

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

Ferdinando Bersani



Electrical Properties Of Bone And Cartilage:

Electrical Properties of Bone and Cartilage Carl T. Brighton, Jonathan Black, Solomon R. Pollack, 1979 Electrical Properties of Bone and Cartilage Carl T. Brighton, Jonathan Black, Solomon R. Pollack, 1979 *Biomechanics of Normal and Pathological Human Articulating Joints* N. Berme, 2012-12-06 The widespread occurrence of the various forms of arthritis not only results in a great waste of manpower but also causes immeasurable pain and suffering for the patients Due to the limited understanding of its etiology the currently available treatments are directed at the effects of the disease rather than its causes The solutions available to the clinician at the advanced stages of arthritis are frequently surgical and include prosthetic replacement arthroplasty Many advances have been made in the last decade in the basic understanding of the kinematics and kinetics of anatomical joints as well as in the technology of joint replacement The NATO Advanced Study Institute held in Portugal during June 20 July 1 1983 addressed these topics and provided instruction on the advances in biomechanics of diarthrodial joints The proceedings of this Institute are presented in this volume Many different areas of specialization contribute to the field of joint biomechanics Due to the complexity of each individual topic it was not attempted here to present a complete treatise of each of these areas Each chapter typically gives a review and a flavor of the subject matter as well as discussing the state of the art advances in general or in specific research areas Some of the chapters such as those on lubrication and muscle mechanics are more mathematically oriented than the others Nevertheless the reader with a non engineering background I trust would still find most of the book informative and easy to read **Turek's**

Orthopaedics Principles and Their Applications Anil K. Jain, 2016-01-01 Now in its revised updated Seventh edition this text provides residents and medical students with a broad overview of adult and pediatric orthopaedics Major sections focus on general and regional disorders of the musculoskeletal system *Bones and Cartilage* Brian K. Hall, 2014-12-23 *Bones and Cartilage* provides the most in depth review and synthesis assembled on the topic across all vertebrates It examines the function development and evolution of bone and cartilage as tissues organs and skeletal systems It describes how bone and cartilage develop in embryos and are maintained in adults how bone is repaired when we break a leg or regenerates when a newt grows a new limb or a lizard a new tail The second edition of *Bones and Cartilage* includes the most recent knowledge of molecular cellular developmental and evolutionary processes which are integrated to outline a unified discipline of developmental and evolutionary skeletal biology Additionally coverage includes how the molecular and cellular aspects of bones and cartilage differ in different skeletal systems and across species along with the latest studies and hypotheses of relationships between skeletal cells and the most recent information on coupling between osteocytes and osteoclasts All chapters have been revised and updated to include the latest research Offers complete coverage of every aspect of bone and cartilage with updated references and extensive illustrations Integrates development and evolution of the skeleton as well a synthesis of differentiation growth and patterning Treats all levels from molecular to clinical embryos to evolution and covers

all vertebrates as well as invertebrate cartilages Includes new chapters on evolutionary skeletal biology that highlight normal variation and variability and variation outside the norm neomorphs atavisms Updates hypotheses on the origination of cartilage using new phylogenetic cellular and genetic data Covers stem cells in embryos and adults including mesenchymal stem cells and their use in genetic engineering of cartilage and the concept of the stem cell niche **Wolff's Law and Connective Tissue Regulation** Guenter Regling, 2011-03-02 No detailed description available for Wolff's Law and Connective Tissue Regulation **Biological Effects of Electric and Magnetic Fields** David O. Carpenter, Sinerik Ayrapetyan, 2012-12-02 Recent concerns over the possible hazards of electrical and magnetic fields in the home and workplace are comprehensively addressed within this book The chapters contain detailed research on the biological effects of electric and magnetic fields and evidence for and against any interaction of electromagnetic fields EMFs and the biological systems The relative risk of exposure to EMFs Putative behavioral and neural effects of EMFs EMF effects on cells

Biological Effects of Electromagnetic Fields Peter Stavroulakis, 2013-03-09 Any book under this title which creates both anticipation and anxiety must be the work of a lot of people present any new findings with objectivity and cover the subject as exhaustively as possible As such it must cover the possible reproducible mechanisms of action reaction EMF Biological Organism the appropriate models that allow quantitative measurements the basic biological reproducible effects and possible therapeutic effects along with their prevalent metrics and international exposure criteria This is exactly the main objective of this book It is also believed that it provides some new results and conclusions which complement clarify and verify the existing results in the literature included in the references 1 and 2 Electromagnetic Radiation is a form of energy which is transmitted in the form of waves which correspond to spatial and time variations of the electric and magnetic field Electromagnetic fields appear in a vast set of frequencies spectra that are divided in frequency zones according to the manner they are produced or used Areas greater than 300 gigacycles GHz which include the solar spectrum as well as x and gamma rays have been studied sufficiently under a different angle in relation to possible biological effects People are well aware of the harmful effects of sun radiation when they are exposed to the sunlight for extended periods of time and of the catastrophic effects of nuclear bombs and nuclear reactor leaks Natural and Living Biomaterials Hastings, 2018-05-04 Reasons for the study of tissue materials are discussed Specific aspects of the musculo skeletal system are considered the main emphasis being on bone Structure and different mechanical properties of parying types of bone are discussed by the authors with the concluding chapter dealing with mechanically mediated electrical properties and their relevance to bone structure and to growth or repair *The Biology of Tooth Movement* Louis A. Norton, Charles J. Burstone, 1988-11-30 Written by a broad spectrum of dental medical and basic science researchers from around the world this book presents state of the art knowledge concerning the biology of connective tissues and their response to exogenous mechanical stimulation at the cell biology level The text goes well beyond the traditional morphologic descriptions of tooth movement covering the cell

biology of the connective tissues involved the various in vitro and in vivo research models possible pharmacological means of influencing tissue responses and biophysical considerations Many cellular events that occur during tooth movement are discussed as well as the exciting challenges unanswered questions and possibilities in the future This publication is extremely relevant to the work of dental specialists in orthodontics pediatric dentistry and periodontics plus orthopedists and basic scientists working in connective tissue research

Health Effects of Low-frequency Electric and Magnetic Fields
ORAU Panel on Health Effects of Low-Frequency Electric and Magnetic Fields,1992

Handbook of Biological Effects of Electromagnetic Fields, Third Edition - 2 Volume Set Charles Polk, Elliot Postow,1995-12-21 The first edition of this book has been recognized as the standard reference on biological effects of electric and magnetic fields from DC to microwaves But much has changed in this science since the book's original publication in 1986 With contributions from eighteen leading researchers this latest edition includes authoritative discussions of many new developments and will quickly become the new must have resource handbook Dielectric properties of biological tissue are thoroughly examined followed by chapters on physical mechanisms and biological effects of static and extremely low frequency magnetic fields New chapters on topics that were treated very briefly in the first edition now receive extensive treatment These topics include electric and magnetic fields for bone and soft tissue repair electroporation and epidemiology of ELF health effects The chapter on computer methods for predicting field intensity has been substantially revised to describe new numerical techniques developed within the last few years and includes calculations of power absorbed in the human head from cellular telephones The chapter discussing experimental results on RF interaction with living matter now contains information on effects of very high power very short duration pulses A new appendix on safety standards is based on the latest publications of governmental as well as quasi governmental organizations such as the U S Council on Radiation Protection in the United States Europe and Australia With all its revisions this updated version of the CRC Handbook of Biological Effects of Electromagnetic Fields provides the most comprehensive overview available of this rapidly changing science

Electrical Manipulation of Cells Paul T. Lynch, M.R. Davey, 2012-12-06 Electrical Manipulation of Cells provides an authoritative and up to date review of the field covering all the major techniques in a single source The book features broad coverage that ranges from the mechanisms of action of external electrical fields on biological material to the ways in which electrical stimuli are employed to manipulate cells Bringing together the work of leading international authorities the book covers membrane breakdown gene delivery electroporation electrostimulation cell movement hybridoma production plant protoplasts electrorotation and stimulation and electromagnetic stimulation For each topic the authors discuss the relevance of the approach to the current state of the art of biotechnology Electrical Manipulation of Cells is an unmatched source of information for anyone involved in the manipulation of cells particularly biotechnologists cell biology microbiologists biophysicists and plant scientists For researchers the book provides technical material that can be employed in their own

work Students will gain thorough appreciation of the applications of this important technique

Biomaterials Science and Engineering Joon B. Park, 2012-12-06 This book is written for those who would like to advance their knowledge beyond an introductory level of biomaterials or materials science and engineering This requires one to understand more fully the science of materials which is of course the foundation of biomaterials The subject matter of this book may be divided into three parts 1 fundamental structure property relationships of man made materials Chapters 2 5 and natural biological materials including biocompatibility Chapters 6 and 7 2 metallic ceramic and polymeric implant materials Chapters 8 10 and 3 actual prostheses Chapters 11 and 12 This manuscript was initially organized at Clemson University as classnotes for an introductory graduate course on biomaterials Since then it has been revised and corrected many times based on experience with graduate students at Clemson and at Tulane University where I taught for two years 1981 1983 before joining the University of Iowa I would like to thank the many people who helped me to finish this book my son Yoon Ho who typed all of the manuscript into the Apple Pie word processor my former graduate students M Ackley Loony W Barb D N Bingham D R Clarke J P Davies M F DeMane B J Kelly K W Markgraf N N Salman W J Whatley and S o Young and my colleagues Drs W Cooke D D Moyle Clemson G H Kenner University of Utah F University W C Van Buskirk Tulane University and Y

The Electrical Engineering Handbook, Second Edition Richard C. Dorf, 1997-09-26 In 1993 the first edition of The Electrical Engineering Handbook set a new standard for breadth and depth of coverage in an engineering reference work Now this classic has been substantially revised and updated to include the latest information on all the important topics in electrical engineering today Every electrical engineer should have an opportunity to expand his expertise with this definitive guide In a single volume this handbook provides a complete reference to answer the questions encountered by practicing engineers in industry government or academia This well organized book is divided into 12 major sections that encompass the entire field of electrical engineering including circuits signal processing electronics electromagnetics electrical effects and devices and energy and the emerging trends in the fields of communications digital devices computer engineering systems and biomedical engineering A compendium of physical chemical material and mathematical data completes this comprehensive resource Every major topic is thoroughly covered and every important concept is defined described and illustrated Conceptually challenging but carefully explained articles are equally valuable to the practicing engineer researchers and students A distinguished advisory board and contributors including many of the leading authors professors and researchers in the field today assist noted author and professor Richard Dorf in offering complete coverage of this rapidly expanding field No other single volume available today offers this combination of broad coverage and depth of exploration of the topics The Electrical Engineering Handbook will be an invaluable resource for electrical engineers for years to come

Neural Stimulation Joel B. Myklebust, Joseph F. Cusick, Anthony Sances, Jr., Sanford J. Larson, 2019-06-04 First Published in 1985 this book offers a full comprehensive investigation into Stimulation of the brain Carefully compiled and filled with a vast

repertoire of notes diagrams and references this book serves as a useful reference for Neurobiologists and other practitioners in their respective fields *Modern Bioelectricity* Andrew A. Marino, 2020-08-26 This book presents an overview of the field of bioelectricity by demonstrating the biological significance of electromagnetic fields electrical properties of tissue biological effects of electromagnetic energy and therapeutic applications and health hazards of electromagnetic energy **Electricity and Magnetism in Biology and Medicine** Ferdinando Bersani, 2012-12-06 In the last few decades the research on bioelectromagnetics has expanded worldwide About one thousand researchers are now working in the field in a variety of institutions throughout the world including medical biological engineering and technical laboratories and protection agencies After many years of research a clear picture is now emerging Initially the research was mainly interested in the therapeutic applications of ELF electric and magnetic fields and the RF range was mainly taken into consideration with respect to thermal effects only Then the growing body of biological effects of ELF fields on cells and biological tissues particularly for the repair processes in bone have drawn the attention of researchers to non thermal effects ranging from static fields to microwaves A specific field of interest that has been the object of a large debate in the last twenty years has been the potential health risk associated with electric power production and distribution and more recently with domestic and industrial appliances In the last few years the explosion of the market for cellularphones has highlighted the issue of possible health dangers related to their use and to the widespread presence of base stations The first World Congress on Electricity and Magnetism in Biology and Medicine was held in Orlando Florida in 1992 and collected the widest amount of contributions from almost all the major researchers involved in the field **Electrochemistry in Research and Development** R. Kalvoda, Roger Parsons, 2012-12-06 This volume contains the papers presented at the UNESCO Scientific Forum on Chemistry in the Service of Mankind Electrochemistry in Research and Development held in Paris June 4 6 1984 Electrochemistry is concerned with the way electricity produces chemical changes and in turn chemical changes result in the production of electricity This interaction forms the basis for an enormous variety of processes ranging from heavy industry through batteries to biological phenomena Although there are many established applications modern research has led to a great expansion in the possibilities for using electrochemistry in exciting future developments To encourage this progress UNESCO has set up an Expert Committee on Electrochemistry and its Applications in the European and North American region which has already held a number of meetings devoted to specific topics To achieve a synthesis of the main directions of development and to demonstrate the importance of these for the needs of our modern society the Expert Committee organized a Forum on Electrochemistry in Research and Development The object of this was to assess the future trends in research and development and to establish a dialogue between experts in electrochemistry and their colleagues in the many other disciplines which can make use of electrochemistry The Forum was also intended to present electrochemistry and its applications in a form accessible to non specialists so that science policy makers will be aware of the potentialities of this

subject for the future needs of mankind Electropharmacology Hendrik Keyzer, George M. Eckert, Felix Gutmann, 1990-09-25 This extraordinary book covers the extremely broad subject of electropharmacology defined here as the application of principles and methods of electrochemistry to biological topics associated with the action of drugs It focuses on the physical principles of the movement of electrical charges across interfaces in pharmacological phenomena It also covers drugs and the electrical procedures which modify a natural process having an electrochemical basis or component This outstanding report studies the pharmacologically important properties and effects by electrochemical methods the electrochemical alternatives or adjuncts to drug therapy and the pharmacology involved Easy to read and understand this is an ideal reference for all researchers and practitioners of pharmacology and related fields

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