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Advancements for artificial ligaments: enhancing biological activity and antibacterial performance

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Abstract. Anterior cruciate ligament (ACL) reconstruction is one of the most frequently performed orthopedic procedures, particularly for athletes seeking to restore knee stability and function. Polyethylene terephthalate (PET) is widely used for artificial ligaments due to its durability and chemical stability. However, PET's inherent limitations, including poor osteoconductivity and biocompatibility, contribute to graft failure and postoperative infections. Recent advancements in surface functionalization, including the incorporation of hydroxyapatite (HAp) and bioactive glass, have significantly improved PET's osteoconductive and osteoinductive properties, promoting enhanced bone integration and healing. Additionally, innovations in antibacterial coatings, such as silver nanoparticles and polydopamine, have demonstrated potential in reducing infection rates and improving the longevity of implants. This review highlights these technological advances, emphasizing how biomaterials and surface modifications are transforming the performance of PET-based artificial ligaments, leading to more successful ACL reconstructions and improved patient outcomes.

Keywords: ACL reconstruction, Polyethylene terephthalate, Hydroxyapatite, Bioactive glass, Antibacterial coatings.

1. Introduction

Anterior cruciate ligament (ACL) reconstruction has emerged as the primary treatment for ACL rupture over the past two decades [1]. It is now the sixth most common orthopedic procedure in the United States, with over 150,000 cases performed annually [2]. This surgery is essential for restoring knee stability and proper joint function after injury, particularly for athletes [3] and active individuals aiming to return to pre-injury performance levels. By repairing the damaged ACL, reconstruction not only prevents further injuries, such as meniscal tears, but also alleviates pain and discomfort, allowing patients to resume their daily activities. Moreover, timely ACL reconstruction is crucial for reducing the risk of long-term complications, such as osteoarthritis, thus contributing to better overall knee health [4].

An ideal artificial ligament material should combine high tensile strength [5], moderate viscoelasticity, friction resistance, fatigue resistance, and strong bioinductance [6]. However, early evaluations of synthetic grafts identified several challenges, including high failure rates, sterile effusions from wear particles, bone tunnel enlargement, and late-onset infections [7]. While synthetic grafts offer certain advantages, they are generally more expensive and have been associated with complications, limiting their widespread adoption.

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Polyethylene terephthalate (PET) is currently the most widely used material for artificial ligaments due to its durability, impact resistance, and chemical stability [8]. However, PET's lack of mechanical viscoelasticity and weak bioinductance can hinder tendon-to-bone healing increasing the risk of bone tunnel enlargement and graft failure [9]. To address these limitations, researchers have developed PET-based composite materials by incorporating functional coatings and additives. These modifications enhance PET's biological activity, osteogenic potential, and antibacterial properties while improving its heat resistance and crystallization rate. This review will examine the advancements in surface functionalization of PET to enhance its performance as an artificial ligament material, with a particular focus on biological activity and infection prevention.

2. Enhancing osteoconductive and osteoinductive properties

Osteoconductivity in artificial ligaments refers to the ability to support the growth and integration of bone tissue around the implant [10]. Materials with strong osteoconductivity promote better growth and attachment of surrounding bone tissue on their surface, enhancing the stability and durability of the artificial ligament [11]. To integrate effectively with bone tissue, artificial ligaments must possess good biocompatibility, avoiding inflammatory responses and facilitating proper ligament-to-bone integration. A strong connection between the artificial ligament and bone tissue improves the functionality and long-term success of the implant.

However, PET by itself lacks osteoconductivity and osteoinductivity, which can affect the ligament's long-term prognosis [12]. Coating modifications aimed at improving surface hydrophobicity and bioinertness offer a solution, helping the graft achieve "ligamentization." Through surface coating techniques, a mineralized coating with both osteoconductive and osteoinductive properties can be applied to PET [13].

Jafari et al. has demonstrated the effectiveness of hydroxyapatite (HAp) coatings on PET ligaments [14]. A study focused on enhancing the biocompatibility and osseointegration of titanium-based implants by depositing HAp coatings using the sol-gel method [15]. The study further explored composite HAp coatings on PET ligaments, finding that incorporating gel (Gel) into the coating significantly improved both biocompatibility and mechanical properties. The combination of HAp's osteoconductivity and Gel's biocompatibility promoted bone integration and tissue regeneration, addressing the inherent bioinertness of PET [16]. Additionally, the coating increased the mechanical stability of PET ligaments by improving surface hardness, wear resistance, and stiffness, enhancing the implant's load-bearing capacity and reducing the risk of stress shielding.

HAp is chemically similar to natural bone, providing excellent osteoinductivity and promoting strong bonding with bone tissue [17]. Its corrosion resistance also acts as a protective barrier, preventing metal ion release from the implant and extending the lifespan of the material. Mechanically, HAp increases coating hardness, wear resistance, and adhesion strength, minimizing the risk of failure due to stress mismatches at the bone-implant interface [18].

Advances in biomaterials continue to show promise for improving implant performance. Nanotechnology could create more uniform HAp coatings at the nanoscale, improving bioactivity and mechanical properties [19]. Combining HAp with bioactive materials or growth factors could further enhance osteoinductivity. Additionally, incorporating antibacterial agents into the HAp matrix may help prevent postoperative infections. Long-term in vivo studies will be essential for assessing durability under physiological conditions, and personalized coatings tailored to individual patients could optimize implant success [20].

Recent studies have also focused on bioactive glass-modified PET ligaments. These studies show that integrating bioactive glass into PET enhances both its biocompatibility and osteoinductive properties. In vitro tests using MC3T3-E1 cells demonstrated superior cell density and alkaline phosphatase activity in bioactive glass-PET composites compared to pure PET [21], indicating an improved environment for osteogenesis. In vivo, the composite outperformed pure PET in bone integration and healing, particularly in a rabbit knee ligament rupture model, where it exhibited higher

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pull-out strength and more extensive new bone formation [22]. Future research could further optimize bioactive glass integration with different biomaterials to improve outcomes in clinical settings.

3. Enhancing antibacterial capabilities

Despite the superior mechanical properties of traditional PET artificial ligaments, their poor biocompatibility often results in postoperative complications, including synovitis and infection [23, 24]. These complications not only delay patient recovery but can also lead to the eventual failure of the surgery. Therefore, enhancing the antibacterial capabilities of PET-based artificial ligaments has become a key focus in this field.

Recent advances in nanotechnology have highlighted the potential of silver coatings due to their excellent antibacterial properties and bioactive repair characteristics. By modifying PET ligaments with silver coatings, researchers aim to significantly improve the material's antibacterial capabilities, thereby reducing postoperative infections and inflammation, which in turn enhances the clinical outcomes of artificial ligament applications. Experimental studies have systematically explored the antibacterial, biocompatible, and mechanical properties of silver-coated PET ligaments, providing a theoretical foundation and technical support for the development of more advanced artificial ligaments [25].

The application of nanosilver coatings, ranging in thickness from 50 to 500 nm, has been shown to markedly enhance the antibacterial properties of PET ligaments. These coatings inhibit the growth of various bacterial strains, achieving an antibacterial rate exceeding 90%, while also displaying strong anti-inflammatory effects. Notably, nanosilver-coated ligaments exhibit reduced incidence of postoperative synovitis [25]. In addition to their biological benefits, nanosilver coatings improve the mechanical stability of PET ligaments [26], supporting better tendon-bone healing. The uniformity and stability of the coating ensure long-lasting antibacterial effects, meeting the clinical requirements for bioactivity as well as mechanical performance.

In addition to surface coatings, the chemical modification of PET by incorporating antibacterial agents directly into the polymer matrix is another promising approach. A notable study on the integration of polyhexamethylene guanidine (PHMG), a potent antibacterial agent, into PET fibers demonstrated significant improvements in both antibacterial performance and material durability. The modified PET material (PET-g-PHMG), with a PHMG content of 15%, exhibited a bonding efficiency of 93.7% [27]. Transmission electron microscopy revealed uniform distribution of PHMG at the nanoscale within the PET matrix, which enhanced its compatibility with the polymer.

PET-g-PHMG samples demonstrated superior antibacterial efficacy, with inhibition rates exceeding 99% against Escherichia coli and Staphylococcus aureus [28]. Importantly, the antibacterial effect was sustained even after repeated washings, highlighting the durability of the modification. The incorporation of PHMG also improved the mechanical properties of PET, reducing material degradation while preserving mechanical viscosity. Furthermore, the modified PET exhibited excellent spinnability, allowing for the production of antibacterial PET fibers through melt spinning [29], which retained their antibacterial properties even after washing, making them suitable for various medical applications.

The incorporation of antibacterial agents like PHMG into the PET matrix represents a significant advancement, addressing PET's limitations in both biocompatibility and infection control. Such innovations not only improve the antibacterial properties of PET but also ensure that the material maintains its functional and mechanical integrity [30]. These findings underscore the potential of material innovation in tissue engineering, particularly in advancing artificial ligament development. Future research should explore further enhancements in antibacterial activity and broader applications of these materials across the biomedical field.

Building on these advancements, another innovative approach involved coating PET ligaments with a polydopamine (PDA) nano-layer and embedding silver atoms to improve antibacterial performance. PET artificial ligaments, known for their excellent biomechanical properties [31], remain susceptible to infection due to their biological inertness. The PDA coating serves as an adhesion layer, enhancing the surface for embedding silver atoms, which are well-known for their antimicrobial properties. Studies showed that silver-modified PET ligaments significantly inhibited the growth of Staphylococcus aureus, reducing bacterial proliferation and providing effective antibacterial protection [32].

The PDA-nano-hydroxyapatite (nHA)-silver coating not only imparts strong antibacterial properties but also strengthens the mechanical stability of PET ligaments [33], improving their potential in clinical applications. This coating approach highlights the importance of multifunctional coatings that address infection control while enhancing mechanical performance.

As biomedical engineering continues to evolve, the application of advanced materials in artificial ligaments holds promise for improving patient outcomes by simultaneously enhancing antibacterial properties and mechanical stability. However, long-term biocompatibility and stability remain areas for further exploration, particularly in dynamic biological environments. Future research should focus on the durability of these modified materials under real-life conditions, including their long-term interaction with host tissues. Additionally, the development of 3D printing and nanotechnology opens the door for personalized, patient-specific artificial ligaments, enabling precise customization to meet individual patient needs [34].

Another exciting direction for future research is the exploration of multifunctional coatings and composite materials that simultaneously address antibacterial, anti-inflammatory, and tissue-regenerative challenges. For instance, coatings that combine antibacterial agents, anti-inflammatory factors, and bioactive substances could offer comprehensive post-surgical protection, promoting faster recovery and tissue integration. While laboratory research has demonstrated promising results, translating these innovations to clinical applications presents challenges, particularly in large-scale production. Collaboration between material scientists, clinical researchers, and manufacturers will be essential to ensure that these novel materials are successfully implemented in real-world medical settings and can benefit a wider patient population [35].

4. Conclusion

The development of artificial ligaments, particularly those utilizing PET, has made considerable progress in addressing its inherent shortcomings. While PET exhibits excellent mechanical properties, its poor osteoconductivity and biocompatibility have limited its long-term success in ligament reconstructions, especially for ACL repairs. Recent advancements in surface functionalization, such as the incorporation of HAp, bioactive glass, and silver nanoparticles, have significantly improved PET's biological activity, mechanical strength, and antibacterial properties. These innovations not only enhance bone integration and promote healing but also effectively mitigate the risk of postoperative infections. Additionally, the integration of nanotechnology and bioactive agents has the potential to create multifunctional coatings that further support tissue regeneration and infection prevention. However, long-term clinical studies are necessary to fully evaluate the durability and performance of these enhanced materials under real-world conditions. Future research should prioritize personalized, patient-specific approaches, utilizing 3D printing and advanced biomaterials to optimize the success of ligament implants. Continued collaboration among material scientists, biomedical engineers, and clinicians will be essential to translate these promising innovations into clinical practice, ultimately improving patient outcomes in ACL reconstruction and other ligament repair surgeries.

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