Electrostrategies in orthopaedic research

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ABSTRACT

Electrostrategies encompassing electrical stimulation and biomaterials with conductive or piezoelectric properties have garnered escalating interest within the orthopaedic research domain. We conducted a comprehensive bibliometric analysis of 2810 publications on electrostrategies in orthopaedic research a field for which no extensive overview has been provided to date. This study highlighted two main phases of progress since 1980 indicating an increasing emphasis on electrostrategies. We identified key contributors including institutions and authors with concentrated activity in North America, Europe and Asia. The study also outlined the most influential and co-cited journals in this domain. Our keyword analysis underscored "electrical-stimulation" "bone" and "in vitro" as prevalent themes with a significant focus on the effects of electrical stimulation on bone growth proliferation differentiation and its applications in bone surgeries. The keyword co-occurrence analysis revealed four major thematic clusters: "electrical-stimulation" "bone" "surgery" and "bone-mineral density." Our findings underscored essential research directions such as the manufacturing and application of conductive and piezoelectric biomaterials and electrically-guided stem cell differentiation. The study also pointed out the potential to enhance orthopaedic treatment methods and patients' quality of life. Future research should focus on refining electrical stimulation conditions developing new piezoelectric materials and advancing personalised tissue engineering strategies. In conclusion this study illuminates the global trends and emerging hotspots of electrostrategies in orthopaedic research providing a valuable reference for its further application and understanding in the field.

Keywords:
Bibliometric analysis; Conductive biomaterials; Electrical stimulation; Electrostrategies; Piezoelectric properties

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1. Introduction

The application of electrical strategies in orthopaedic research has emerged as a focal point in the scientific community.[1-3] The physiological attributes of bone, especially its electrical properties, have long been significant areas of research. The "piezoelectric properties" of bone, a complex physiological phenomenon in orthopaedic studies, stem from Julius Wolff's perspective that bones arrange themselves along the primary direction of stress.[4] Although this theory has expanded across various skeletal studies, it remains contentious partly because it might oversimplify the characteristics of such a complex organ as bone.[4]

Regarding how bones respond to their mechanical environment, particularly how osteocytes and osteoblasts perceive force, the piezoelectricity of collagen is postulated as a potential mechanism.[5] In the 1960s, piezoelectricity garnered significant attention, but its prominence dwindled with the emergence of other mechanisms such as streaming potentials and fluid shear stresses. However, the discovery of potential differences generated by mechanical strains in cortical bone rekindled interest in piezoelectricity.[6] In dry bone, piezoelectricity is considered the primary mechanism for strain-generated potentials, largely attributed to the non-centrosymmetric nature of collagen. However, in wet bone, the mechanism of piezoelectric action remains unclear, with some evidence suggesting that streaming potentials might be its main driver.[6-8] The characteristics of collagen in cortical bone, particularly its highly oriented and ordered structure, make it especially conducive for piezoelectric processes.[8] The piezoelectric properties of bone and their intimate connection with electricity have sparked considerable interest among researchers regarding the application of electrical strategies in bone studies.[9]

The application of electrical strategies in skeletal research has been thoroughly explored theoretically and has extensive practical implementations in bone healing, regeneration, and tissue engineering. The use of electrical stimulation to promote bone regeneration stands out in this field.[9] Electrical stimulation has been used as a physical cue to guide the differentiation of mesenchymal stem cells (MSCs) towards the osteogenic lineage.[9] In the field of bone regeneration, research on electroactive materials is also propelling advancements.[10-12] A biomaterial based on the electroactive polyvinylidene fluoride (PVDF) composite demonstrated commendable efficacy in promoting osteogenic cell proliferation, migration, and osteogenesis.[11] The biomechanical properties of electroactive materials are also crucial aspects in bone regeneration applications.[13-15] A study evaluated the power generation and fatigue resistance performance of three different configurations of commercial piezoelectric composites in enhancing implant design. The findings revealed that all configurations generated sufficient power under physiological lumbar load conditions to stimulate bone healing.[13] Furthermore, innovative wireless electrical stimulation systems and scaffolds fabricated from piezoelectric materials have introduced novel possibilities for bone repair.[16,17] Simultaneously, electroactive antimicrobial materials present substantial potential for bone engineering.[18]

In summary, the application of electrical strategies in bone tissue regeneration,[19] bone remodelling,[20] bone repair,[21] and tissue engineering[22] presents a vast horizon of potential,[19-22] but it has yet to be thoroughly validated in humans. Further research is imperative to ascertain optimal electrical stimulation parameters and establish evidence-based treatment standards.[23] Bibliometrics, a scientific method for studying the characteristics, generation, dissemination, and utilisation of scientific literature, can elucidate research trends and dynamics in a specific domain.[24] Moreover, bibliometrics can unveil pivotal themes in research areas, thereby guiding future research trajectories.[25] Our research aim is to employ bibliometric tools for an exhaustive review of the advancements in electrical strategies within the skeletal domain, revealing primary research themes and tendencies, exploring its practical potential, and hoping that through this research we can further the application of electrical strategies in orthopaedics, addressing the therapeutic needs for skeletal ailments.

Our research aim is to employ bibliometric tools for an exhaustive review of the advancements in electrics within the skeletal domain, revealing primary research themes and tendencies, exploring its practical potential, and hoping that through this research, we can further the application of electrics in orthopaedics, addressing the therapeutic needs for skeletal ailments.

2. Methods

2.1. Source of bibliometric data and search strategy

We employed the Web of Science (WoS) (Clarivate Analytics, Philadelphia, PA, USA) core collection databases (SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI, CCR-EXPANDED, and IC) to identify relevant articles concerning electrical strategies in the field of skeletal research. Data within WoS originates from a plethora of sources encompassing journals, books, patents, conference proceedings, and online resources, both freely available and open-sourced. We opted for the WoS database, discerning its superiority over alternatives such as Scopus or MEDLINE/PubMed for several reasons. The WoS database facilitates the extraction of a multitude of articles replete with comprehensive details, including titles, author names, and cited references. Its coverage spans citations of scientific publications since 1900 and encompasses all high-impact scientific journals.[26,27] Moreover, two salient strengths of this database are its capability for reference tracing and citation reporting. It not only allows intricate searches within preeminent academic journals and citation networks but also adeptly tracks references and citation activities, fostering an in-depth exploration of research outputs in a designated area.[28]

The search formula was: #1 = [(((((TS=(Piezoelectricity OR Electrical stimulation OR Electroactive OR Piezoelectric OR Bioelectricity)) OR TI=(Piezoelectricity OR "Electrical stimulation" OR Electroactive OR Piezoelectric OR Bioelectricity)) OR AB=(Piezoelectricity OR "Electrical stimulation" OR Electroactive OR Piezoelectric OR Bioelectricity)) OR AK=(Piezoelectricity OR "Electrical stimulation" OR Electroactive OR Piezoelectric OR Bioelectricity)) OR KP=(Piezoelectricity OR "Electrical stimulation" OR Electroactive OR Piezoelectric OR Bioelectricity)]; #2 = [((((TS=(bone)) OR TI=(bone)) OR AB=(bone)) OR AK=(bone)) OR KP=(bone)]; #3 = "#1" AND "#2". Utilising the aforementioned search formula, a cross-sectional search conducted on March 16, 2023, yielded a total of 2955 publications from WoS. Subsequently, we meticulously reviewed and evaluated all available published data to pinpoint those publications that focus on the application of electrical strategies in skeletal research. **Figure 1** delineates the search inclusion and exclusion protocol employed in this study to identify pertinent publications from the WoS database. The culminating results from this screening were exported into datasets encompassing citation details (authors, document titles, publication years, source titles, volume, issue, pages, citation counts, source, and document types) and bibliographic

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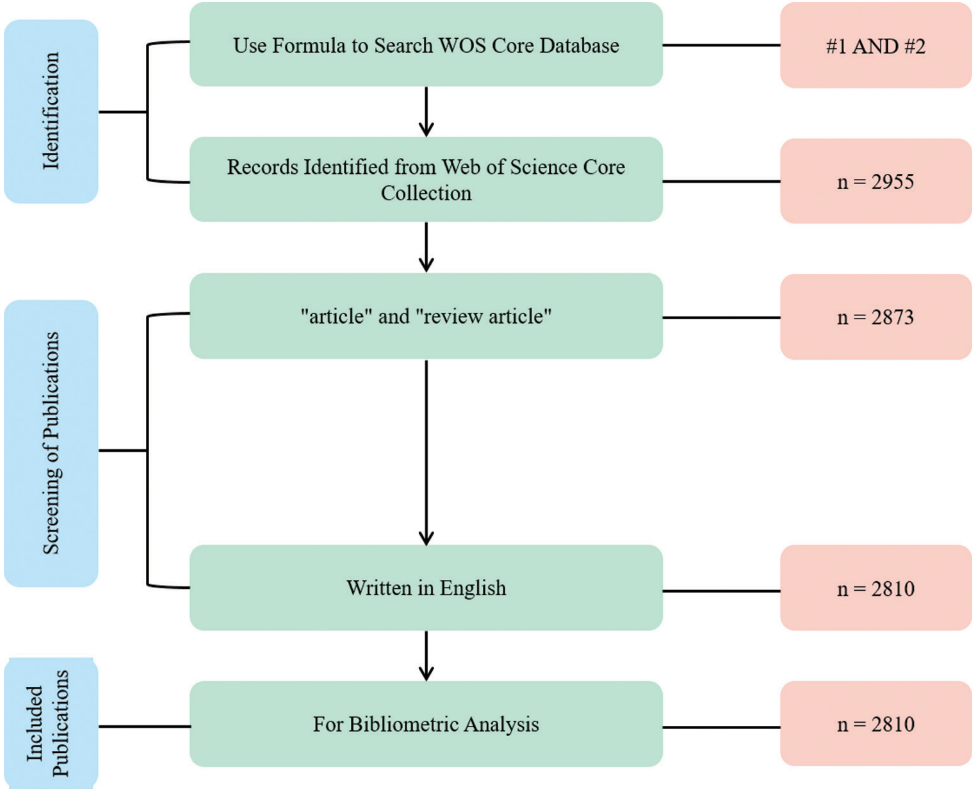

Figure 1. Flowchart of the search approach

information (affiliations, editors, keywords, and funding details). Full records and cited references of the procured articles were downloaded from the WoS database and archived in. BibTeX format for subsequent analysis. Since the data used in this study were obtained from public databases and involved no direct interaction with human or animal subjects, ethical approval was not necessary.

2.2. Analysis tools

To delineate the entire landscape of literature characterising the nexus between gut microbiota and pain, we subjected all pertinent data to rigorous analyses using Bibliometrix (R Studio V1.4),[29] CiteSpace V5.8 R3 (Drexel University, Philadelphia, PA, USA),[30] and VOSviewer 1.6.15 (Leiden University, Leiden, The Netherlands).[31]

2.3. Bibliometric analysis

The datasets were channeled into the R package 'bibliometrix', enabling an annual trend analysis of publications, which was subsequently rendered as a line graph. Additionally, the same R package was employed to assess the trajectory of publications across journals, distinct nations and regions, as well as inter-country/regional collaborations and citation patterns. The 'bibliometrix' R package was utilised to project the top 100 high-frequency keywords as a word cloud and ThematicMap. ThematicMap initiates with a co-occurrence keyword network, graphically representing typological themes within a two-dimensional space. The 'Walktrap algorithm' was employed for clustering, ensuring effective modularity and community structure detection within the co-occurrence keyword network. This methodology draws its inspiration from the proposition by Cobo et al.[32] facilitating a more intuitive interpretation of research themes framed within the context. Analyses were grounded on KeyWords Plus, which encompasses terms or phrases frequently manifested in referenced article titles albeit absent from the article's primary title. The generation of KWP is an exclusive procedure within the Clarivate Analytics database. Both CiteSpace and VOSviewer were leveraged for visual representation of collaborations between countries/regions, research institutions, co-authors, and co-citations, alongside the computation of keyword bursts.

3. Results

3.1. Global publication and citation

A total of 2955 articles were obtained based on the search strategy. Following further refinement, 2810 articles met the inclusion criteria. The general characteristics of these included publications are presented in **Table 1**. The overall citation count for these articles is 74,325, averaging 26.45 citations per article. Among these, research papers accounted for 2452 (87.3%) while reviews comprised 358 (12.7%). Broadly, contributions to this field stem from 81 countries/regions, 2816 institutions, 10,888 authors, and 1030 journals.

The annual publication and citation trends for research pertaining to electrostrategies and bone are illustrated in **Figure 2**. Overall, there is an upward trend with an average annual growth rate of 5.03%; 37.4% of these (or 1052 articles) were published in the last five years. Roughly, this trend can be divided into two phases: The first phase spans from 1980 to 2005. During this period, the number of new annual publications never exceeded 50, maintaining stability with a peak of 45 publications in 2005 and a low of 2 in 1987. The second phase covers 2006 to 2022. Here, annual additions consistently surpassed 50 publications, revealing a rising trend with numbers increasing from 72 in 2006 to 206 in 2022. The annual publication volume surged 60-fold from 4 in 1980 to 240 in 2020.

3.2. Countries/regions

Overall, 81 countries/regions have contributed to this research domain. The United States has established tight collaborations with 48 countries, including China, Italy, and Germany. The United States exhibits the highest collaboration frequency (359), followed by Germany (124), with China in third (110). The U.S. collaborates with 48 countries, China with 39, and Germany with 38. **Figure 3** presents the top ten countries with the most substantial contributions in this domain. The United States leads with 1988 articles, followed by China with 1341, and Italy ranked third with 534 publications. In terms of citations, the United States boasts the highest total citations (TC, 23,510) and average article citations (AAC, 35.8). China comes second in TC numbers (8588), with its AAC ranking seventh (21.4). Germany is third in TC counts (4154) and fourth in AAC (25). Canada ranks second in AAC (35.3), while the UK holds the third spot (30.9).

Table 1. General information

Description	Results
Main information about data	
Timespan	1980:2023
Sources (journals)	1030
Documents	2810
Annual growth rate %	5.03
Document average age (year)	10.2
Average citations per document	26.45
References	93941
Document contents	
Keywords plus (ID)	6129
Author's keywords (DE)	5839
Authors	
Authors	10888
Authors of single-authored docs	103
Authors collaboration	
Single-authored documents	121
Co-authors per documents	5.39
International co-authorships %	23.42
Document types	
Article	2452
Review	358

3.3. Institutions

In terms of publication ranking, the top 10 contributing institutions are presented in **Table 2**. Based on the number of published articles, the five most active institutions are: Chinese Academy of Sciences with 46 papers, Sichuan University (32), University of Genoa (31), University of São Paulo (31), and University of Toronto/University of Minho/University of Michigan (29). In the research collaboration network, the most active institutions ranked by total link strength are: Chinese Academy of Sciences (48), University of Toronto (28), University of Michigan (26), University of Minho (26), and Tsinghua University (22). These entities have played pivotal roles in the progression of electrical strategies in orthopaedic research.

A cluster analysis of institutions is shown in **Figure 4A**, broadly dividing them into five clusters, each representing distinct research directions or teams in the field. Cluster 1 consists of 18 institutions, including the University of São Paulo (Brazil) and primarily American universities such as the University of Iowa and Johns Hopkins University. Cluster 2 encompasses 17 institutions, notably from mainland China, including

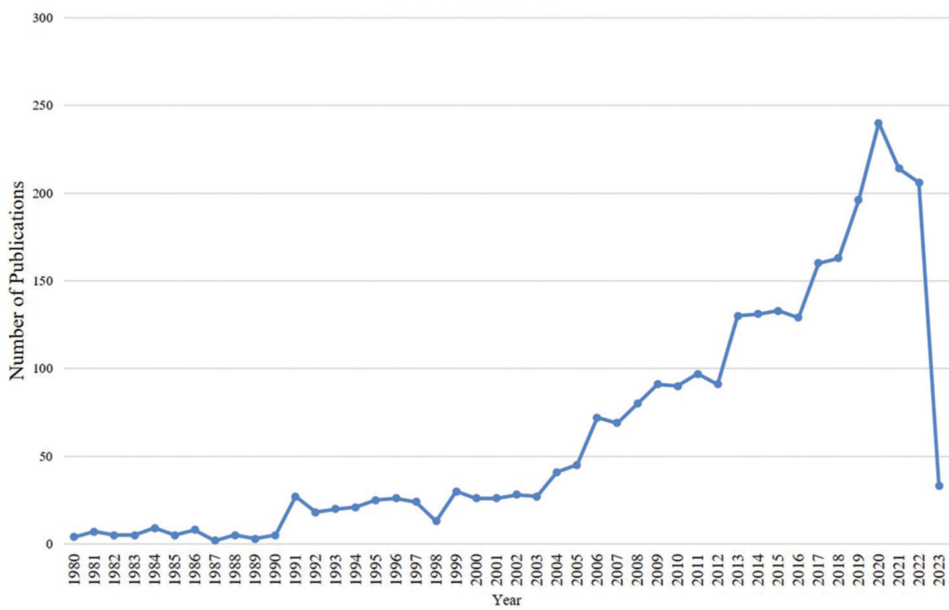

Figure 2. Annual number of publications

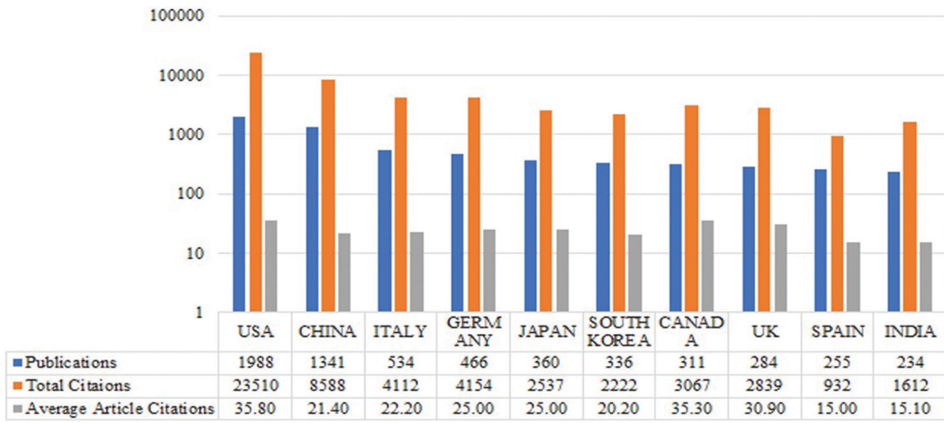

Figure 3. Top 10 most prolific countries/regions based on number of publications, total citations, and average article citations

Table 2. Top 10 prolific institutions

Institutions	Documents	Citations	Total link strength
Chinese Academy of Sciences	46	1288	48
Sichuan University	32	723	7
University of Genoa	31	1002	10
University of São Paulo	31	461	5
University of Michigan	29	1692	26
University of Minho	29	1139	26
University of Toronto	29	1404	28
Harvard University	28	1335	17
Shanghai Jiao Tong University	27	490	8
Tsinghua University	26	614	22

the Chinese Academy of Sciences, Sichuan University, and Peking University. Cluster 3 comprises diverse institutions like Harvard University (USA) and the University of Genoa (Italy), suggesting a shared interest in another orthopaedic research direction. Cluster 4, dominated by German institutions, includes entities like the University of Rostock and the University of Aveiro (Portugal). Cluster 5 includes 10 institutions, primarily universities from Portugal and Spain, such as the University of Minho, Polytechnic University of Valencia, and the Basque Foundation.

Geographically, the global trends and research hotspots of electrical strategies in orthopaedics primarily concentrate in North America, Europe, and Asia. Institutions in these regions exert significant influence in terms of research collaboration, publication quantity, and research focal points.

As indicated in **Figure 4B**, based on average publication year, institutions that have received heightened attention in recent times include Rostock University (average year 2022.5), Huazhong University of Science & Technology (2022.2), and Beijing University of Chemical Technology (2022.2). These institutions have taken the lead in recent research, reflecting the latest trends of electrical strategies in orthopaedics.

3.4. Journals

Table 3 shows the top 10 prolific journals and those frequently cited in collaboration. In terms of publication counts, the *Journal of Craniofacial Surgery* (Q4) leads with 40 articles, followed closely by *Hearing Research* (39 articles, Q1) and *Otology and Neurotology* (38 articles, Q2). With citation counts of 433, 1298, and 1463 respectively, these journals manifest significant impact. Among these, *Otology and Neurotology* boasts the highest H-index of 20, while *Meat Science* stands out with the top impact factor of 7.077 (Q1). According to the 2021 JCR classification, these ten prolific journals are distributed across quartiles as follows: Q1 (2 journals), Q2 (5 journals), Q3 (1 journal), and Q4 (2 journals).

To further dissect global trends and focal points of electrical strategies in orthopaedic research, we analysed journals frequently cited in collaboration. The top three journals in this category are *Biomaterials* (with 787 citations, impact factor 15.304, Q1), *Clinical Orthopaedics and Related Research* (601 citations, impact factor 4.755, Q1), and *Nature* (560 citations, impact factor 69.504, Q1). The co-citation of these journals in orthopaedic research signifies their considerable influence and interconnectedness in the domain.

3.5. Authors

As presented in **Table 4**, in the realm of author contributions, Lanceros-Mendez S emerges as the most prolific, having penned 24 articles. This author also stands as the most cited (1093), boasting an H-index of 15. Sohn DS occupies the second rank with 22 publications, closely trailed by Dubey AK

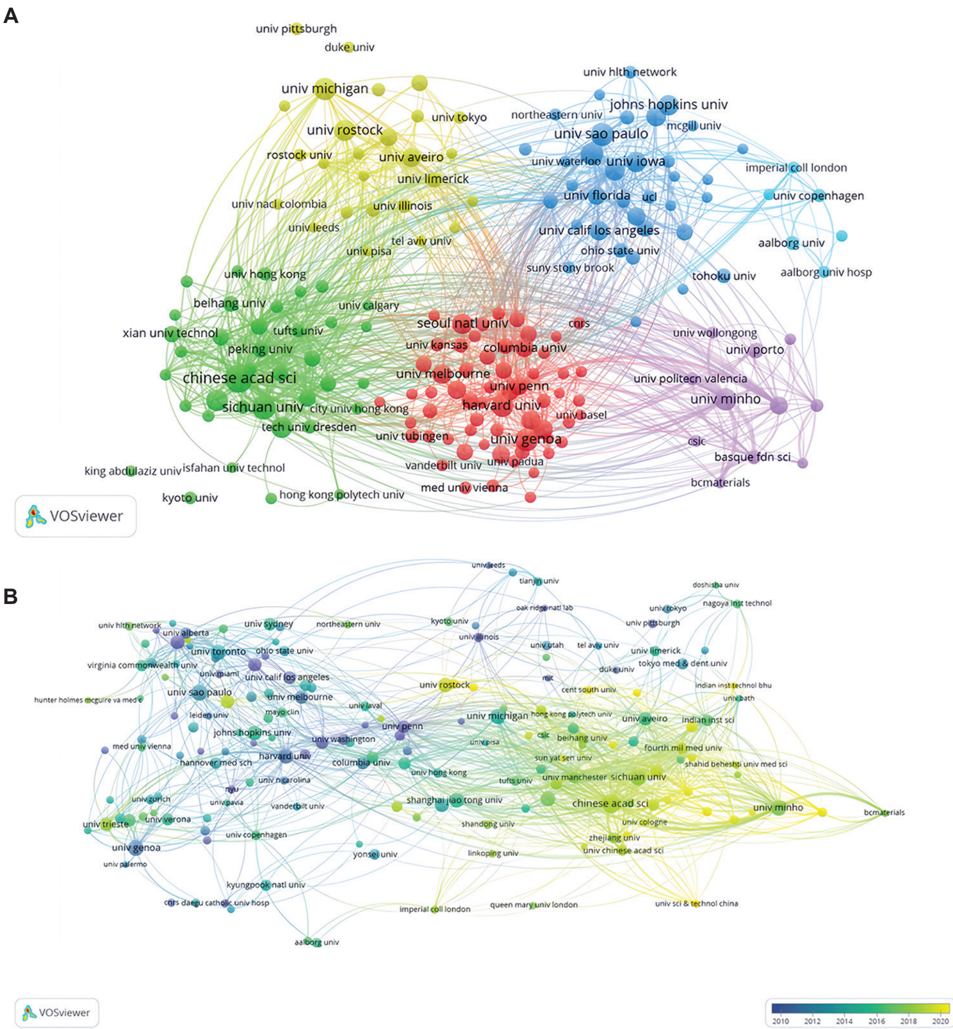

Figure 4. Network visualisation of inter-institution collaborations in the field of osteology electrical studies. (A) Overall inter-university collaboration network based on co-authorship. (B) Temporal evolution of inter-university collaborations from 2010 to 2020. Node size represents the number of publications, and the connecting lines indicate collaborative relationships, with colour indicating the year of collaboration. Data visualised using VOSviewer.

Table 3. The top 10 prolific and influential journals

Prolific journal	Publication	Total Citations	H_index	IF (2021)	JCR	Influential journal	Co-cited	IF (2021)	JCR
Journal of Craniofacial Surgery	40	433	12	1.172	Q4	Biomaterials	787	15.304	Q1
Hearing Research	39	1298	19	3.672	Q1	Clinical Orthopaedics and Related Research	601	4.755	Q1
Otology and Neurotology	38	1463	20	2.619	Q2	Nature	560	69.504	Q1
Meat Science	33	861	18	7.077	Q1	The Journal of bone and joint surgery - American volume	543	6.558	Q1
Scientific Reports	30	829	17	4.996	Q2	Science	529	63.714	Q1
Journal of Oral and Maxillofacial Surgery	29	744	13	2.136	Q4	Bone	517	4.626	Q2
PLoS One	27	964	15	3.752	Q2	Acta Biomaterialia	508	10.633	Q1
Spinal Cord	25	1017	17	2.473	Q2	Journal of Biomedical Materials Research Part A	457	4.854	Q2
International Journal of Oral and Maxillofacial Surgery	25	478	11	2.986	Q3	Scientific Reports	449	4.996	Q2
Journal of Orthopaedic Research	22	795	15	3.102	Q2	Proceedings of the National Academy of Sciences of USA	434	12.779	Q1

Table 4. Top 10 profilic authors

Authors	Articles	Local citations	H_index	Institution	Country
Lanceros-MENDEZS	24	1093	15	University of Minho	Portugal
Sohn DS	22	504	13	Catholic University of Deagu	Korea
Dubey AK	20	445	10	Banaras Hindu University	India
Stacchi C	19	358	9	University of Genoa	Italy
Mora R	18	374	12	University of Genoa	Italy
Ribeiro C	18	1036	14	University of Minho	Portugal
Salami A	18	374	12	University of Genoa	Italy
Shields RK	18	782	14	University of Iowa	USA
Basu B	17	503	11	Indian Institute of Technology	India
Dellepiane M	17	334	11	University of Genoa	Italy

with 20. In terms of citations, Ribeiro C takes the second spot (1036) and holds an H-index of 14. Among the top ten authors by publication count, four are affiliated with the University of Genoa in Italy, two hail from the University of Minho in Portugal, and two are associated with distinct institutions in India.

3.6. Keywords' evolution

This study extracted 5779 keywords from a total of 2870 publications using the R Package 'Bibliometrix' and generated a word cloud of the top 50 keywords by frequency, where the size of each keyword represents its frequency of occurrence (**Figure 5A**). Among these keywords, the top 10 most frequent keywords and their frequencies were listed, including: electrical stimulation (475 occurrences), bone (366 occurrences), *in vitro* (178 occurrences), stimulation (150 occurrences), proliferation (140 occurrences), differentiation (139 occurrences), MSCs (123 occurrences), surgery (120 occurrences), and growth (107 occurrences). This research identified the top 25 keywords with the strongest citation bursts, which are shown in **Figure 5B**. The keywords cover a wide range of topics such as *in vitro* studies, osteoporosis, fracture, spinal cord injury, and bone mineral density. Electrical stimulation had the highest citation burst strength with a value of 16.84, and the burst period was from 1998 to 2005. Scaffold had the second-highest citation burst strength with a value of 13.45, and the burst period was from 2019 to 2023. Other highly cited keywords included functional electrical stimulation, osteogenic differentiation, and bone regeneration. It is worth noting that several keywords such as PVDF, fabrication, nanofibre, and nanoparticle (NP) had strong citation bursts in recent years, indicating their emergence as research hotspots.

3.7. Research topics

In this study, we identified four major research clusters based on the co-occurrence of keywords in the field of orthopaedic research related to electrical strategies. The clusters were characterised by their respective keywords, centrality, and density measures (**Figure 6A**). The first cluster, labelled "electrical stimulation," featured high occurrences of keywords such as "electrical stimulation", "*in vivo*", "MSCs", "osteogenic differentiation", and "expression". This cluster demonstrated a research focus on the application of electrical stimulation techniques in the context of *in vitro* studies, particularly for promoting osteogenic differentiation in MSCs.

The second cluster, labelled "bone," was characterised by keywords like "bone", "stimulation", "differentiation", "proliferation", "growth", and "cells". This cluster represented studies on bone-related topics such as bone stimulation and differentiation and the role of electrical strategies in promoting bone growth, cell proliferation, and scaffold development.

The third cluster, labelled "surgery," included keywords such as "surgery", "piezosurgery", "osteotomy", "device", "therapy", "implants", and "repair". This cluster centered around the application of electrical strategies in surgical interventions, including the use of piezosurgery devices and techniques for bone repair and management.

The fourth cluster, labelled "bone mineral density," was characterised by keywords like "bone mineral density", "osteoporosis", "skeletal muscle", "functional electrical stimulation", "individuals", "muscle", "exercise", and "spinal cord injury". This cluster focused on studies investigating the relationship between electrical strategies, bone mineral density, and the role of functional electrical stimulation in the context of osteoporosis, skeletal muscle, and spinal cord injury.

Based on the cluster-time series visualisation generated by VOSviewer (**Figure 6B**), the more yellow a node appears, the closer it is to the present time. The average publication year for the keywords provided offers insight into the temporal trends of the research topics related to electrical strategies in orthopaedic research. These average publication years indicate that research related to scaffolds, fabrication, stem cells, osteogenic differentiation, composites, nanofibres, and NPs has been particularly active in the last 5 years. This result suggests increasing interest in the field among researchers.

3.8. Theme map

In this study, keywords were analysed through the co-occurrence network of the R Package Bibliometrix, and a thematic map was drawn to present clusters and keywords from 1980 to 2023 (**Figure 7**). The first quadrant identifies driving themes (i.e., well-developed and structurally important themes for the research field); the second quadrant draws highly developed and isolated themes (i.e., themes of limited importance to the field);

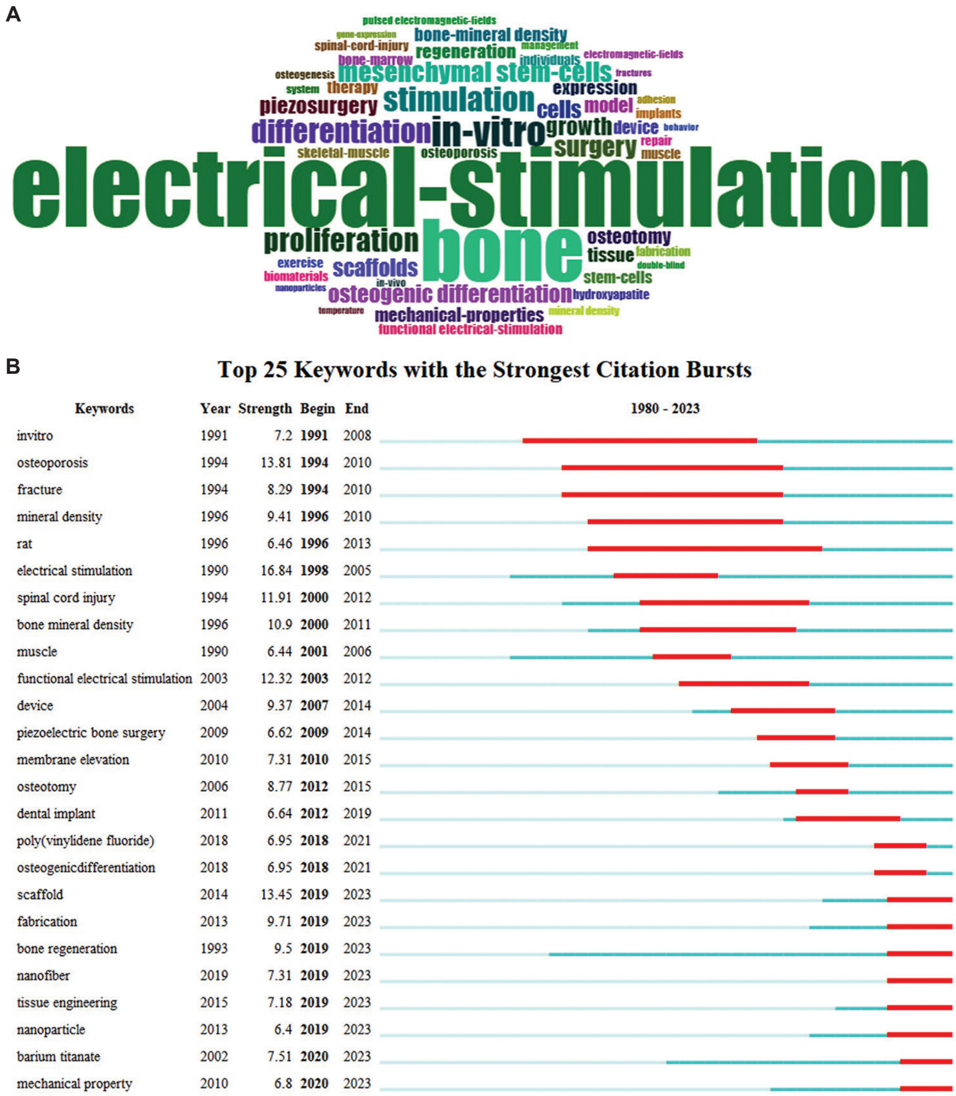

Figure 5. Analysis of keyword trends in osteology electrical studies from 1980 to 2023. (A) Word cloud visualisation highlighting the frequency of keywords. Size of each keyword is proportional to its frequency in the dataset. (B) Top 25 keywords with the strongest citation bursts over the years. The table displays the keyword, the year of the burst's start, its strength, and the range (Begin to End) of the burst. The bar chart represents the duration and intensity of each keyword's citation burst. Red bars indicate a higher burst intensity.

the third quadrant contains emerging or declining themes (i.e., weakly developed and marginal themes); and the fourth quadrant contains basic and horizontal themes (i.e., general themes involving different research fields in the field).

Basic theme: The clustering is mainly based on electrical stimulation technology, and the main keywords include: "electrical stimulation", "model", "MSCs", and "osteogenic differentiation", among others. Motor theme: This cluster has high centrality and high density and represents the core theme of this research field. Key keywords include: "bone", "*in vitro*", "stimulation", "differentiation", "proliferation", "growth", "cells", "scaffolds", "model", "regeneration", "mechanical properties", "stem cells", "hydroxyapatite", "biomaterials", and "fabrication", among others. Niche theme: This cluster has low centrality and high density and represents a dedicated research theme. Key keywords include: "bone mineral density", "osteoporosis", "skeletal muscle", and "functional electrical stimulation", among others. Emerging or declining theme: This cluster has low centrality and low density, representing a gradual decline in research heat in this field. This cluster is focused on surgical interventions and devices. The main keywords include: "surgery", "piezosurgery", "osteotomy", "device", "therapy", "implants", "repair", and "management".

4. Discussion

In the era of big data, bibliometric analyses enable researchers to swiftly identify evolutionary trends and focal issues within specific research domains. However, no comprehensive overview has yet detailed the global trends and research focuses on electrostrategies in orthopaedic research. Thus, in this study, we retrieved a corpus of 2810 publications relevant to electrostrategies in orthopaedic research and identified its principal contributors. Additionally, we visualised the evolution of the domain's prominent topics over the past two decades.

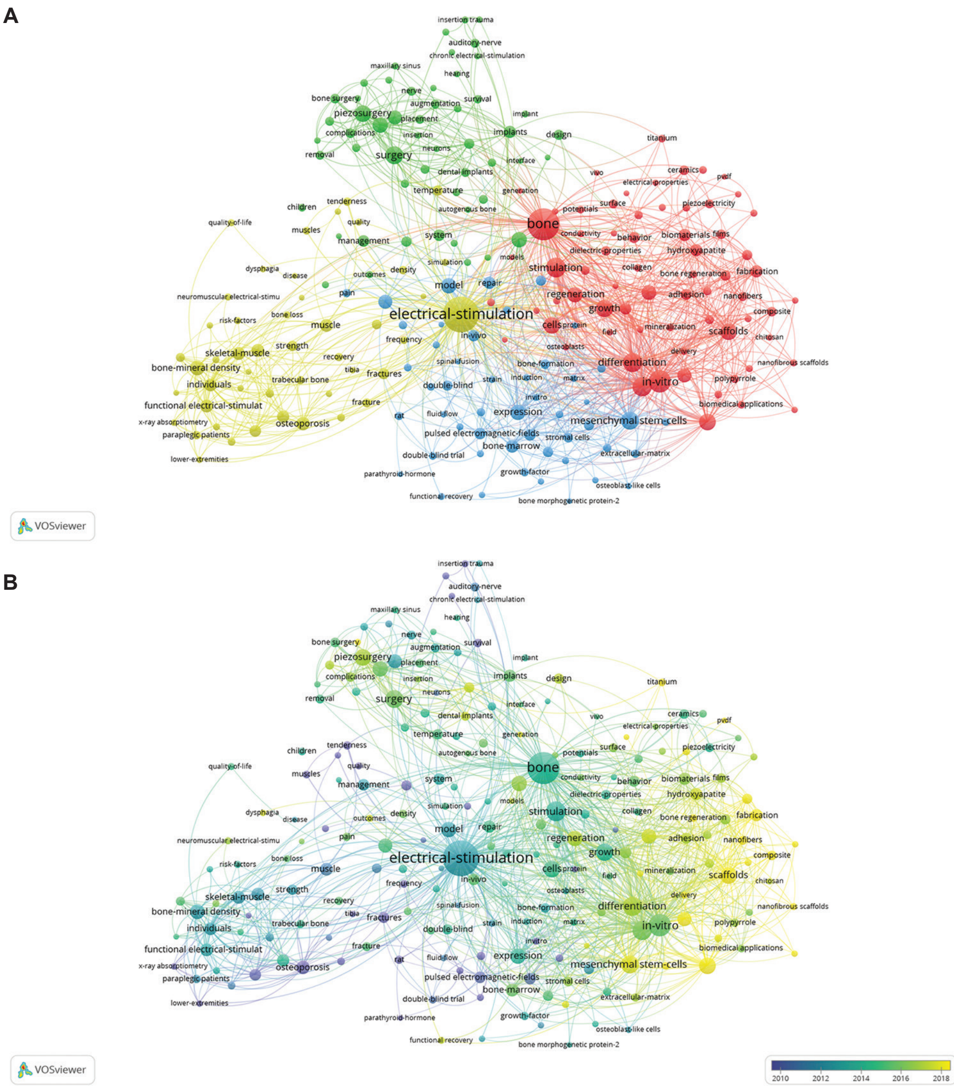

Figure 6. Co-occurrence network visualisation of keywords related to electrical stimulation in bone research. (A) Comprehensive keyword network showcasing the interconnections and clusters among different terms. Size and colour of each node correspond to its frequency and cluster, respectively. (B) Temporal distribution of keyword prominence from 2010 to 2018. The colour gradient of the network nodes indicates the year of peak prominence, with lighter shades representing earlier years and darker shades corresponding to later years. All visualisations are generated using VOSviewer.

Our retrieval indicates that the advancement of electrostrategies in orthopaedic research since 1980 can be divided into two phases. The first phase (1980–2005) experienced a relatively low literature output, with annual publications never exceeding 50, indicating a steady trajectory. The second phase (2006–2022) saw an annual increase in literature, rising from 72 publications in 2006 to 206 in 2022. This trend highlights a growing applicability and emphasis on electrostrategies within orthopaedic research.

4.1. Active institutions and authors

The global trend and research hotspots of electrical stimulation strategies in orthopaedics are primarily concentrated in North America, Europe, and Asia, as indicated by our study's results. Institutions in these regions exert significant influence in terms of research collaboration, number of published papers, and research hotspots. The top ten most representative authors are listed in **Table 4**, which includes their number of published papers, local citation counts, and H-index. Among these, Lanceros-Mendez S. and Ribeiro C. from Minho University in Portugal have published 24 and 18 papers, respectively, with high citation counts and H-indexes. In Korea, Sohn D.S. from Catholic University of Daegu has published 22 papers with a local citation count of 504 and an H-index of 13. In Italy, Stacchi C., Mora R., Salami A., and Dellepiane M. from various universities have made significant contributions to the field of electrical stimulation strategies in orthopaedics. In India, Dubey A.K. and Basu B. from Banaras Hindu University and Indian Institute of Technology, respectively, have published 20 and 17 papers with high local citation counts and H-indexes.

4.2. Journals

Understanding the most prolific journals is paramount for researchers contemplating submission choices, while journals with extensive co-citations can be regarded as authoritative within a given domain. This study identifies the high-yield journals within our field of investigation and offers insights

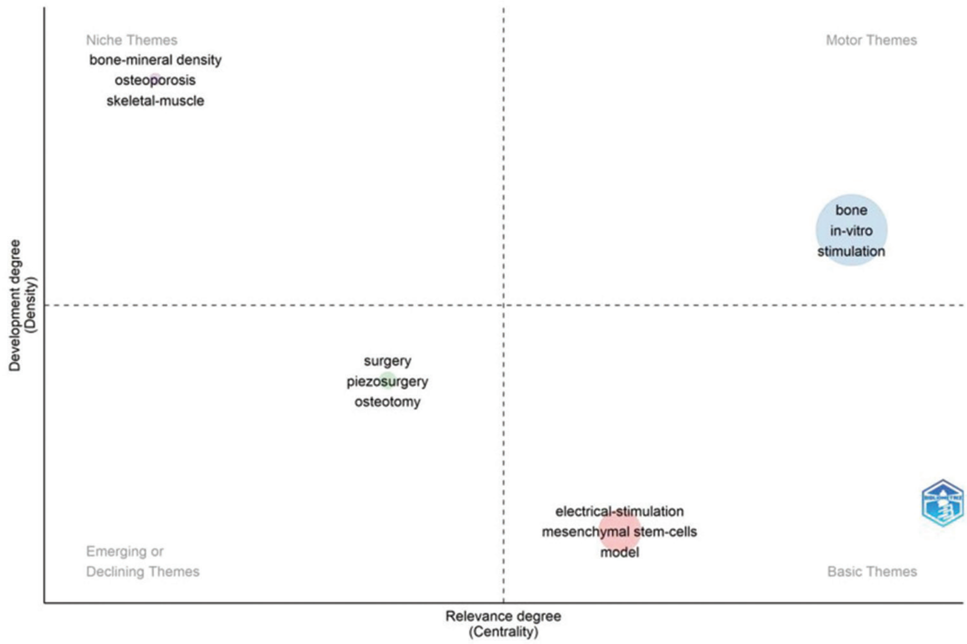

Figure 7. Theme map illustrating the thematic structure of research topics in the field of electrical stimulation and bone research. The *x*-axis in the figure represents centrality (i.e. the degree of interaction of a network cluster compared to other clusters), which provides information about the importance of the topic. The *y*-axis indicates density (i.e. measures the internal strength of a clustered network and can be seen as a measure of theme development). Themes are categorised based on their developmental degree (vertical axis) and relevance degree or centrality (horizontal axis). The diagram identifies four main categories: Motor Themes (high centrality, high development), Basic Themes (high centrality, low development), Niche Themes (low centrality, high development), and Emerging or Declining Themes (low centrality, low development). Each theme is represented by a set of keywords.

into the influential journals frequently co-cited therein. The substantial publications from journals like the *Journal of Craniofacial Surgery*, *Hearing Research*, and *Otology and Neurotology* signify their elevated esteem among scholars in this field, suggesting these journals as primary venues for submissions. *Biomaterials*, *Clinical Orthopaedics and Related Research*, and *Nature* emerge as the top three co-cited journals, indicating prospective authors seeking to publish in impactful journals might consider submissions here. Concurrently, these journals may serve as authoritative sources for researchers to grasp the cutting-edge advancements in the domain. In summary, this analysis provides valuable insights into the influential and co-cited journals within the orthopaedic research arena. Such findings could prove instrumental for scholars aiming to publish in high-impact journals or to stay abreast of the latest advancements in this domain.

In summary, this analysis provides valuable insights into the influential and co-cited journals within the orthopaedic research arena. Such findings could prove instrumental for scholars aiming to publish in high-impact journals or to stay abreast of the latest advancements in this domain.

4.3. Keywords' evolution

The keyword landscape, illustrated by a word cloud featuring the top 50 terms, underscored "electrical stimulation", "bone", and "*in vitro*" as the most prevalent terms. The most recurrent top 10 keywords included "electrical stimulation", "bone", "*in vitro*", "stimulation", "proliferation", "differentiation", "MSCs", "surgery", "growth", and "scaffold". Furthermore, the top 25 keywords manifesting the most pronounced citation bursts spanned diverse themes from *in vitro* studies to osteoporosis, fractures, spinal cord injuries, and bone mineral density. Emerging research foci identified via citation burst analysis included themes like "polyvinylidene fluoride", "fabrication", "nanofiber", and "nanoparticle".

Globally, it becomes evident that the focal areas of research regarding electrical strategies in orthopaedic studies largely revolve around the effects of electrical stimulation on bone growth, proliferation, differentiation, and its applications in bone surgeries. These insights provide invaluable guidance for delving deeper into the applications of electrical strategies within the orthopaedic field.

4.4. Research themes and frontier trend

This bibliometric study explored the global research trends and hotspots of electrical strategies in orthopaedic research. Based on keyword co-occurrence analysis, we identified four major research clusters. These clusters were labelled "electrical stimulation", "bone", "surgery", and "bone mineral density", each with its respective keywords and research focus. Through co-occurrence network analysis, a thematic map was generated to present the clusters and keywords from 1980 to 2023. The map identified four quadrants based on centrality and density, including motor themes, niche themes, emerging or declining themes, and basic themes. These four major research clusters are further discussed in the following section (**Table 5**).

4.4.1. Motor themes

This cluster, characterised by high centrality and density, epitomizes the foundational themes of this research

Table 5. Applications and advantages/disadvantages of materials and technologies

Theme category	Material/technology	Application field	Advantage	Disadvantage
Motor themes	Graphene and its derivatives	Bone repair, bone regeneration	Excellent mechanical properties, electrical conductivity, promotes osteogenic cell activities	Pure graphene is difficult to form three-dimensional scaffolds, requires surface modification to enhance dispersibility
	Metal nanoparticles (e.g., gold, silver)	Bone tissue engineering, antibacterial materials	Excellent electrical conductivity, antibacterial properties, promotes cell adhesion and proliferation	Degradation products may be toxic, metal materials can be too rigid causing stress shielding
	Conductive polymers (e.g., polypyrrole)	Bone tissue engineering, electrical stimulation applications	High electrical conductivity, antioxidant properties, modulates cell behaviour	Requires further optimisation for biocompatibility, processability
	Piezoelectric materials (e.g., $BaTiO_3$)	Bone regeneration, tissue repair	Generates electrical charges under mechanical stress, mimics bone tissue electrophysiological environment	Requires further optimisation to enhance bone regeneration efficiency
Basic themes	Functional electrical stimulation technology	Osteoporosis treatment, bone density enhancement	Non-invasive, side-effect-free, significantly promotes bone formation	Needs optimisation of electrical stimulation protocols for better clinical application
Emerging themes	Piezoelectric surgical devices	Oral and maxillofacial surgery, bone graft surgery	Precise cutting, reduces complications, less postoperative pain	Slower cutting speed, potential risk of nerve damage in some surgeries
Niche themes	Functional electrical stimulation technology	Osteoporosis treatment, bone density enhancement	Non-invasive, side-effect-free, significantly promotes bone formation	Needs optimisation of electrical stimulation protocols for better clinical application

domain. Prominent keywords encapsulate "bone", "*in vitro*", "stimulation", "differentiation", "proliferation", "growth", "cells", "scaffolds", "model", "regeneration", "mechanical properties", "stem cells", "hydroxyapatite", "biomaterials", and "fabrication", among others. The focus of this cluster predominantly lies in harnessing diverse biomaterials to fabricate scaffolds and models, instigating stem cell proliferation and differentiation upon them, and investigating their mechanical properties and regenerative capacities to advance bone tissue repair and regeneration. Following the relatively recent discoveries of natural bioelectricity and piezoelectricity, there has been escalating interest in developing biomaterials that can steer cellular behaviour and tissue regeneration. This represents an interdisciplinary nexus of molecular chemistry and physics, engineering, materials, biology, and medicine.[33] Considerable efforts have been directed toward designing and fabricating scaffolds constituted by electrically active biomaterials, inclusive of biocompatible conductive and piezoelectric materials.

Conductive biomaterials: In the domain of bone tissue engineering, electrically conductive biomaterials manifest substantial potential. Such materials are proficient in mediating charge transfer between cells and the matrix, subsequently modulating interactions either intercellularly or between cells/tissues and biomaterials.[34,35] These materials wield influence over cellular behaviours encompassing adhesion, proliferation, self-renewal, differentiation, and intracellular signalling processes.[36] The ensemble of electrically conductive biomaterials primarily encompasses carbon-based and metal-based nanomaterials, conductive polymers (e.g., polypyrrole, polyaniline, and poly(3,4-ethylenedioxythiophene)), and ceramics. These substrates stand out for their exemplary electrical conductivity, commendable mechanical properties, and adeptness in fostering intercellular signalling.

Graphene and its derivatives (GDs) emerge as two-dimensional nanomaterials boasting superior mechanical properties, electrical conductivity, expansive surface area, and atomic structural stability, all of which earmark them as promising candidates in the realm of bone repair.[37-40] GDs furnish bone repair scaffolds with requisite mechanical reinforcement, offering optimal electrical stimulation conducive for osteogenic cellular activities and bone formation, alongside promoting the adsorption of bioactive agents.[41] However, challenges ensue as pure graphene particles grapple with the formation of three-dimensional scaffolds and exhibit suboptimal flowability upon *in vivo* injections. Consequently, they are often synergistically combined with other matrices for bone repair endeavors. To address the dispersion heterogeneity of graphene particles within composite materials, surface modifications are typically mandated. By introducing functionalities like carboxyl, amino, and hydroxyl groups, not only can graphene's flowability and dispersity be augmented, but it also paves the way for new attributes such as carrying various bioactive agents to enhance bioactivity.[42,43] At present, functionalised GDs have been amalgamated with metals, inorganics, natural polymers, and synthetic polymers to craft scaffolds, coatings, membranes, and injectable hydrogels.[44,45] A plethora of *in vitro* and *in vivo* studies vouch for the efficacy of GDs-infused composites in modulating the extracellular microenvironment, accentuating bone regeneration.[46-48] GDs not only foster the adhesion, proliferation, and mineralisation of osteogenic cells but also uphold the vitality of bone marrow MSCs and their soft tissue derivatives, coaxing them toward osteoblastic differentiation.[45,49,50] Further scrutiny into associated signalling pathways reveals that GDs orchestrate osteogenic effects on MSCs by activating the Wnt/β-catenin, phosphatidylinositol 3-kinase/Akt/GSK 3β/β-catenin, and mitogen-activated protein kinase pathways, while concurrently modulating the Wnt and bone morphogenetic protein signalling pathways in monocytes and macrophages.[40,51-54]

Conductive metallic materials have emerged as a cornerstone in bone tissue engineering, drawing extensive attention. These materials, characterised by their unique attributes in biocompatibility, bioactivity, and bone defect repair, illuminate novel possibilities for the advancement of bone tissue engineering. Metals, exemplified by stainless steel, titanium, and cobalt, and their respective alloys, renowned for their biocompatibility, superior corrosion resistance, and mechanical strength, are prevalently incorporated in bone scaffolds.[55-57] However, the use of metallic materials in bone tissue engineering is circumscribed by issues such as excessive rigidity, relative stiffness inducing stress shielding compared to natural bone, and the toxic byproducts from their degradation.[57-59]

Metallic NPs have carved a niche in the realm of biomaterials, with prominent examples including noble metallic NPs like gold and silver, as well as metal oxide NPs like iron oxide and zirconium oxide.[60-64] Owing to their pronounced electrical conductivity, magnetism, and antibacterial attributes, nanocomposites laden with metallic or metal oxide NPs have garnered applications spanning conductive scaffolds, electronic switches, actuators, and sensors.[64] Foreseeably, metallic NPs such as gold NPs (AuNPs),[65] silver NPs (AgNPs),[66] and platinum NPs[67] will command an augmented role in biomedicine. AuNPs, distinguished by their facile synthesis, tunable chemical and electrical properties, anti-inflammatory features, and successful applications as osteoinductive materials, stand poised as high-potential materials in bone tissue engineering.[65,68,69] Beyond their role as conductive elements in scaffolds, studies have illuminated that AuNPs modulate osteogenic cell behaviour, including differentiation, and alter pathways associated with osteogenic cell formation.[69,70] Furthermore, AuNPs have demonstrated capabilities in angiogenesis induction, underscoring their multifaceted role in bone tissue engineering applications.[65,70,71] AgNPs, armed with unique optical, electronic, and antibacterial properties, are conceived as ideal constituents for crafting conductive hydrogels.[72-74] Hydrogels derived from silk fibroin/nano-hydroxyapatite modified *in situ* with AgNPs and AuNPs manifest robust antibacterial capabilities and favourable cellular compatibility; concurrently, freeze-dried chitosan-AgNP composite scaffolds, fabricated via green synthesis methods, exhibit exemplary antioxidative and antibacterial traits.[65,75] These characteristics amplify their potential and prospects in biomedical arenas like bone tissue engineering, wound healing, and bone regeneration.[75] Titanium and its alloys, principal materials for orthopaedic implants, have witnessed augmented antimicrobial and osteoinductive capabilities via laser-induced nanotexturing coupled with AgNP fixation.[76] AgNP on laser-nanotextured titanium surfaces exhibit superlative antimicrobial attributes and osteoblastic mineralisation traits, expanding the application spectrum of AgNPs in bone tissue engineering. In essence, AgNPs showcase immense potential in bone tissue engineering, particularly in domains addressing bone defects, osteomyelitis, and antibiotic-resistant diseases. Platinum NPs, recognised for their catalytic and optical features, have found broad applications in biosensors and bio-catalysts.[64,77]

Conductive metallic materials hold immense promise in the realm of bone tissue engineering. The advent of metallic NPs and their applications in biomaterials has heralded a new frontier for possibilities within bone tissue engineering. In the horizon, by delving into the synergy between metallic NPs and other biomaterials, and optimising the characteristics of these NPs, one anticipates the realisation of more efficacious, safe, and reliable solutions for bone defect repair. Concurrently, it remains imperative for researchers to continually unearth novel biomaterials and fabrication techniques, aiming to elevate the efficacy of conductive metallic materials in bone tissue engineering applications.

Conductive polymeric materials, characterised by their intrinsic conductivity, are a subset of high molecular weight materials with antioxidative functions, which allow for cellular behaviour modulation via electrical stimulation.[78,79] Increasingly garnering attention for tissue engineering applications, the composite materials derived from conductive polymers boast notable mechanical, electrical, optical, and chemical functionalities—elements deemed pivotal. Widely utilised conductive polymers encompass poly(aniline), poly(pyrrole), poly(3,4-ethylenedioxythiophene), and poly(thiophene) among others.[78,80] In bone tissue engineering, conductive polymer materials can be harnessed for bone regeneration through various fabrication methods and application strategies. A successful paradigm involves the layer-by-layer pulsed electrodeposition of porous titanium scaffolds exhibiting electroactivity, cytocompatibility, sustained reactive oxygen species scavenging, and osteoinductivity, all enveloped by a poly(pyrrole)-dopamine-hydroxyapatite film.[78] Additionally, studies have noted that electroporation of bioactive conductive substrates of poly(pyrrole)/heparin prepared on porous poly(acrylic acid) matrices significantly enhances osteoblast adhesion, proliferation, and mineralisation, enriching the calcium and phosphorus content within mineral depositions.[79]

Applications of conductive polymers in bone tissue engineering bifurcate into two distinct avenues. Firstly, the pivotal feature of these polymers—electrical stimulation—can modulate cellular activities, thereby fostering bone tissue regeneration.[81] Such stimulation on conductive matrices can collaboratively bolster osteogenic differentiation.[82] Specifically, electroporation on these conductive polymer substrates notably upregulates the expression of osteoblastic-specific markers such as alkaline phosphatase, bone morphogenetic protein 2, RUNX2, and osteocalcin, thereby facilitating bone regeneration.[79,83] For instance, the integration of poly(thiophene) NPs into poly(caprolactone) nanofibres augments cell viability, proliferation, differentiation, and mineralisation, ultimately expediting bone tissue regeneration and repair.[83] Additionally, utilising conductive hydroxyapatite-perovskite composites as scaffolds, intermittent electrical stimuli directed human MSCs towards osteogenic differentiation, underpinning elevated expressions of bone-specific markers and heightened extracellular matrix mineralisation.[84] Secondly, the antioxidative capacity of these polymers offers protection against excessive reactive oxygen species damage.[85,86] For example, poly(lactic-co-glycolic acid)/PATGP core-shell nanofibres outperform poly(lactic-co-glycolic acid)/PATGP blended nanofibres and poly(lactic-co-glycolic acid) nanofibres in reactive oxygen species scavenging, promoting osteogenic differentiation, and accelerating neo-ossification.[85]

Despite the substantial strides in harnessing conductive polymer materials for bone tissue engineering, showcasing expansive application vistas, capitalising fully on their potential still mandates further refinement in biocompatibility, processability, and mechanical properties. Such advancements would lay the groundwork for more promising conductive polymer materials, presenting superior therapeutic avenues for bone tissue engineering.

Piezoelectric materials: The application of piezoelectric materials in bone tissue engineering, particularly for bone regeneration, has attracted considerable attention, akin to the behaviour observed in natural bone tissue.[17,19,87-98] An important component of bone tissue, collagen fibres, has been proven to possess piezoelectric properties, which has deepened our understanding of bone physiology and Wolff's law.[5,99] Piezoelectric materials, due to their ability to generate electrical charges under mechanical stress, mirror the behaviour observed in natural bone tissue. This unique property enables piezoelectric scaffolds to mimic the electrophysiological microenvironment of bone, and thereby provide osteogenic cues to facilitate bone regeneration.[15,100,101] Furthermore, various types of piezoelectric materials, such as bio-ceramics and polymers, have been evaluated for their potential to promote cell growth, proliferation, and bone regeneration.[90,91,102]

Numerous piezoelectric materials have been utilised in tissue engineering to enhance bone regeneration and repair outcomes. For instance, piezoelectric scaffolds constructed from materials such as GaN/AlGaN and PVDF have shown potential in promoting bone repair, cell attachment, and osteogenic differentiation.[103,104] Particularly, scaffolds with a 3D fibrous structure can generate surface charges under mechanical loading, stimulating MSC differentiation, showing potential in biomimetic tissue engineering.[101]

In the context of bone regeneration, different piezoelectric materials have demonstrated promising potential. For instance, poly(L-lactic acid) nanofibre scaffolds, which produce surface charges via externally controlled ultrasound, can enhance *in vitro* osteogenic differentiation of stem cells and *in vivo* bone growth.[105] Similarly, a composite electroactive film of silica dioxide electric stone can promote the bioelectric potential of bone by adjusting the concentration of electric stone, thereby promoting the cellular activity and osteogenic differentiation of *in vitro* MSCs and *in vivo* bone regeneration.[10] More innovative applications involve the use of a PVDF-based composite material containing Barium titanate ($BaTiO_3$; 30 wt%) and multi-walled carbon nanotubes (3 wt%). Under electrical stimulation, this composite can enhance adhesion, proliferation, migration, and osteogenesis of preosteoblasts (MC3T3-E1), presenting promising bioengineering strategies for bone tissue engineering.[11] Innovations in piezoelectric materials continue to evolve. Researchers have developed piezoelectric Whitlockite ($Ca_{18}Mg_2(HPO_4)_2(PO_4)_{12}$) NPs with superior ferroelectric and dielectric properties to promote osteogenic differentiation.[106] Furthermore, both piezoelectric $BaTiO_3/Ti_6Al_4V$ scaffolds and piezoelectric PVDF scaffolds have demonstrated potential for promoting osteogenesis and bone repair both *in vitro* and *in vivo*.[12,107]

Simultaneously, certain piezoelectric materials have shown promise as bone substitutes due to their positive bioactivity, antibacterial effects, and customizable porosity and electromechanical properties.[93,95] For example, hydroxyapatite-barium titanate composites and lithium sodium potassium niobate ceramics are noteworthy in this respect. The potential of $BaTiO_3$ NP-decorated titanium scaffolds and $BaTiO_3$ nanofibres to enhance osteogenic differentiation of bone marrow MSCs further underscores the potential of piezoelectric materials in this domain.[12,108]

Several studies have explored wireless electrical stimulation systems. For instance, one innovative approach is to create a core-shell structure with piezoelectric $BaTiO_3$ grown on magnetostrictive $CoFe_2O_4$ within a polymer scaffold. This system can promote cell proliferation and differentiation and upregulate gene expression, providing a feasible application of wireless electrical stimulation in bone repair.[16] Among the wide array of research, Barium titanate nanofibres co-doped with Mn^{4+} (2 mol%) and Ca^{2+} (10 mol%) have demonstrated significant potential in bone tissue engineering scaffolds due to their robust ability to promote osteogenic differentiation of bone marrow MSCs and their non-cytotoxic characteristics.[108]

In conclusion, piezoelectric materials are significantly impacting regenerative medicine, paving the way for novel possibilities in tissue regeneration and joint replacement. As our understanding of these materials and their interactions with biological systems deepens, the potential to revolutionise treatment options for diseases affecting bone and cartilage, such as osteoarthritis, increases.[15,109] The electromechanical interactions of these materials can stimulate cellular activities related to tissue growth, potentially leading to improved clinical outcomes in bone regeneration. As such, the application of piezoelectric materials in the biomedical field is a fertile ground for future exploration.[12,110]

4.4.2. Basic theme

This cluster presents significant focus on electrical stimulation technology. Central keywords encompass: "electrical-stimulation", "model", "MSCs", and "osteogenic differentiation" among others. The core research in this cluster is primarily dedicated to understanding how electrical stimulation can be utilised *in vitro* to drive osteogenic differentiation in MSCs.

In recent years, the application of electrical stimulation in guiding the behaviour and differentiation of MSCs has emerged as a promising strategy in regenerative medicine.[9,10] Harnessing the potential of MSCs renowned for their ability to differentiate into various cell types, has been significantly enhanced by the understanding of how electrical stimulation can direct their fate.[9,10] In particular, bone tissue engineering has greatly benefited from MSCs due to their capacity for osteogenic differentiation and easy availability.

It has become increasingly evident that the physiological relevance of electrical microenvironments cannot be overstated. Such microenvironments play a crucial role in directing the differentiation of MSCs contributing significantly to the fields of tissue engineering and regenerative medicine.[9,10] *In vivo*, MSCs are exposed to an electroactive microenvironment in the bone niche, which has piezoelectric properties.[9] The correlation between the electrically active milieu and bone's ability to adapt to mechanical stress and self-regenerate has led to the use of electrical stimulation as a physical cue to direct MSC differentiation towards the osteogenic lineage in bone tissue engineering.[9]

Building upon this understanding, various technologies have been developed, such as electrospun sandwich membranes and piezoelectric nanocomposites, which can mimic these native electric microenvironments.[10,111] These advancements have provided new avenues for the treatment of a variety of conditions, from neurodegenerative disorders to bone defects.[111] In bone tissue engineering, materials with piezoelectric properties, such as barium titanate and PVDF, have been shown to promote the osteogenic differentiation of MSCs.[112,113] When fashioned into scaffolds with appropriate structures, these materials can enhance bone regeneration by providing a suitable environment that mimics the piezoelectric nature of bone.[111,112]

Several techniques have been employed to electrically stimulate MSCs and induce their osteoblastogenesis *in vitro*, including general electrical stimulation and substrate-mediated stimulation through conductive or piezoelectric cell culture supports.[9] These approaches encompass various aspects, such as stimulation parameters, treatment times, and cell culture media, with the aim of identifying the optimal conditions for inducing MSC osteogenic commitment via electrical stimulation.[9]

Electrical stimulation activates different signalling pathways, including bone morphogenetic protein Smad-dependent or independent pathways, regulated by mitogen-activated protein kinase, extracellular signal-regulated kinase, and p38.[114-116] The roles of voltage-gate calcium channel and integrins are also highlighted according to their application technique and parameters, mainly converging in the expression of RUNX2, the master regulator of the osteogenic differentiation pathway.[9] Despite the evident lack of homogeneity in the approaches used, the ever-increasing scientific evidence confirms electrical stimulation potential as an osteoinductive cue, mimicking aspects of the *in vivo* microenvironment and moving one step forward to the translation of this approach into the clinic.

The therapeutic potential of electrical stimulation extends beyond bone tissue engineering. In the treatment of neurodegenerative disorders, electrical stimulation has been shown to effectively guide MSCs towards neurogenic differentiation.[9] Furthermore, the use of ultrasonic-driven electrical signals, in conjunction with iron ion stimulation, has significantly enhanced the neural differentiation of MSCs.[117] Similarly, the synthesis of functional piezoelectric thin films has yielded promising results for stimulating neuronal differentiation of MSCs offering potential for neuroregenerative applications.[118]

Interestingly, research has found that the source of MSCs can influence the response to electrical stimulation. This underlines the importance of considering patient-specific factors in tissue engineering and paves the way for personalised medicine in this field.[119]

In the realm of cardiac regeneration, MSC cardiomyoplasty has shown significant potential for the treatment of myocardial infarction. MSC implantation has been found to lead to enzymatic and nonenzymatic antioxidant changes in a swine myocardial infarct model, suggesting the potential of MSCs in cardiac regeneration.[120]

In conclusion, electrical stimulation holds immense potential in directing the behaviour and differentiation of MSCs for a variety of applications in regenerative medicine. However, the journey is just beginning. Future research directions may include further exploration of the conditions for electrical stimulation, the development of novel piezoelectric materials, and the advancement of personalised tissue engineering strategies based on the MSC source. These efforts will undoubtedly bring us closer to harnessing the full potential of MSCs in regenerative medicine and realising the promise of truly personalised treatments.

4.4.3. Emerging theme

Paramount keywords encompass: "surgery", "piezosurgery", "osteotomy", "device", "therapy", "implants", "repair", and "management". The focal research within this cluster is principally committed to understanding and improving upon existing surgical techniques and devices, as well as developing new ones.

Piezoelectric surgery, a surgical method utilising piezoelectric devices, has been examined across a wide range of surgical applications, exhibiting substantial potential and value. While the usage of this technology has extended beyond orthopaedic surgery to find applications in other areas, further research and improvements are still needed.

The potential of piezoelectric surgical devices has been demonstrated in endoscopic sinus surgery, otolaryngological bone surgery, and obstructive mandibular third molar treatments, where the advantages include risk reduction of complications, less postoperative pain, and better preservation of bone integrity.[121-124] In addition, a novel bone conduction hearing device utilising piezoelectric components has been developed to alleviate discomfort and skin erosion associated with conventional devices. This device has shown effective sound transmission to the cochlea, potentially replacing current bone conduction hearing devices.[125] Nevertheless, despite the advantages of piezoelectric surgery in many aspects, there are limitations. For instance, in implant site preparation techniques, piezoelectric systems may generate higher temperatures and lower primary stability.[126] Moreover, compared to traditional drills, piezoelectric devices can demonstrate higher bone cell activity and more precise, silent cutting, but they are slower and produce less environmental noise.[127]

In applications such as orbital surgery, cleft lift surgery, bone graft surgery, and paediatric surgery, piezoelectric surgical devices have also shown their merits, including providing larger safety margins, shortening treatment periods, and limiting blood loss while maintaining brief operation times.[128-131] Furthermore, a new ultrasonic bone piezoelectric surgical device has been tested and found to effectively remove dental calculus, demonstrating its potential applications in dental hygiene.[132] However, it should be noted that for maxillofacial surgery, piezoelectric surgical devices could potentially cause severe nerve damage during surgery, similar to traditional rotary instruments, and thus should be used with caution.[133] Moreover, piezoelectric surgery has been observed to improve the quality of life in the immediate postoperative period, leading to reduced levels of pain and swelling, less use of analgesics, and better bleeding control during surgery.[134] Despite the promising prospects of this technology, there is still no single ultrasonic or sonic device that can combine all the optimal characteristics of speed, precision, and preservation of bone microstructure in bone surgery.[135]

In summary, piezoelectric surgery and related devices present a promising future for a variety of surgical procedures, especially in the field of oral and maxillofacial surgery. However, potential nerve damage should be cautiously avoided. While this technology can improve patient outcomes post-surgery, overall, piezoelectric surgery is a method that uses piezoelectric devices and shows significant potential and value in various surgical applications. In endoscopic sinus surgery, otolaryngological bone surgery, and obstructive mandibular third molar treatments, piezoelectric surgical devices exhibit the ability to reduce the risk of complications, lessen postoperative pain, and better preserve bone integrity.

4.4.4. Niche theme

This cluster, characterised by low centrality and high density, focuses intensely on a specific research area. Principal keywords include: "bone-mineral density", "osteoporosis", "skeletal-muscle", and "functional electrical-stimulation" among others. The main objective within this cluster is to explore how functional electrical stimulation can influence bone mineral density in the context of osteoporosis.

In recent years, electrical stimulation has garnered significant attention and research as a non-invasive, side-effect-free treatment for osteoporosis. Studies have shown that electrical stimulation not only promotes bone healing and regeneration but also significantly enhances bone formation, offering new perspectives and methods for osteoporosis treatment. The mechanism by which electrical stimulation promotes bone formation through mechanical stress has been validated in animal experiments and clinical treatments. For instance, a study found that a 20 Hz frequency of electrical stimulation significantly increased the expression level of osteocalcin mRNA in a rat model, with the highest rate of bone formation observed at this frequency.[136,137] In the treatment of osteoporosis and related fractures, combining electrical stimulation with other mechanical stress methods, such as radial extracorporeal shockwave therapy and ultrasound, has shown promising results.[138] Moreover, self-powered flexible implanted electrical stimulators based on triboelectric nanogenerators have shown potential for treating osteoporosis. These devices, driven by the daily activities of rats, significantly promoted osteoblast differentiation and bone remodelling, demonstrating their practical application potential as implantable medical electronic devices.[139] This novel electrical stimulation technology not only offers new methods for clinical treatment of osteoporosis but also advances the application of triboelectric nanogenerators in implantable medical devices. By further optimising electrical stimulation protocols and combining them with other treatment methods, electrical stimulation is expected to become an important treatment option for osteoporosis patients, providing more effective means for improving bone density and preventing fractures. Future research should continue to explore the specific mechanisms of electrical stimulation in bone formation to better guide its clinical application.

The primary limitation of our bibliometric analysis is the exclusive use of the WoS database. WoS is widely recognised for its comprehensive coverage and high-quality citation information, which are essential for bibliometric studies. Unlike other databases such as Scopus or PubMed, WoS provides detailed citation information necessary for tracking research trends and impact. Consequently, only WoS datasets can be effectively used for bibliometric analysis, as other databases lack the necessary citation information. Additionally, our analysis focuses solely on English-language publications due to the predominance of English as the primary language of scientific communication and publication. Bibliometric analysis is primarily designed for and applied to English-language research, which ensures the inclusion of most high-impact studies. However, this introduces a linguistic bias by potentially overlooking significant contributions published in other languages. These limitations may result in an underrepresentation of non-English-speaking regions and their research outputs. Future studies could benefit from incorporating multiple databases and multilingual datasets to provide a more holistic and inclusive view of the research landscape.

5. Conclusions

In this comprehensive research, we conducted a bibliometric analysis on the electrostrategies in the field of orthopaedics to probe into the global trends and research hotspots. The results illustrated a two-phase development of electrostrategies in orthopaedic research since 1980, signifying an escalating application and attention in the field. In addition, we identified key participating institutions and authors, as well as the most influential and co-cited journals. The analysis of keyword evolution revealed the evolution of research hotspots in this field over the past two decades, providing valuable references for further in-depth study of the application of electrostrategies in orthopaedics.

Through keyword co-occurrence analysis, we identified four major research clusters: electrical stimulation, bone, surgery, and bone mineral density. These clusters represent the main research subjects and frontier trends of electrostrategies in the field of orthopaedic research. Based on these research themes, we discerned several important research directions, including the manufacturing and application of biomaterials, electrically-guided stem cell behaviour and differentiation, and the development of innovative surgical techniques and equipment. This study reveals multiple aspects that significantly impact clinical practice and research strategies. Firstly, there is growing evidence supporting the efficacy of electrical stimulation in promoting bone growth and healing within clinical practice. Physicians can integrate electrical stimulation techniques into treatment plans for fractures and osteoporosis to enhance patient outcomes. Secondly, research hotspots on conductive and piezoelectric biomaterials highlight the immense potential of these materials in developing novel implants and scaffolds. These materials can improve the integration and durability of orthopaedic implants, offering better long-term results. Additionally, personalised tissue engineering strategies show great promise. By utilising patient-specific data, physicians can optimize electrical stimulation parameters and select appropriate biomaterials, thereby enhancing treatment effectiveness and shortening recovery times. In terms of research strategies, we recommend prioritising the development and refinement of conductive and piezoelectric materials, further exploring the specific mechanisms by which electrical stimulation affects cellular behaviour, and strengthening cross-regional collaboration and innovation. These key research directions will help accelerate the application of electrical stimulation strategies in orthopaedics, ultimately enhancing patient care and innovating treatment plans. Future research directions include further exploring the conditions for electrical stimulation, developing new piezoelectric materials, and advancing stem cell-derived personalised tissue engineering strategies. These studies not only hold the potential to drive the development of orthopaedic electrical stimulation strategies but also promise to provide more effective, safe, and reliable orthopaedic treatments. Moreover, this study uncovers new research hotspots and trends, such as focusing on conductive biomaterials, piezoelectric materials, and electrically guided stem cell behaviour and differentiation. These research hotspots and trends offer valuable references for further in-depth studies on the application of electrical stimulation strategies in orthopaedics.

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