior leaf-spring ankle-foot orthosis (AFO) or a flexible transfemoral prosthetic socket (Kogler et al., 2020).

2.5. Ease of Fabrication

The ease of fabrication is a practical consideration when selecting polymer materials. Thermoplastics, for example, can be reheated and reshaped multiple times, allowing for minor adjustments during fittings. Techniques like thermoforming, where sheets of thermoplastic are heated and shaped over molds, are commonly employed in the production of orthotic and prosthetic devices. In contrast, thermosetting materials require chemical curing, limiting their ability to be reshaped once set (Kogler et al., 2020).

2.6. Mechanical Properties and Applications

The mechanical properties of polymers, including strength, ductility, and yield strength, are critical in ensuring the reliability of orthotic and prosthetic devices. High strength-to-weight ratios are particularly important for components subjected to repetitive loading. Low-alloy and high-alloy steels are also utilized in conjunction with polymer materials for certain joint components, balancing the mechanical properties of both materials for optimal performance under load (Kogler et al., 2020).

3. Applications in Orthotics

Orthoplast is a material commonly used in orthotics, favored by occupational therapists, orthotists and prosthetists, orthopedic technicians, and physicians due to its direct application on patients, which eliminates the need for a negative impression. It is made from thermoplastic polymers, typically polyolefins like polyethylene (PE) or polypropylene (PP). These materials can be heated to become soft and flexible, allowing them to be molded around body parts (e.g., limbs) to create protective splints, braces, or orthotics. Once the material cools, it hardens and retains its shape, providing solid support and protection for injured or weakened areas of the body. Its thermoplastic properties make it easy to mold, while still maintaining strength and stability after cooling, making it ideal for orthopedic applications where flexibility and support are essential. This material is frequently employed in the fabrication of orthoses for the treatment of fractures, providing ease of molding and adaptability (Showers & Strunck, 1984; Drijkoningen et al., 2018).

3.1. Characteristics of Orthoplast

Orthoplast has the capability to be custom molded over two positive models, allowing for flexibility in design. While it is often utilized in various applications, it is not always the preferred choice due to its comparatively shorter life expectancy when juxtaposed with other more durable flexible sheet plastics. Despite this, orthoplast remains a popular choice for certain applications, such as the orthotic treatment of scoliosis using Milwaukee style orthoses or T.L.S.O. "body jackets" (Karimi & Kavyani, 2015). The material's ability to be easily adjusted with a heat gun post-fabrication enhances its usability, particularly for patients who require modifications after initial fitting.

3.2. Advancements in Orthotic Technology

The integration of thermo-plastics has marked significant advancements in orthotic practices. The process typically involves taking a negative impression of the body segment, followed by laboratory assembly to create a custom-molded orthotic device tailored to the patient’s specific disability.

3.3 Other Materials and Techniques

In addition to orthoplast, other materials such as ortholene are also utilized in orthotics, particularly for posterior leaf spring ankle-foot orthoses (AFOs) designed for patients with weak dorsiflexors. However, the durability of ortholene has been questioned, leading to the exploration of subortholene, a newer material reported to offer improved longevity (Gatt et al., 2016).

4. Applications in Prosthetics

The application of polymer materials in prosthetics has revolutionized the design, functionality, and comfort of artificial limbs. Modern prosthetic devices leverage advanced polymers and composites to enhance user experience and performance.

4.1. Lightweight and Durable Design

One of the key benefits of polymer materials is their lightweight nature. Traditional prosthetics made from wood or metal often resulted in cumbersome and uncomfortable devices. In contrast, polymers like carbon fiber composites and medical-grade silicone provide significant weight reduction while maintaining structural integrity. This improvement allows users to wear their prosthetics for extended periods without discomfort, enabling a more active lifestyle (Howington, 2023).

4.2. Customization and Fit

Customization is essential in prosthetics, as each user's needs can vary widely based on factors such as the type of amputation and personal preferences. The use of 3D printing technology allows for rapid production of tailored prosthetic limbs that fit the unique contours of the user's body. This adaptability is crucial for enhancing the functionality and aesthetic appeal of prosthetic devices (Howington, 2023; Sakib-Uz-Zaman & Khondoker, 2023). Moreover, the ability to create complex designs with polymers can lead to improved fit and performance, addressing the individual needs of each patient (Choo et al., 2020; Huber et al, 2023; Sakib-Uz-Zaman & Khondoker, 2023; Thibodeau et al., 2022).

4.3. Advanced Features

Recent advancements have seen the integration of smart technologies into prosthetic devices. Polymers facilitate the development of bionic and myoelectric prosthetics that utilize sensors to detect electrical signals from the user's residual muscles. This enables the prosthetic to respond to the user's intentions, allowing for more natural movements such as grasping and walking (Grace Prosthetic Fabrication, 2024; Howington, 2023, Shallal et al., 2019). Furthermore, incorporating antimicrobial properties into polymer materials helps reduce the risk of infection, especially for users in warm and humid climates (Grace Prosthetic Fabrication, 2024).

4.4. Cost-Effectiveness

In addition to performance benefits, polymer materials can also contribute to cost reductions in prosthetic manufacturing. The affordability of 3D printing and the low material costs associated with polymers make it possible to produce high-quality prosthetics at a fraction of the price of traditional methods. Reports indicate that 3D-printed prosthetic devices can be 56–95% less expensive than their laminated counterparts, making them accessible to a broader range of individuals (Sakib-Uz-Zaman & Khondoker, 2023; Huber et al, 2023; Thibodeau et al, 2022).

4.5. Future Directions

The ongoing research and development of polymer materials in prosthetics indicate a promising future for the field. Innovations such as topologically optimized designs and smart prosthetics are expected to further enhance the functionality and usability of these devices. As manufacturers continue to explore advanced polymers and composites, the potential for even greater improvements in comfort, safety, and performance is substantial (Grace Prosthetic Fabrication, 2024).

5. Advantages of Using Polymer Materials

Polymer materials have become increasingly prominent in the field of orthotics and prosthetics due to their unique properties and advantages.

5.1. Cost-Effectiveness

Recent developments in additive manufacturing (AM) have demonstrated that polymer-based prosthetic devices can be produced at significantly lower costs compared to traditional methods. Reports indicate that 3D-printed prosthetic devices can be 56-95% less expensive than those fabricated using conventional techniques (Sakib-Uz-Zaman and Khondoker, 2023). This reduction in cost, coupled with improved manufacturing efficiency, can increase access to these life-enhancing technologies for individuals who may otherwise be unable to afford those (Huber et al., 2023).

5.2. Durability and Fatigue Resistance

One of the primary benefits of polymers, such as polyethylene and polypropylene, is their excellent durability and fatigue resistance. These materials are capable of withstanding repeated cycles of loading and unloading, which is crucial for devices that endure significant mechanical stress during daily activities (Nagarajanet al., 2023). The long fatigue life of polyethylene, for example, makes it suitable for various applications, including prosthetic sockets and orthotic components, ensuring longevity and reliability.

5.3. Lightweight Design

The density of polymer materials allows for the creation of lightweight devices that enhance user comfort and mobility. Since lighter prosthetics reduce the physical burden on the user, polymers are often preferred over traditional metals, striking a balance between strength and weight. This is particularly important for patients who rely on these devices for mobility, as excessive weight can impede movement and increase fatigue.

5.4. Customizability and Design Flexibility

Polymers can be easily formed, die cut, and machined, allowing for a high degree of customizability in orthotic and prosthetic design (Professional plastics, 2024). Advanced manufacturing techniques such as 3D printing have further enhanced this ability, enabling the production of highly customized implants that ensure optimal fit and performance for individual patients. This customization is critical for addressing the unique needs of each user, potentially leading to better outcomes and increased satisfaction (Huber et al, 2023; Thibodeau et al, 2022).

5.5. Biocompatibility

Another significant advantage of polymer materials is their biocompatibility. Many polymers are well-tolerated by the human body, minimizing the risk of adverse reactions when used in orthopedic devices. This makes them suitable for both temporary and long-term applications, which is essential in the development of prosthetics and implants that integrate seamlessly with biological tissues.

6. Challenges and Limitations

The integration of polymer materials in orthotics and prosthetics presents several challenges and limitations that practitioners and manufacturers must navigate to optimize device efficacy and patient satisfaction. These issues can broadly be categorized into material properties, manufacturing processes, and economic factors.

6.1. Material Properties

The selection of appropriate polymer materials is crucial for the performance of orthotic and prosthetic devices. Durability, fatigue resistance, and corrosion resistance are key considerations. For instance, materials must withstand repeated cycles of loading without succumbing to failure, particularly in applications where high stress is anticipated, such as lower limb devices (Caselli, 2004). The challenge lies in balancing the need for lightweight materials against the requirements for strength and durability, as denser materials may provide necessary mechanical support but can compromise patient comfort and energy efficiency during use. Additionally, the viscoelastic properties of certain polymers can complicate the design process. For example, materials like Sorbothane and Viscolas, which exhibit stress relaxation and creep, must be carefully considered to ensure they provide adequate support while allowing for necessary movement and comfort (Caselli, 2004).

6.2. Manufacturing Processes

The traditional methods of fabricating orthotic and prosthetic devices often involve manual processes that can produce significant waste and pose health hazards due to dust from cutting and grinding materials like fiberglass and carbon fiber (Sakib-Uz-Zaman & Khondoker, 2023). These conventional approaches not only increase costs but also create environmental concerns. Recent advancements in additive manufacturing (AM) have shown promise in addressing these limitations by enabling more efficient use of materials and reducing waste. However, the transition to AM is not without its own set of challenges, including the need for substantial investment in new technologies and training for personnel to operate these advanced systems (Sakib-Uz-Zaman and Khondoker, 2023).

6.3. Economic Factors

Economic constraints represent a significant barrier to the widespread adoption of innovative materials and manufacturing technologies in the O&P field. Many small and medium-sized facilities may find it economically unfeasible to invest in expensive 3D printing equipment, which can hinder their ability to provide cutting-edge solutions. While some practices have begun outsourcing fabrication to larger manufacturers, this approach may not be sustainable or practical for all providers (Sakib-Uz-Zaman & Khondoker, 2023). The cost-benefit analysis of adopting advanced manufacturing techniques continues to be a pivotal factor that influences decision-making in the industry.

7. Recent Innovations and Trends

The field of orthotics and prosthetics has seen significant advancements in recent years, particularly through the application of innovative polymer materials. These developments not only enhance the functionality and comfort of prosthetic devices but also improve patient outcomes.

7.1. Advancements in Polymer Technologies

Recent innovations in polymers are transforming orthopedic medicine. Key breakthroughs include the introduction of bioabsorbable and shape-memory polymers, as well as antimicrobial materials. These advanced polymers are paving the way for more effective and sustainable orthopedic treatments, ensuring better integration with the body and reducing the need for additional surgeries.

7.2. 3D Printing and Customization

One of the most impactful technologies in this domain is 3D printing, which allows for the creation of highly customized implants and prosthetics. This technology enables the production of devices tailored to the unique anatomy of each patient, significantly improving fit and performance. Moreover, the ongoing research into new thermoplastics and composites aims to further enhance the strength, flexibility, and antimicrobial properties of 3D-printed orthotic devices (Choo et al., 2020; Huber et al., 2023; Thibodeau et al, 2022).

7.3. Smart and Biodegradable Polymers

The exploration of smart polymers—materials that can respond to external stimuli such as temperature and pH—holds great promise for future prosthetic development. These materials can adapt over time to meet the changing needs of patients, thus enhancing the usability of prosthetic devices (Shallal et al., 2019; Nagarajanet al., 2023). Additionally, research into biodegradable polymers is advancing, which aims to create prosthetic components that safely degrade within the body, thereby improving patient recovery and reducing the need for surgical removal of temporary implants.

8. Challenges and Future Directions

Despite the promising advancements, several challenges remain in the use of polymers for prosthetic devices. Material degradation due to prolonged exposure to physiological conditions poses risks to the durability and effectiveness of these devices. Additionally, ensuring a perfect fit through customization remains a critical aspect of prosthetic design. However, the continued evolution of polymer technology, coupled with innovative manufacturing techniques such as CAD/CAM milling and light-curing, presents exciting opportunities for the future (Ardelean et al., 2023).

Conflicts of Interest: The author declares no conflict of interest.

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