

Advances in Electrical Materials for Bone and Cartilage Regeneration: Developments, Challenges, and Perspectives

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Severe bone and cartilage defects caused by trauma are challenging to treat, often resulting in poor outcomes. An endogenous electric field (EnEF) is crucial for bone regeneration, making electrical materials a promising therapy. This review provides a comprehensive overview of the role of bioelectric signals in bone and cartilage cells, alongside recent advancements in electrical biomaterials, with particular emphasis on nanogenerators, piezoelectric materials, triboelectric scaffolds, and zwitterionic hydrogels. It further investigates the impact of these electrical biomaterials on bone and cartilage regeneration, as well as the applications of both endogenous and exogenous electrical stimulation (ES) and the mechanisms underlying ES-induced cellular and molecular responses. Finally, the review underscores future directions for ES systems in tissue engineering, emphasizing the critical importance of integrating structural integrity, mechanical properties, and electrical signal delivery into intelligent implantable scaffolds.

1. Introduction

Bone and cartilage injuries caused by factors such as trauma, tumors, strain, and osteoarthritis are becoming increasingly common in daily life. Among the various treatment methods, such as bone transplantation, membrane-induced regeneration, gene therapy, and tissue engineering, bone tissue regeneration has received widespread attention from researchers owing to its low surgical difficulty and significant repair effects.^[1] The key to bone tissue engineering lies in regulating the directional differentiation of stem cells to promote bone regeneration. However, the development of ideal bone tissue regeneration materials still faces enormous challenges. Recently, the use of implanted synthetic scaffolds to mimic the osteogenic microenvironment has emerged as a promising approach for modulating the extracellular environment at wound sites to enhance bone

regeneration.^[2] However, because of the limited effectiveness of bone and cartilage repair after implantation, relying exclusively on biological materials for *in vivo* restoration is insufficient. One contributing factor is that the critical influence of physical signals such as bioelectricity within the bone and cartilage microenvironments is frequently neglected.^[3] Lacking endogenous electric fields (EnEFs) and the ability to detect mechanical stimuli, these tissues suffer further microenvironmental damage.^[4] Fortunately, mechanical stimulation can be transformed into electrical signals by modifying the activity of the mechanically sensitive channels associated with piezoelectric materials.^[5]

Electrical stimulation (ES) has garnered significant attention as a crucial biophysical regulatory factor and non-pharmacological intervention in clinical settings, owing to its remarkable capacity to influence cell activity and promote tissue repair.^[6–8] Emerging nanogenerators, which are considered promising candidates for future energy technologies, can convert mechanical energy into electrical energy via frictional or piezoelectric effects.^[9] Piezoelectric nano-materials are functional substances that show great potential for nano-scale conversion of mechanical energy into electrical signals. Furthermore, researchers have designed friction electric scaffolds (TESs) that facilitate the development of dense and mature cartilage by inoculating chondrocytes, followed by subcutaneous implantation.^[10] Electrical nano-materials have extensive applications in energy-harvesting, sensors, actuators, resonators, and medical detection devices owing to their exceptional electromechanical properties, catalytic performance, and sensitivity to stimuli.^[11] Micro/nanoelectrical materials demonstrate distinctive electrical and chemical behaviors within the realm of biomedical engineering, especially in bone and cartilage injury treatments. Importantly, osteochondral defects implanted with micro/nanoelectrical materials *in vivo* show good hyaluronic acid cartilage regeneration and complete cartilage healing.^[12,13]

Although electrically active materials have shown excellent results in bone and cartilage repair, particularly in bone, many studies have highlighted their limitations. Traditional ES therapy requires bulky equipment, reducing patient comfort and limiting personalized treatment, which hinders its clinical use.^[14] Additionally, traditional energy-storage devices are rigid and difficult to integrate into wearable technologies. To address this, flexible electrical materials capable of converting mechanical energy, such as body movement, into electricity have gained popularity due to their adaptability, simplicity, and lightweight

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Electrical Properties Of Bone And Cartilage

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