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Original Article

Bibliometric Mapping of Digitalization in Orthodontics: Evaluating Scientific Contributions, Collaboration Networks, and Future Directions

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Main Points

- Digital technologies such as cone-beam computed tomography, intraoral scanners, computer-aided design and computer-aided manufacturing, and three-dimensional printing have significantly improved diagnostic accuracy and treatment planning in orthodontics.
- Clear aligners, virtual surgical planning, and artificial intelligence -based tools are increasingly shaping daily orthodontic practice.
- The coronavirus disease 2019 pandemic accelerated the adoption of digital workflows, thus enhancing patient monitoring, remote care, and treatment efficiency.
- Despite clinical advantages, high costs, technical requirements, and limited accessibility remain barriers to the widespread use of digital orthodontics.
- Understanding global research trends in digital orthodontics can help clinicians to adapt evidence-based innovations into practice.

ABSTRACT

Objective: To map scholarly trends in digital orthodontics by quantifying publication growth, identifying influential contributors and collaboration networks, and delineating emerging research themes.

Methods: A bibliometric analysis was conducted using the records published between January 2000 and May 2024 from the Web of Science Core Collection; VOSviewer was used to analyze co-authorship networks, keyword co-occurrence, institutional productivity, and citation patterns.

Results: A total of 1,567 publications were analyzed. Research output markedly increased after 2020 and peaked in 2023. The United States, Italy, and China were the leading contributing countries. Key institutions included Peking University, Radboud University, and the University of São Paulo. The most frequently cited authors were Xu, Kuijpers-Jagtman, and Lo Giudice. Major thematic clusters were centered on three-dimensional printing, artificial intelligence, and digital modeling.

Conclusion: In recent years, digital orthodontics research has considerably accelerated, thus expanding international collaboration and rapid technological innovation. A limitation of this study is that coverage may differ from that of multi-database approaches. In addition, future bibliometric assessments should be complemented by qualitative appraisals and clinical outcome- oriented evaluations to strengthen translational relevance.

Keywords: Digital orthodontics, bibliometrics, collaboration networks, artificial intelligence

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INTRODUCTION

In recent years, the integration of digital technologies has significantly transformed healthcare, and conventional orthodontic methods are being increasingly replaced by digital applications to enhance diagnostic precision, treatment predictability, and personalization. Two-dimensional imaging techniques, such as panoramic and cephalometric radiographs, have long been used in orthodontics. However, due to magnification, distortion, and superimposition, these methods are limited in accurately assessing anatomical structures.[1,2] Three-dimensional (3D) imaging modalities, particularly computed tomography (CT) and cone-beam CT (CBCT), have addressed some of these limitations by enabling detailed visualization and reconstruction of craniofacial structures.[3] In particular, CBCT has become increasingly popular due to its low radiation dose and high-resolution imaging capabilities. At present, CBCT plays an important diagnostic tool in selected complex cases, including localizing impacted teeth, assessing root resorption, evaluating temporomandibular joint disorders, and planning orthognathic surgery.[4]

Intraoral scanners have replaced conventional impression techniques, offering a more comfortable and efficient digital modeling process.[5] By producing high-resolution digital models, intraoral scanners enable a wide range of analyses, including arch width and length measurements, Bolton analysis, tooth segmentation, and occlusion evaluation.[6,7] Virtual treatment planning software facilitates digital manipulation of teeth to their ideal positions, supporting indirect bonding, custom arch wires, and aligner therapy.[8] Similarly, virtual surgical planning in orthognathic surgery enables osteotomy simulation, evaluation of surgical strategies, prediction of postoperative facial profiles, and fabrication of surgical splints and fixation plates.[9,10] Computer-aided design and computer-aided manufacturing (CAD/CAM) systems and 3D printing technologies have enabled high-precision customized fabrication of orthodontic appliances.[11] These technologies support the production of various devices such as retainers, functional appliances, expansion devices, indirect bonding trays, splints, labial and lingual bracket systems, and clear aligners.[6,12] While clear aligner therapy relies on digitally planned sequential corrections, lingual orthodontics benefits from robotically bent arch wires and customized brackets designed using CAD/CAM technology.

More recently, artificial intelligence (AI) offers the potential to enhance speed, accuracy, and individualization in clinical processes such as diagnosis, treatment planning, and patient monitoring. AI is particularly valuable in orthognathic surgical decision-making.[13] At present, AI is being explored for decision-making in areas such as camouflage versus surgical treatment, extraction planning, identification of cephalometric landmarks, and skeletal maturation assessment based on cervical vertebrae.[14,15]

Despite the rapid expansion of digital technologies in orthodontics, a comprehensive understanding of how this field has evolved at the scientific level remains limited. Bibliometric analysis is a quantitative method used to evaluate relationships and impact among published works within a specific research domain.[16,17] Unlike conventional literature reviews, bibliometric methods allow for the rapid and systematic identification of prominent research directions and knowledge structures, guiding future research efforts.[18] Accordingly, this study aimed to map the evolution of digitalization in orthodontic research by analyzing publication trends and citation patterns; identifying the contributions and collaboration networks of authors, institutions, and countries; determining influential journals and highly cited publications; and characterizing established and emerging research themes through keyword and reference analyses.

METHODS

Data Collection

A comprehensive literature search on the use of digital technologies in orthodontics was conducted using the Web of Science (WoS) core database. An advanced search was performed using the query TS=[(digital and orthodontics) or (digital* and orthodont*)] without any field restrictions. The publication period for the articles was set to the period from January 1, 2000, to May 31, 2024. A preliminary screening indicated that the number of eligible publications prior to 2000 was negligible; therefore, to ensure a consistent and meaningful time window for trend evaluation, the analysis was restricted to the records published from 2000 onwards. Only original research articles and review articles were included. No language restrictions were applied since the search was restricted to WoS, the coverage may differ from that of multi-database approaches; therefore, publications indexed exclusively in Scopus, PubMed/MEDLINE, and regional databases were not captured.

This study was a bibliometric analysis based exclusively on publicly available, previously published bibliographic data retrieved from the Web of Science Core Collection. No human participants, patient records, or animal subjects were involved, and no personal or identifiable data were collected. Therefore, ethics committee approval and informed consent were not required.

Data Transfer and Processing

The retrieved records were exported from WoSCore Collection (WoSCC) as plain-text files compatible with VOSviewer (Centre for Science and Technology Studies, Leiden University, The Netherlands; version 1.6.20). The dataset included metadata such as authorship, affiliations, abstracts, citations, and keywords. Before network analysis, the data were reviewed and standardized to reduce inconsistencies in terminology.

Bibliometric and Network Analysis

VOSviewer was used to generate co-authorship maps (authors, countries, institutions), citation networks (journals, references), and keyword co-occurrence clusters. All metrics were calculated using full counting methods. Total link strength was interpreted as a measure of influence within the network. To improve map interpretability, the following threshold criteria were applied: for collaboration maps, only authors, institutions, and countries with ≥5 publications were included; for keyword co-occurrence analysis, only author-provided keywords with a minimum occurrence of ≥10 were included. Keyword mapping was based on author-provided keywords, and thesaurus-based harmonization was applied to merge synonyms and spelling variants (e.g., "AI" and "artificial intelligence").

Statistical Analysis

The analyses were primarily descriptive and bibliometric; therefore, no inferential statistical tests were performed. However, relative comparisons (e.g., growth rates, citation trends) were discussed to contextualize patterns across regions and years.

RESULTS

General Information

As a result of the search query, a total of 1567 articles were identified. After using VOSviewer software to apply the specified filters to the articles, the analyses were conducted. Of the identified studies, 1464 (94.6%) were original research articles and 103 (6.6%) were review articles. The highest number of publications was observed in 2023, with a peak of 218 (Table 1). Most publications (78.4%) were categorized within the WoS research category Dentistry, Oral Surgery and Medicine (Table 2).

Countries and Institutions

The United States (USA) was the most productive country, with 282 publications, followed by Italy with 201, and China with 150 (Table 3). According to countries' total link strength scores, the USA ranked first. In the country-based citation analysis, the highest number of citations was observed in the USA, Italy, the Netherlands, Germany, and the United Kingdom (Table 3). With regard to institutional distribution, the top five institutions in terms of publication volume were Peking University, University of São Paulo, University of Ferrara, University of Michigan, and Radboud University. The top five institutions with the highest number of citations were Radboud University, University of Alberta, University of Michigan, University of Groningen, and Peking University (Table 4).

Authors

With respect to the number of published articles, the leading authors were Tianmin Xu, Anne Marie Kuijpers-Jagtman, Antonino Lo Giudice, Guilherme Janson, and Vincenzo Ronsivalle (Table 5). Based on the author citation analysis, the most cited author was Carlos Flores-Mir, with 627 citations. This

Table 1. Annual distribution of publications

Years	Number of articles
2000	5
2001	4
2002	7
2003	7
2004	6
2005	19
2006	13
2007	25
2008	38
2009	30
2010	37
2011	45
2012	46
2013	37
2014	41
2015	56
2016	53
2017	67
2018	86
2019	91
2020	138
2021	180
2022	212
2023	218
2024	106

Table 2. Distribution of publications by web of science research category

	Journal type	Records	% of 1567
1	Dentistry oral surgery medicine	1228	78.4
2	Medicine general internal	99	6.3
3	Material science multidisciplinary	54	3.5
4	Physics applied	51	3.3
5	Chemistry multidisciplinary	47	3

Table 3. Country-wise publication output, citation counts, and total link strength

	Country	Article	% of 1567 article	Citation counts	Total link strength
1	USA	282	18	6539	1409
2	Italy	201	12.8	2972	716
3	China	150	9.6	1402	412
4	Brazil	123	7.8	1465	567
5	Germany	121	7.7	2011	679
6	India	103	6.6	458	319
7	Türkiye	97	6.2	1028	381
8	England	74	4.7	1667	562
9	South Korea	72	4.6	1611	587
10	Sweden	58	3.7	990	358

Table 4. Institution-wise publication output, citation counts, and total link strength

	Institution	Article	% of 1567 article	Citation counts	Total link strength
1	Radboud University	31	2	1360	238
2	University of Michigan	34	2.2	862	212
3	Peking University	74	4.7	426	153
4	Groningen University	12	0.8	679	138
5	São Paulo University	46	2.9	295	138
6	University of Alberta	21	1.3	894	137
7	University of Bern	18	1.1	235	123
8	Aarhus University	13	0.8	202	115
9	Yonsei University	15	0.9	352	104
10	Case Western Reserve University	17	1.1	375	102

Table 5. Author-wise publication output

	Author	Article
1	Xu, Tianmin	21
2	Kuijpers-Jagtman, Anne Marie	20
3	Lo Giudice, Antonino	19
4	Janson, Guilherme	19
5	Ronsivalle, Vincenzo	16
6	Garib, Daniela	16
7	Cevidanes, Lucia Soares	15
8	Cossa, Paola	15
9	Leonardi, Rosalia	14
10	Cattaneo, Paolo	14

Table 6. Author-wise citation counts

	Author	Citation counts
1	Flores-Mir, Carlos	627
2	Ren, Yijin	606
3	Major, Paul W	540
4	Heo, Giseon	458
5	Kuijpers-Jagtman, Anne Marie	422
6	Fields, Henry W	401
7	Hatcher, David	353
8	Huang, John C	353
9	Maki, Koutaro	353
10	Miller, Arthur J	349

author was followed by Yijin Ren, Paul W. Major, Giseon Heo, and Anne Marie Kuijpers-Jagtman (Table 6). In terms of total link strength, Luca Lombardo, Antonino Lo Giudice, and Vincenzo Ronsivalle had the highest values in the author collaboration network (Supplementary Table 1).

Journals

The top five journals where the identified articles were most frequently published included the American Journal of Orthodontics and Dentofacial Orthopedics (AJODO) (320), European Journal of Orthodontics (147), Orthodontics and Craniofacial Research (73), Korean Journal of Orthodontics (57), and Journal of Orthodontics (51). According to the journal citation analysis, the three journals with the highest number of citations were AJODO, European Journal of Orthodontics, and The Angle Orthodontist. In terms of total link strength scores, the top five journals were AJODO, European Journal of Orthodontics, Orthodontics and Craniofacial Research, The Angle Orthodontist, and Korean Journal of Orthodontics (Supplementary Table 2).

Keywords

Following the keywords "orthodontics" and "digital orthodontics," the most frequently used keywords were digital models, digital dentistry, 3D printing, accuracy, and clear aligners. In terms of total link strength scores, the top five keywords were 3D printing, digital dentistry, digital models, accuracy, and AI (Supplementary Table 3).

Reference Impact

The most cited references included Fleming et al.,[19] Stevens et al.,[20] and Santoro et al.[21] These studies focused on the comparative accuracy of digital vs. conventional measurements (Supplementary Tables 4 and 5). More recent studies are increasingly cited, suggesting that digital orthodontics is a field driven by innovation and evolving clinical paradigms.

DISCUSSION

The thematic structure revealed by the bibliometric mapping has direct implications for everyday orthodontic practice. The prominence of clusters related to intraoral scanning and digital models aligns with the ongoing clinical transition from conventional impressions to digital data acquisition, facilitating more efficient storage and retrieval of patient records and potentially improving interdisciplinary communication and case transfer within digital workflows.[22] In their review on the future of digital orthodontics, Tarraf and Ali[4] emphasized the transformative impact of the widespread adoption of 3D imaging and intraoral scanners on clinical practice. In parallel, the integration of technologies such as CBCT, intraoral scanners, and CAD/CAM systems into routine care has likely contributed to the growth of scientific output in these domains.[23] The prominence of 3D printing and additive manufacturing represents another major component of this digital transformation. These technologies have enabled the fabrication of patient-specific orthodontic appliances and auxiliaries-such as aligner-related workflows, retainers, indirect bonding trays, surgical splints, and customized adjunctive devices-with potential gains in turnaround time, standardization, and reproducibility.[24] Likewise, the rapid increase in AI-focused themes indicates the growing clinical interest in automated image interpretation and clinical decision-support applications (e.g., cephalometric landmark identification, decision-making regarding extractions in orthodontic treatment planning, and growth monitoring based on cervical vertebrae).[15,25,26] Collectively, these developments may enhance consistency across diagnostic and planning stages and reduce operator-dependent variability. Overall, the observed trends suggest that "digitalization" is evolving beyond standalone tools towards integrated, end-to-end digital workflows encompassing diagnosis, treatment planning, appliance fabrication, and follow-up monitoring.

The acceleration in publication output observed after 2020 may reflect not only technological maturation but also the pandemic-driven need for digital data sharing, remote communication, and care strategies that minimize physical contact. During the period analyzed,the observed increase in attention to tele-orthodontics and remote patient monitoring suggests that digital workflows have expanded beyond diagnosis and planning to also include follow-up stages, such as supporting control appointments and enabling remote treatment monitoring. Beyond this acute phase, hybrid care models, in which in-office procedures are complemented by digitally supported monitoring and follow-up processes, are likely to be adopted on a more permanent basis. While routinization of digital records and standardized data formats may facilitate remote case assessment, interdisciplinary consultation, and patient communication,[27,28] emerging AI-based analytics could support triage and prioritization in high-volume clinical settings.[29] However, the long-term sustainability of this transformation will depend on clinician training, interoperability across software ecosystems, data-quality standards, and evidence regarding clinical effectiveness and cost-effectiveness. Accordingly, future research should not only map publication dynamics but also evaluate the real-world impact of digital workflows on clinical outcomes, efficiency, and patient-reported experiences in orthodontic care.

Countries and Institutions

In terms of publication output, the USA, Italy, China, Brazil, and Germany were the most productive countries. In co-authorship analysis, total link strength reflects the intensity of international research collaborations (Table 3). The co-authorship network map (Figure 1A) highlights the central role of the USA. The results suggest that the USA maintains extensive collaborations with multiple countries, supported by the country's high output and strong link strength. Furthermore, Italy, Brazil, Switzerland, and Germany follow the USA in collaborative output. Although China has substantially increased its research output in certain fields, it remains behind the Euro-American axis in citation impact.[30] Despite a high number of publications, China's comparatively low link strength suggests a more limited role in international co-authorship networks. According to the results of citation analysis, the most frequently cited countries were the United States (6539 citations), Italy (2972 citations), and Germany (2011 citations) (Table 3). International collaborations are considered an effective means of enhancing the quality of scientific research and the resulting scholarly output.[31] Moreover, internationally co-authored publications generally achieve a greater impact than those arising solely from national collaborations.[32,33] The overlay visualization of country citations (Figure 1B) shows a steady increase in U.S. citations since 2018. Following the COVID-19 pandemic, the widespread use of online communication tools appears to have facilitated cross-continental collaboration. As shown in Figure 1B, the constraining effect of geographic distance on collaboration has diminished since 2020, enabling broader international research networks. China, Italy, Sweden, and Germany have shown marked increases in citations during the post-pandemic period.

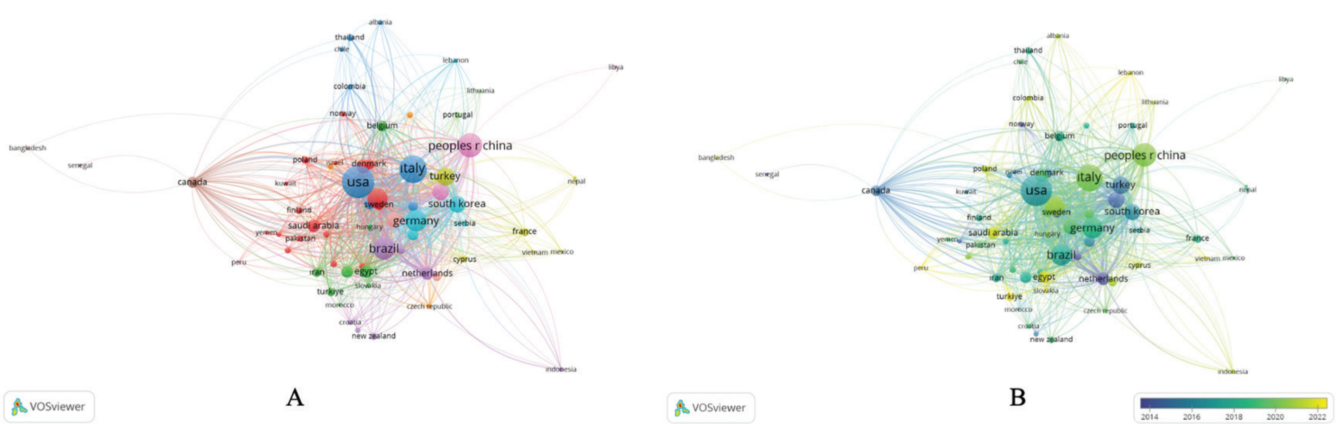

Figure 1. A) Network visualization of co-authorship among countries **B)** overlay visualization of country citations.

Since institutional prestige is closely associated with the quantity and quality of scientific publications, scholars at such institutions tend to produce more publications and receive higher citation counts.[34] At the institutional level, Peking University had the highest publication volume, indicating that a significant portion of China's contributions to digital orthodontics originates from this institution. Furthermore, the University of São Paulo and the University of Michigan stand out as key global research hubs. In particular, the University of São Paulo emerged as a major contributor in Latin America, reflecting Brazil's scientific productivity. Despite a lower publication count, Radboud University, with 1360 citations and a total link strength of 238, ranked highest in citation impact and link strength, indicating its influential role in the field (Table 4). This conclusion is supported by the institutional co-authorship network (Figure 2). The University of Michigan (862 citations, 212 link strength) and Peking University (426 citations, 153 link strength) also demonstrated considerable academic influence. Groningen (679 citations; link strength 138) and São Paulo (295 citations; link strength 138) demonstrated strength in both citations and collaborative networks. Groningen's citation performance further underscores the Netherlands' contribution to this domain. Taken together, these findings suggest that institutional performance should be interpreted using multiple indicators (output, citation impact, and collaboration), rather than publication volume alone.

Authors

Authorship analysis revealed that the most prolific contributors in this field were Xu Tianmin (21 publications), Kuijpers-Jagtman (20) publications, and Lo Giudice (19) publications (Table 5). While high productivity indicates sustained scholarly engagement, publication counts alone do not fully capture academic influence. An author's influence in the literature depends not only on the quantity of their output, but also on the number of citations their work receives and the extent of their scholarly collaborations. In this context, authors with high publication volume should also be evaluated based on their citation frequency and collaborative networks.

When examining citation counts, Flores-Mir (627), Ren Yijin (606), and Major (540) emerged as the most highly cited authors (Table 6). A comparison of publication volumes and citation counts revealed that some authors, despite having relatively few publications, achieved substantial academic influence. For instance, Kuijpers-Jagtman ranked highly by publication count, and they were also among the most frequently cited authors. This highlights that not only the quantity but also the quality of scientific work are critical factors in shaping academic success.

The total link strength values presented in Supplementary Table 1 are important indicators of the intensity of academic collaborations. Authors such as Luca Lombardo (20.0), Antonino Lo Giudice (17.0), and Vincenzo Ronsivalle (16.0) had high link strength scores, reflecting their active engagement in extensive academic collaboration networks. A high link

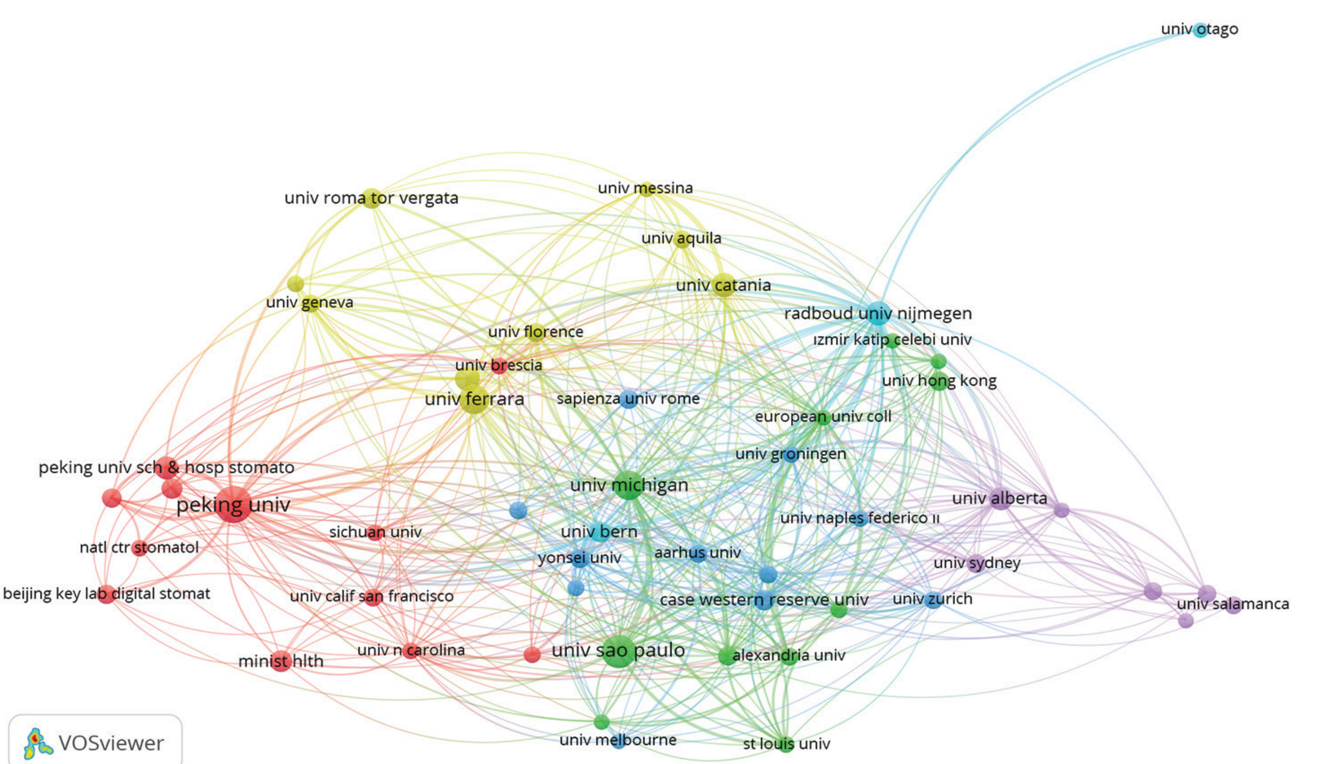

Figure 2. Network visualization of co-authorship among institutions.

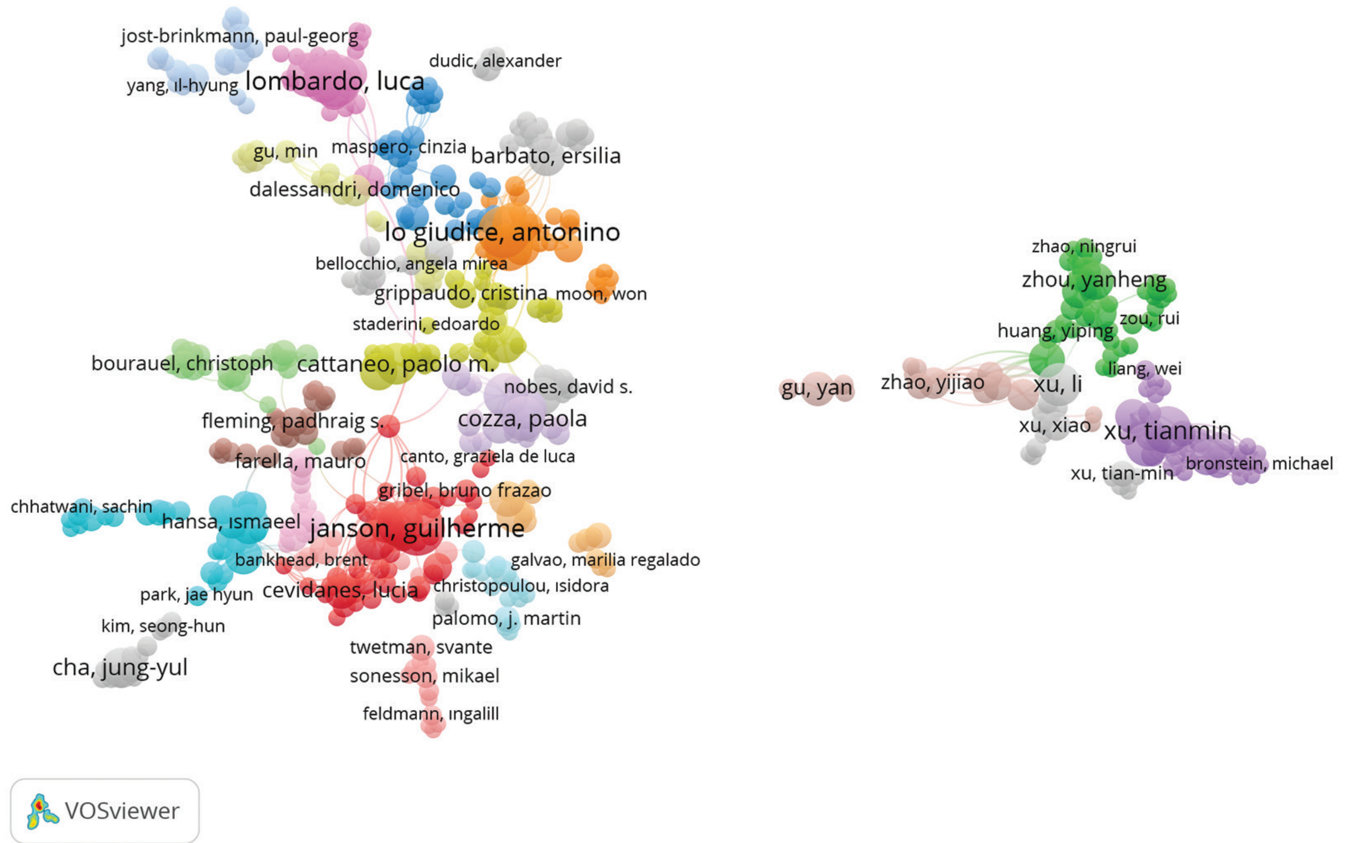

Figure 3. Network visualization of co-authorship among authors.

strength score suggests that these authors frequently collaborate with other researchers and participate in joint research projects. For instance, Lo Giudice appears to play a key role not only by contributing individually to the literature, but also by supporting international academic collaborations, given this author's high scores in both publication volume and link strength.

The co-authorship network map in Figure 3 shows that geographic and institutional proximity plays an important role in collaboration preferences among authors. Academic communities based predominantly in Europe and North America tended to establish broader collaborations and foster global interactions. Although Chinese researchers form a distinct cluster, their connections with Western academic communities remain limited. Authors appearing as isolated nodes may represent smaller teams or comparatively independent lines of work. As shown in Figure 4, future growth in international collaboration may increase interactions among these major clusters.

Journals

AJODO emerged as the most productive and widely preferred journal. While the European Journal of Orthodontics predominantly features Europe-based research, Orthodontics & Craniofacial Research focuses on more specialized and multidisciplinary studies in orthodontics. Although The Angle Orthodontist and Orthodontics & Craniofacial Research publish fewer articles, their high citation rates suggest a selective publication policy and a substantial scientific impact. AJODO leads the field not only in volume and number of citations, but also in collaborative strength. Since 2014, as shown in Figure 5, AJODO, European Journal of Orthodontics, Journal of Orthodontics, and The Angle Orthodontist have been prominent in citation trends. Since 2020, Orthodontics & Craniofacial Research and Progress in Orthodontics have experienced increased visibility. The recent rise in open-access journals, such as Progress in Orthodontics and Journal of Digital Orthodontics, has likely facilitated broader dissemination of research in digital orthodontics.

Keywords

The results of the keyword analysis highlight the prominent research foci in this field. After the terms "orthodontics" and "digital orthodontics," the most frequently used keywords related to digital orthodontics and associated technologies were "digital models" (52 occurrences), "digital dentistry" (45), and "3D printing" (44) (Supplementary Table 3). The frequent appearance of these three keywords suggests that research in the field of digital orthodontics has increasingly focused on digital modeling, digital dentistry applications, and 3D printing techniques. Terms such as "accuracy" (35) and "clear aligners" (31) emphasize the relationship between digital approaches and the precision and fit achieved in treatment processes. In

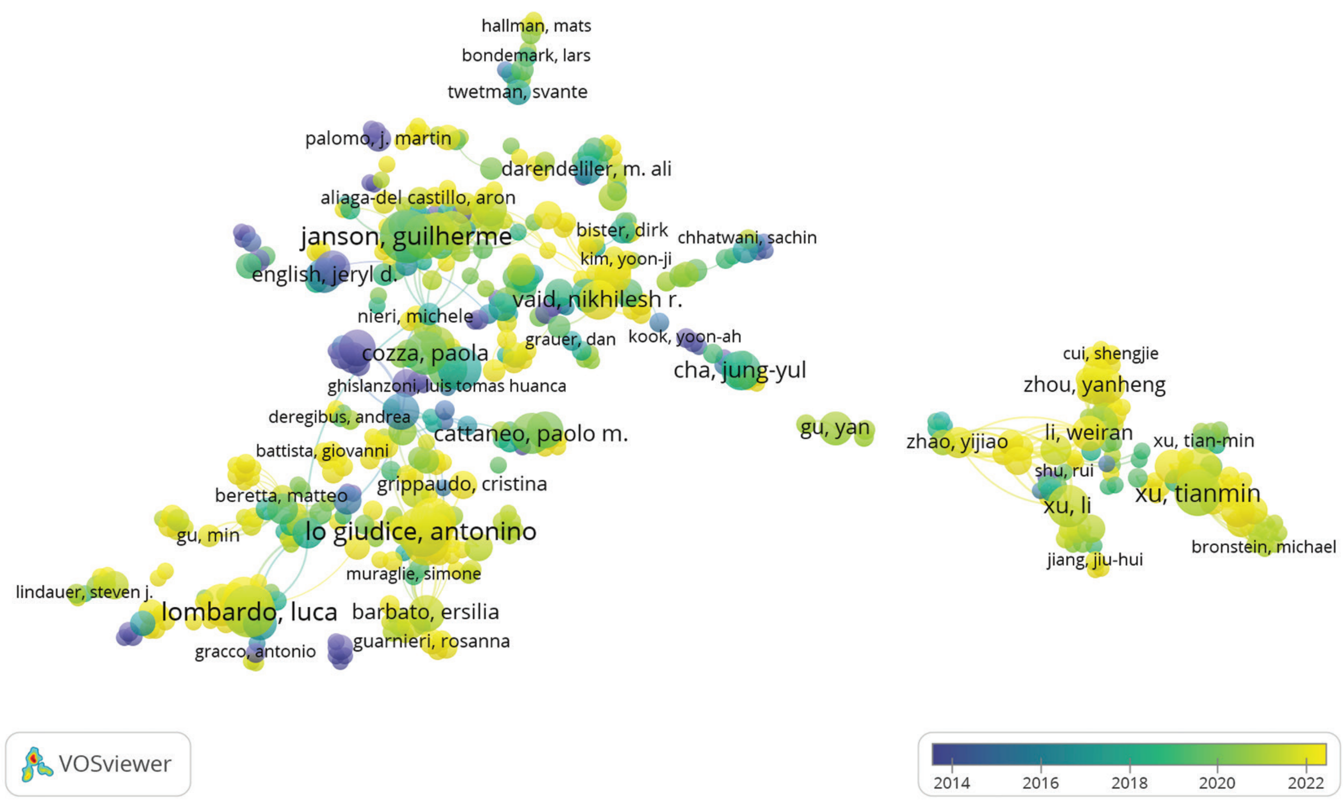

Figure 4. Overlay visualization of co-authorship among authors.

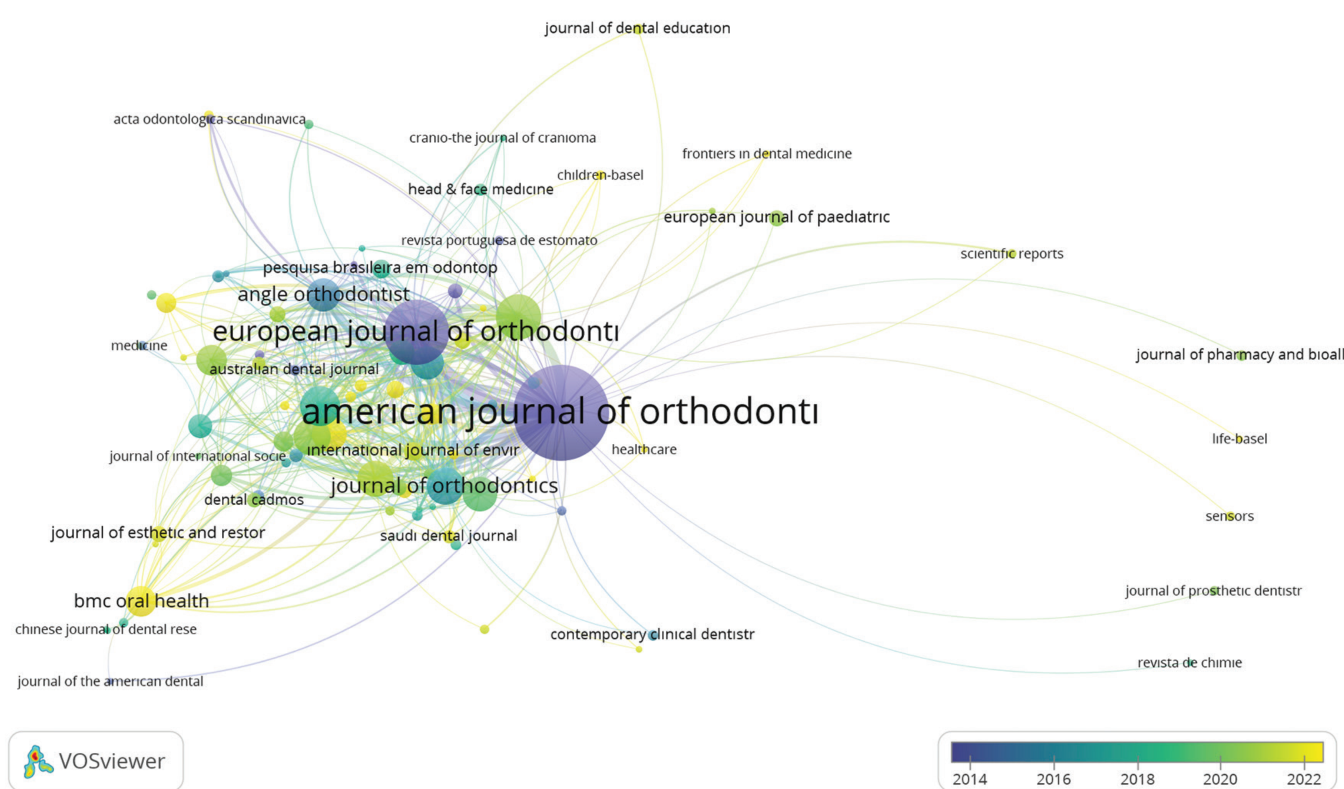

Figure 5. Overlay visualization of journal citations.

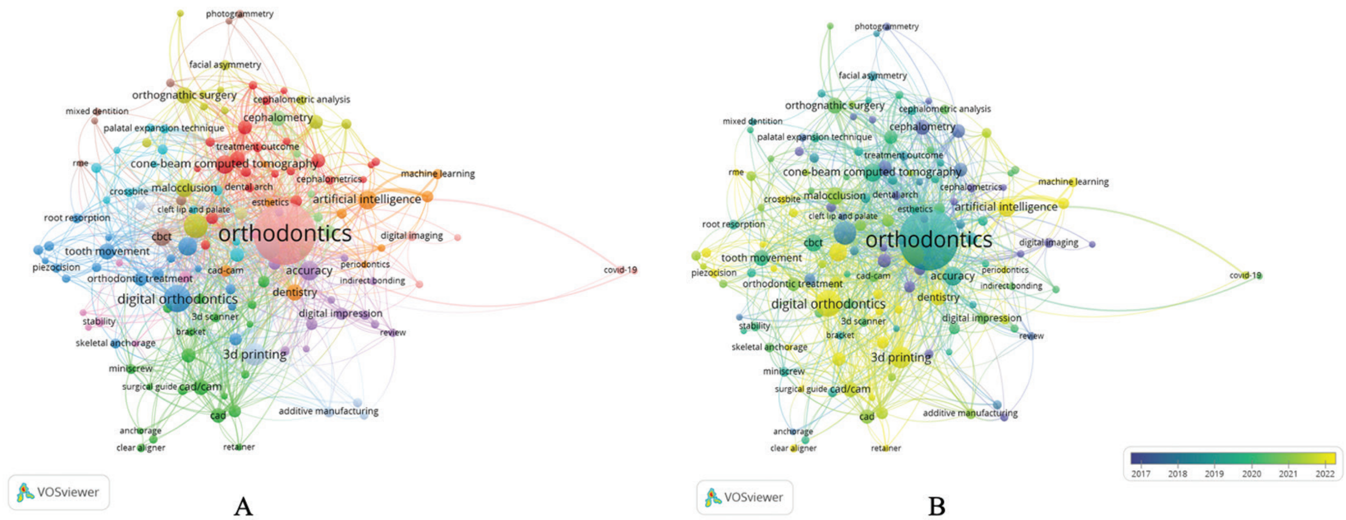

Figure 6. A) Keyword co-occurrence analysis **B)** overlay visualization of keyword co-occurrence.

addition, "AI" (30) and "CBCT" (29) are additional significant terms that reflect the expanding applications of digital technologies in dentistry and orthodontics.

As shown in the keyword co-occurrence map in Figure 6A, the 144 nodes correspond to 144 unique keywords used across 1567 articles. A total of 995 links were identified among these nodes, indicating that pairs of keywords co-occurred in articles 995 times. The central placement of the terms "3D printing," "digital dentistry," and "AI" on the map, combined with these keywords' high total link strength scores, confirms that the corresponding concepts possess the strongest connections within the network (Supplementary Table 3). This finding demonstrates that the digitalization of orthodontic applications is no longer confined to imaging techniques but also extends to production processes and decision-support systems. Indeed, Choi et al.[14] emphasized the significant contribution of AI-based models in orthognathic surgery decision making.

In the longitudinal keyword analysis presented in Figure 6B, an increase in the frequency of use of the terms "3D printing," "clear aligner," "AI," "machine learning," and "digital workflow" has been observed since 2022. This trend can be attributed to the growing adoption of personalized systems produced via digital workflows, such as clear aligners.[35] Similarly, recent clinical developments have become the subject of bibliometric research. The increase in publications on miniscrew-assisted maxillary expansion -following the widespread adoption of miniscrews, the integration of AI into orthodontics, and the growth in literature output accompanying the emergence of clear aligner therapy- has been visualized and quantitatively monitored through bibliometric analyses.[36-38] Collectively, these developments confirm a consistent transition from conventional orthodontic methods toward digital and data-driven approaches.

Reference Analysis

The data presented in Supplementary Table 4[19-21,39,40] and 5[19-21,39,41] indicate that the most frequently cited studies are those by Fleming et al.,[19] Stevens et al.,[20] and Santoro et al.[21] These authors examine the differences between digital and conventional orthodontic measurements, and their studies serve as foundational works in the field. Fleming et al.,[19] emerged as the author with both the highest citation frequency and the greatest total link strength. These findings clearly demonstrate the critical role of Fleming et al.,[19] in shaping and advancing this research area. Stevens et al.,[20] closely follows Fleming et al.,[19] in this field. We also observed that more recent studies tend to receive higher citation counts, indicating that newly developed methods are increasingly preferred over traditional approaches and that there is a growing academic interest in this area.

Over the last decade, intraoral scanning, 3D printing, and related software applications have gained significant interest in the orthodontic literature and among both healthcare providers and patients. Accordingly, it is anticipated that 3D applications will replace two-dimensional methods as the most frequently used measurement techniques.[42] The increasing adoption of 3D technologies in orthodontics has also driven academic research forward. Initially, the primary goal of digital technology in orthodontics was to enhance diagnostic accuracy; however, current advancements have contributed to a more streamlined and efficient workflow. Future technological developments are expected not only to refine treatment outcomes but also to improve patients' access to care and to facilitate better adherence to treatment protocols. In addition, the ease of digital data sharing has strengthened academic collaborations across institutions and countries. The recent rise in open-access publications has further expanded the availability of digital orthodontics research to a broader scientific community, thus accelerating the dissemination of knowledge and contributing to a more dynamic and rapidly evolving body of literature.

While the adoption of digital technology in orthodontic applications has brought significant improvements in diagnostic accuracy and workflow efficiency, several technical and economic challenges remain to be addressed in this transition. First, the acquisition costs and maintenance requirements of digital orthodontic systems (e.g., intraoral scanners, CAD/CAM software, 3D printers) pose certain financial constraints.[43] This may hinder the adoption of digital technology, particularly for institutions and clinics with limited capacity to invest in technological infrastructure. The varying degrees of acceptance of digital technologies among patients demand effective teamwork and prioritization of patient education. Practitioners must also adapt to evolving legal standards and navigate administrative challenges throughout this transition. In addition, ensuring the optimal functioning of digital hardware and software requires regular maintenance and specialized technical support. Despite these challenges, carefully and flexibly implemented digital orthodontic technologies have the potential to significantly enhance patient care and overall efficiency.

Study Limitations

The present study has several limitations. First, the analysis was based exclusively on the WoSCC. Although WoSCC is widely used in bibliometric research, reliance on a single database may have excluded relevant publications indexed only in other databases, such as Scopus, PubMed/MEDLINE, Embase, or regional databases. Consequently, the publication, citation, geographic, and institutional patterns identified in this study should be interpreted within the context of WoSCC coverage.[35]

Second, citation indicators were not adjusted for author- or journal-level self-citations. Highly productive authors, research groups, or journals may accumulate self-citations, potentially affecting citation-based rankings and comparisons.[17] Therefore, citation counts should be interpreted as indicators of citation visibility rather than direct measures of scientific quality or impact.

Third, although no language restrictions were applied, the indexing practices of WoSCC may favor English-language journals and specific publication types, potentially limiting the representation of research from certain countries or regions.

Fourth, bibliometric analysis is inherently quantitative and primarily characterizes publication output, citation patterns, collaboration networks, and thematic structures. It does not evaluate the methodological quality, risk of bias, strength of evidence, or clinical effectiveness of the individual studies included in the analysis. Accordingly, the prominence of a research theme or highly cited publication should not necessarily be interpreted as evidence of greater clinical relevance or scientific quality.

Finally, keyword-based analyses are influenced by variations in terminology because author-provided keywords are not standardized. Conceptually similar terms, such as "clear aligner" and "clear aligners," "CBCT" and "cone-beam computed tomography," or "3D printing" and "additive manufacturing," may therefore fragment related research themes. Although thesaurus-based harmonization was performed to minimize this variability, some differences in terminology and loss of contextual information may have persisted and influenced cluster composition.

Future bibliometric studies could address these limitations by integrating multiple bibliographic databases, performing sensitivity analyses with and without self-citations, and combining bibliometric mapping with qualitative assessments of methodological quality and clinical outcomes. Such approaches may provide a more comprehensive understanding of not only the evolution of digital orthodontic research but also its clinical and translational relevance.

CONCLUSION

The results of this bibliometric study revealed a significant upward trend in literature production regarding the use of digital techniques in orthodontic practices, especially after 2020, with a peak reached in 2023. Furthermore, the results showed that academic collaborations have evolved into a more extensive global network, with a notable rise in internationally co-authored publications in the post-pandemic period. The observation that more recent studies receive higher citation rates suggests that newly developed methods are increasingly adopted over conventional approaches and that scientific interest is increasingly focused on emerging innovations. Despite the potential clinical benefits of digital technologies, the pace and direction of research and publication trends in digital orthodontics can be adversely affected by barriers to widespread implementation, such as costs, infrastructure requirements, training needs, and workflow integration.

Ethics

Ethics Committee Approval: Not applicable. This study is a bibliometric analysis of publicly available published literature and did not involve human participants or animals; therefore, ethics committee approval was not required.

Informed Consent: Not applicable, as no human participants were involved in this study.

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