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Digital Transformation of Zygomatic Implant Supported Maxillofacial Rehabilitation: A Bibliometric and Thematic Mapping Study

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ABSTRACT

Purpose: This study aimed to characterize publication activity, contributing communities, citation patterns, and thematic structures in Scopus-indexed research on digital zygomatic implant rehabilitation.

Materials and Methods: Bibliometric analysis and keyword co-occurrence mapping were performed on a provisional corpus of 94 publications retained from 128 retrieved records. Metadata and keyword variants were standardized. Biblioshiny supported descriptive analysis, and VOSviewer generated author-keyword and indexed-keyword networks, an overlay visualization, and an author-keyword threshold sensitivity analysis.

Results: The corpus encompassed 49 sources and accumulated 1,286 citations. Publications from 2021–2025 represented 54.3% of the corpus, with 2025 recording the highest output among completed years. Five sources contributed 38.3% of publications. China and Italy led corresponding-author locations; 17 publications involved international collaboration when sovereign countries were distinguished from territories. The ten most cited publications accounted for 51.9% of citations. The author-keyword network comprised 45 terms in six clusters, spanning guidance, navigation, robotics, biomechanics, and prosthetic rehabilitation. Its structure showed substantial agreement across occurrence thresholds among shared terms (adjusted Rand index, 0.899). The indexed-keyword network contained 82 terms in four clusters. Dynamic navigation, augmented reality, and robotics had comparatively recent average publication years.

Conclusion: Research activity has expanded across interconnected surgical and prosthetic applications. Bibliometric prominence does not establish clinical effectiveness or adoption. Prospective multicentre research should evaluate integrated rehabilitation workflows, technical reliability, prosthetic outcomes, and patient-reported benefits. Findings remain provisional pending resolution of outstanding records. (*Int J Maxillofac Prosthetics 2026;9:10-25*)

Keywords: Zygomatic implants; Digital dentistry; Maxillofacial rehabilitation; Bibliometric analysis; Keyword co-occurrence; Computer-assisted surgery.

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AUDIOABSTRACT

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INTRODUCTION

Rehabilitation of patients with severe maxillary atrophy or acquired maxillary defects remains challenging when residual bone cannot support conventional dental implants. Zygomatic implants provide an alternative anchorage strategy for selected patients, including those with extensive bone deficiency or unsuccessful previous grafting and implant treatment.[1] Their relevance extends beyond restoration of an edentulous arch to prosthetic rehabilitation after maxillary resection. Long-term evidence supports high implant survival, although sinusitis and other biological or prosthetic complications remain important considerations.[2] These outcomes underscore the need to evaluate zygomatic implant treatment as a coordinated surgical and prosthetic intervention rather than implant placement alone.

The anatomical demands of zygomatic implant placement make accurate planning and surgical execution particularly important. Long implant trajectories, variable maxillary and zygomatic anatomy, and proximity to critical structures require careful patient selection, operator expertise, and restorative planning.[3] Digital approaches offer tools for visualizing anatomy, defining implant trajectories, and transferring a virtual plan to the operative setting. Early clinical work by Vrielinck et al. demonstrated computed tomography-based planning and customized drill guides for zygoma and pterygoid implant placement, providing an important foundation for subsequent developments in computer-assisted treatment.[4] Digital transformation in this field therefore represents an evolving response to established anatomical and procedural challenges.

Surgical guidance has expanded from static templates to dynamic navigation and robot-assisted systems. These approaches differ in how the planned trajectory is transferred, monitored, and executed, and their performance depends on registration, guide design, tracking, and clinical circumstances. A systematic review of computer-assisted zygomatic implant placement reported clinically acceptable mean deviations but emphasized the persistence of positional errors and potential complications across guidance approaches.[5] Robot-assisted placement has also been investigated in experimental models, including the phantom study by Cao et al.[6] Such developments broaden the technical scope of the field, while reinforcing the need to distinguish feasibility and placement accuracy from demonstrated improvements in long-term patient outcomes.

Digital developments also affect the prosthetic stages of rehabilitation, including impression acquisition, data integration, prosthesis design, and manufacture. Mazzoni et al. described an impression-reference technique intended to simplify the digital workflow for immediate loading of zygomatic implant-supported prostheses.[7] In patients with maxillectomy defects, acquisition of the defect anatomy and exposed implant surfaces presents additional challenges that are not adequately represented by conventional complete-arch implant models. Elbashti et al. evaluated intraoral scanners for digitizing maxillectomy models with exposed zygomatic implants and demonstrated feasibility with scanner-dependent differences in trueness and precision.[8] These in vitro findings support further investigation of digital prosthetic workflows without establishing equivalent performance in clinical conditions.

The expanding range of applications creates a need to examine how research is distributed across technologies, clinical contexts, and contributing communities. Elbashti et al. previously documented increasing use of digital technologies within selected maxillofacial prosthetics journals, providing a broader perspective on developments in this specialty.[9] Bibliometric and scientometric investigations have also characterized the general zygomatic implant literature, including analyses of publications from 2001–2021 and 1990–2021.[10,11] These broad assessments provide useful background, but a focused examination of digital zygomatic implant rehabilitation can address a more specific question: how surgical guidance, digital prosthetic procedures, and related computational

approaches are represented and connected within the literature. This distinction defines the rationale for the present study.

Bibliometric performance analysis and keyword co-occurrence mapping offer complementary ways to examine publication activity, geographic participation, citation patterns, and conceptual relationships.[12] Their combined application can contextualize the digital zygomatic implant literature while avoiding assumptions that publication frequency or citation prominence establishes clinical superiority. Therefore, this study aimed to characterize Scopus-indexed research on digital technologies in zygomatic implant-supported maxillofacial rehabilitation through analysis of publication trends, sources, authors, corresponding-author geography, collaboration, and citations, together with separate author-keyword and indexed-keyword networks. A temporal overlay and threshold sensitivity analysis were used to explore the timing and stability of the mapped conceptual structure.

MATERIALS AND METHODS

Study Design and Search Strategy

A bibliometric study incorporating descriptive performance analysis and keyword co-occurrence mapping was undertaken to characterize research on digital technologies in zygomatic implant-supported maxillofacial rehabilitation. Scopus was the sole bibliographic data source. The search combined terms describing zygomatic implants and fixtures with terms related to digital planning, computer-assisted surgery, surgical guidance and navigation, computer-aided design and manufacturing, digital impressions and scanning, photogrammetry, additive manufacturing, robotics, augmented and mixed reality, and artificial intelligence. Search terms were combined using Boolean operators within the title, abstract, and keyword fields. The search yielded 128 records, which were exported in comma-separated values format with bibliographic information, abstracts, author and indexed keywords, author identifiers, affiliations, citation counts, and cited references. The original export was preserved, and eligibility assessment, metadata corrections, and keyword normalization were documented in separate working files.

Eligibility Assessment and Corpus Construction

Publications were eligible if they addressed endosseous zygomatic implants for oral or maxillary prosthetic rehabilitation and substantively investigated a digital technology. Relevant applications included digital acquisition or evaluation, virtual planning, static surgical guidance, dynamic navigation, computer-assisted surgery, robotics, augmented reality, digital impressions, computer-aided design and manufacturing, additive manufacturing, and integrated digital workflows. Zygomatic implant-specific computational biomechanical investigations, including finite element analysis, were retained. Relevant original articles, reviews, book chapters, and conference papers were considered; no language-based exclusion was applied during screening.

Publications were excluded when zygomatic implants were mentioned only incidentally, the intervention concerned alternative rehabilitation, or the implant architecture fell outside the endosseous zygomatic implant scope. Subperiosteal frameworks were excluded. General zygomatic segmentation or reconstruction studies without a demonstrated digital zygomatic implant application were also excluded. Related publications were retained as distinct bibliometric records unless they constituted duplicate database entries. Potential duplicates were assessed using Scopus identifiers, digital object identifiers, and normalized titles.

Titles and abstracts were assessed, and available full texts were used to clarify relevance and adjudicate borderline records. The assessment combined title/abstract and full-text evidence; full-text review was not completed for every retained publication. A record-level log documented eligibility decisions, supporting evidence, and retrieval outcomes. Of 128 retrieved records, 94 were provisionally included, 26 were excluded, seven books or book chapters remained awaiting full text, and one report could not be retrieved despite author-contact and institutional-library requests. The eight unresolved records were kept separate from relevance-based exclusions and were not included in the analyses. All findings therefore refer to the current provisional 94-record corpus.

Metadata Validation and Standardization

Metadata completeness and consistency were reviewed before interpretation. Source-title variants were consolidated when bibliographic identifiers and publisher information supported their equivalence. Author attribution was reviewed using Scopus author identifiers, full names, affiliations, and coauthor continuity. Spelling and initial variants associated with the same identifier were combined, whereas different researchers sharing abbreviated names were distinguished. Two cross-identifier merges were adopted as documented analysis decisions: Wu Yi-qun/Wu Yiqun and Fan Shengchi. The latter involved an inference based on an exact full-name match and coauthor continuity because the newer record lacked affiliation information. A possible Feng Wang/F. Wang profile split remained unresolved and was not merged. Author totals were consequently treated as provisional analysis identities rather than definitive counts of unique individuals.

Corresponding-author geography was assigned from the first reported correspondence address. When a country was omitted, it was recovered only if the named corresponding author could be matched to an explicit affiliation or institutional location. Automated geographic assignments were reviewed against the original addresses, and insufficiently documented records remained unassigned. Corresponding-author location was not inferred from first-author position. Hong Kong and Taiwan were retained as separate country or territory reporting units. All corrections were recorded without overwriting the original export.

Bibliometric Performance and Collaboration Analysis

Descriptive analyses were conducted with the bibliometrix R package through its Biblioshiny interface. Indicators included annual publication output, document types, source and author productivity, corresponding-author geography, collaboration patterns, and citation counts. Software-generated summaries were checked against record-level metadata; reviewed source, author, and geographic tables superseded summaries affected by inconsistent naming or automated parsing. Author productivity was reported using both publication counts and fractional credit, assigning each author a share of 1 divided by the number of reviewed author identities on the publication. Ranking displays retained all ties at their specified cutoffs.

Citation analysis used Scopus counts captured in the supplied export. Global citations represented citations received from the wider Scopus database rather than citations restricted to the study corpus. Total and mean citations and the most cited publications were described without treating citation frequency as a direct measure of clinical effectiveness or methodological quality. Annual output retained the exported publication years, with completed years distinguished from partial 2026 output and the single future-dated 2027 record. Incomplete and future-dated years were not interpreted as evidence of declining publication activity.

Collaboration was assessed independently from the countries or territories represented in each publication's affiliation addresses. Single-country publications and multiple-country publications were defined according to this declared geographic convention. A second calculation combined mainland China and Hong Kong to distinguish cross-territory participation from international collaboration under a sovereign-country interpretation. Records without sufficient affiliation information remained unclassified. Proportions were reported with explicit denominators, including the full corpus and, where applicable, the subset with available affiliation data.

Keyword Normalization

A keyword thesaurus was finalized before network construction and subsequently refined through three indexed-keyword synonym

consolidations identified during map review. Author and indexed keywords were processed separately. Cleaning included conversion to lowercase, whitespace standardization, consolidation of clear spelling variants, acronyms, and synonyms, and removal of duplicate terms within each publication after merging. Demographic, indexing, study-design, and selected generic descriptors were removed when they did not contribute meaningfully to conceptual mapping. Clinically relevant distinctions were preserved, including static versus dynamic guidance, accuracy versus trueness, computer-aided design versus computer-aided design and manufacturing, and immediate loading versus immediate implant placement. No keywords were inferred from abstracts or technology-domain codes.

The finalized version 1.1 thesaurus was applied to the two keyword fields, and the normalized Scopus dataset was used for mapping without applying the thesaurus a second time. The audit recorded the original labels, replacements or exclusions, reasons, and document frequencies. Keyword normalization did not alter publication eligibility, citation counts, or metadata outside the keyword fields. Records without a particular keyword field remained in the descriptive corpus but could not contribute to that field's co-occurrence network.

Network Construction and Interpretation

Co-occurrence networks were generated in VOSviewer version 1.6.21 using full counting and association-strength normalization. Author keywords provided the primary conceptual representation. The main author-keyword network used a minimum occurrence threshold of two publications, and a sensitivity analysis increased the threshold to three. Agreement between the resulting cluster partitions was evaluated using the adjusted Rand index for the 33 keywords shared by both networks. The indexed-keyword network was constructed separately using a minimum occurrence threshold of three publications. Author and indexed keywords were not pooled because they reflect different term-selection processes.

Node size represented keyword occurrence frequency, links represented co-occurrence within publications, and link strength reflected the frequency of shared occurrence under full counting. Colours indicated algorithmically identified clusters. Network summaries reported the numbers of retained keywords, clusters, and links, together with the sum of link weights, counting each undirected link once. The temporal overlay used the average publication year of records containing each author keyword, with a displayed colour scale of 2012–2026. These scores describe the temporal distribution of publications and do not establish dates of technological introduction or clinical adoption.

Cluster interpretation considered the constituent terms and their relationships. Groupings were treated as descriptive representations of conceptual structure rather than independently validated clinical categories. The indexed-keyword map supplied a complementary indexing perspective and was not interpreted as interchangeable with the author-keyword network. The analyses did not estimate treatment effects; interpretation accounted for the single-database design, missing metadata, time-dependent citation counts, uncertain author identities, and unresolved eligibility decisions.

RESULTS

Bibliometric Profile and Publication Activity

The provisional analysis corpus comprised 94 Scopus-indexed publications dated 2000-2027, distributed across 49 sources after source-title normalization. It included 83 articles, eight reviews, two book chapters, and one conference paper. Author keywords were available for 74 publications and indexed keywords for 77. The corpus accumulated 1,286 Scopus citations, corresponding to a mean of 13.68 citations per publication (Table 1).

Publication activity was sparse through 2019 and increased in the subsequent period (Fig. 1). Annual output rose from three publications in 2020 to five in 2021, seven in 2022, and 14 in 2023, followed by nine in 2024 and 16 in 2025. The 2021–2025 period accounted for 51 publications (54.3% of the corpus). Eighteen records were dated 2026, which was incomplete at data collection, and one record carried a future publication year of 2027. These records were retained in the corpus but distinguished in the temporal display; the apparent decline to one publication in 2027 was not interpreted as a reduction in research activity.

Table 1: Bibliometric profile.

Indicator	Value
Publications	94
Source titles after normalization	49
Scopus author IDs before cross-profile review	381
Provisional analysis identities	379
Mean co-authors per publication	5.33
Articles / reviews / book chapters / conference papers	83 / 8 / 2 / 1
Publications with author / indexed keywords	74 / 77
Normalized author keywords	169
Total Scopus citations	1286
Mean citations per publication	13.68
Assigned / unavailable corresponding geography	85 / 9
Single / multiple countries or territories / unavailable	73 / 19 / 2

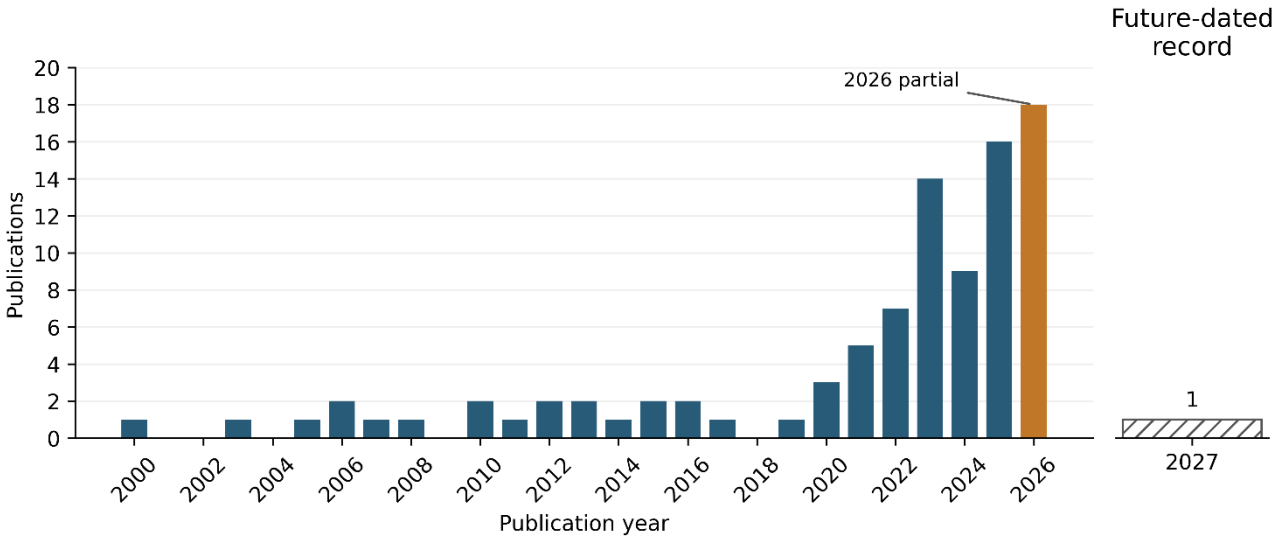


Fig 2: Annual publication counts in the analysis corpus. Blue bars show completed publication years through 2025; the orange bar represents partial 2026 output. The single record dated 2027 is shown separately. All 94 records are retained. No decline in research activity is inferred from the future-dated record.

Publication Sources and Authorship

The International Journal of Oral and Maxillofacial Surgery contributed the largest number of publications (n = 11), followed by the Journal of Prosthetic Dentistry (n = 8) and the Journal of Dentistry (n = 7). The International Journal of Oral and Maxillofacial Implants and the Journal of Craniofacial Surgery each contributed five publications. Together, these five sources accounted for 36 publications (38.3%). Fifteen sources contributed at least two publications (Fig. 2).

The author metadata contained 381 distinct Scopus author IDs. Combining spelling variants within IDs and two evidence-supported split-profile pairs yielded 379 provisional analysis identities. A further possible split involving Feng Wang remained unresolved, so a definitive unique-author count was not assigned. The reviewed ranking attributed 12 publications to Wu Yiqun, seven each to Fan Shengchi and the principal Feng Wang profile, six to James Chow, and five to Baoxin Tao (Table 2). The separate F. Wang profile contained one publication and was retained separately pending confirmation. The imported collection reported a mean of 5.33 co-authors per publication.

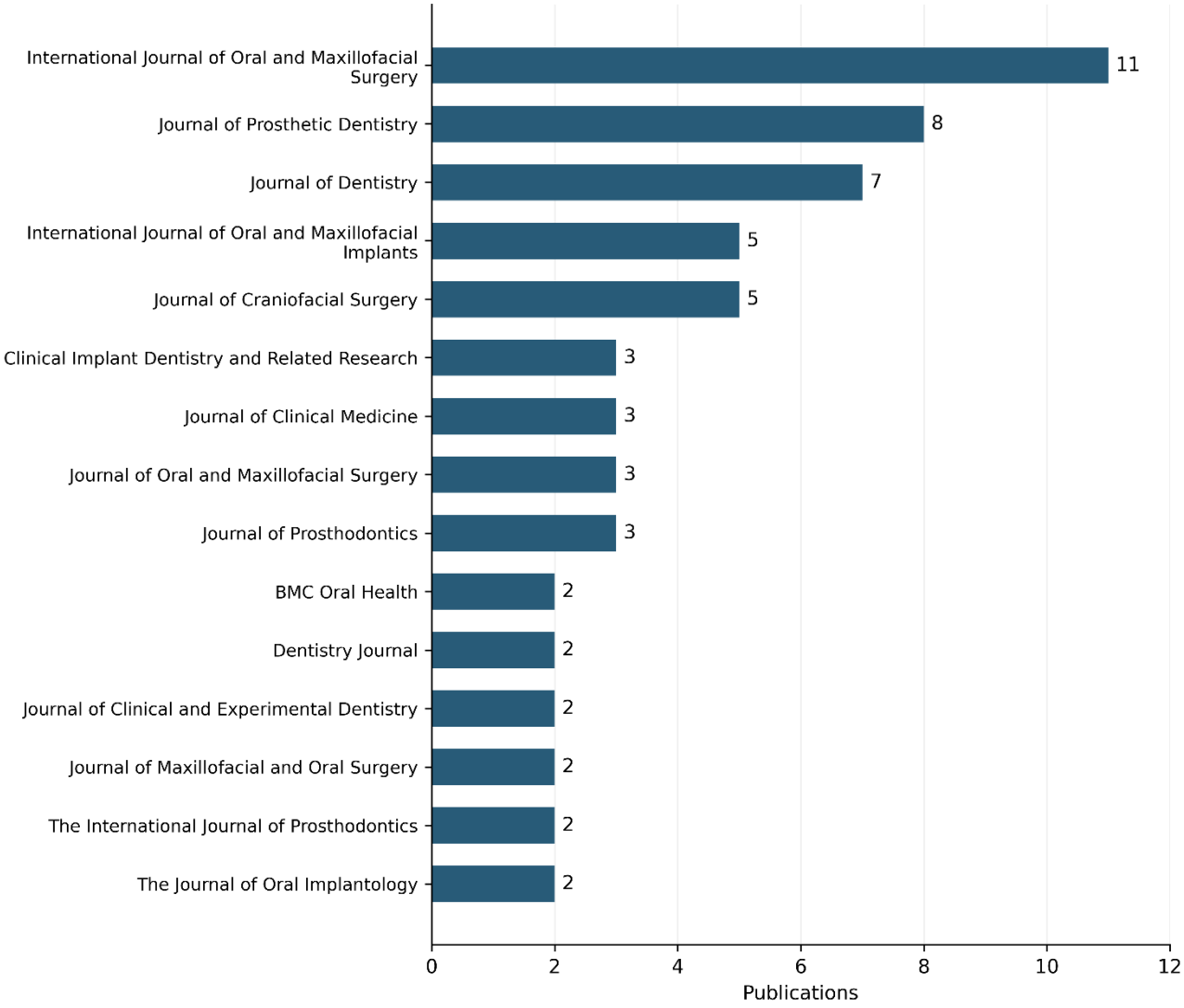


Fig 2: Sources contributing at least two publications. All ties at the tenth rank are included, yielding 15 displayed sources. Counts follow source-title normalization.

Table 2: Authors with at least three publications.

Reviewed name	Publications	Fractional publications
Wu, Yiqun	12	2.02
Fan, Shengchi	7	1.08
Wang, Feng	7	1.44
Chow, James	6	1.83
Tao, Baoxin	5	0.86
Chen, Xiaojun	4	0.56
Huang, Wei	4	0.64
Wang, Wenying	4	0.74
Davó, Rubén	3	0.43
Deglow, Elena Riad	3	0.38
Del Fabbro, Massimo	3	0.34
Grecchi, Emma	3	0.34
Grecchi, Francesco	3	0.34
Grivetto, Fabrizio	3	0.34
Ishak, Muhammad Ikman	3	0.75
Kadir, Mohammed Rafiq Abdul	3	0.75
Kasim, Noor Hayaty Abu	3	0.75
Montero Martín, Javier	3	0.38
Montero, Sofía Hernández	3	0.38
Pato Mourelo, Jesús	3	0.38
Shen, Yihan	3	0.50
Stefanelli, Luigi Vito	3	0.34
Sulaiman, Eshamsul	3	0.75
Zhang, Chen-ping	3	0.51
Zhang, Zhi-yuan	3	0.51
Zingari, Francesco	3	0.48
Zubizarreta-Macho, Álvaro	3	0.38
de Paz Hermoso, Víctor Manuel	3	0.38

Ranking uses Scopus author IDs and reviewed name variants. Wu Yiqun and Fan Shengchi each include an evidence-supported split-profile merge. Feng Wang has seven publications under the principal profile; one F. Wang publication remains separate. Fractional credit assigns 1 divided by the number of reviewed author identities on each publication. All ties at three publications are retained.

Corresponding Author Geography and Collaboration

Corresponding-author countries or territories could be assigned to 85 publications (90.4%); nine remained unavailable. China contributed the largest number of assigned publications (n = 17), followed by Italy (n = 15), Spain (n = 7), the United States (n = 6), and India (n = 5). Hong Kong and Taiwan were retained as separate geographic reporting units. Country assignment was based on the first reported corresponding address, with three country omissions recovered from the named corresponding author's affiliation or explicit institutional location (Fig.3).

The affiliation audit identified 73 publications involving a single country or territory and 19 involving multiple countries or territories; collaboration status could not be established for two records lacking affiliation metadata. The 19 multiple-territory publications represented 20.21% of the full corpus and 20.65% of the 92 records with affiliation data. Two involved only mainland China and Hong Kong; combining these locations reduced the number of publications with international collaboration to 17 (18.09% of the corpus).

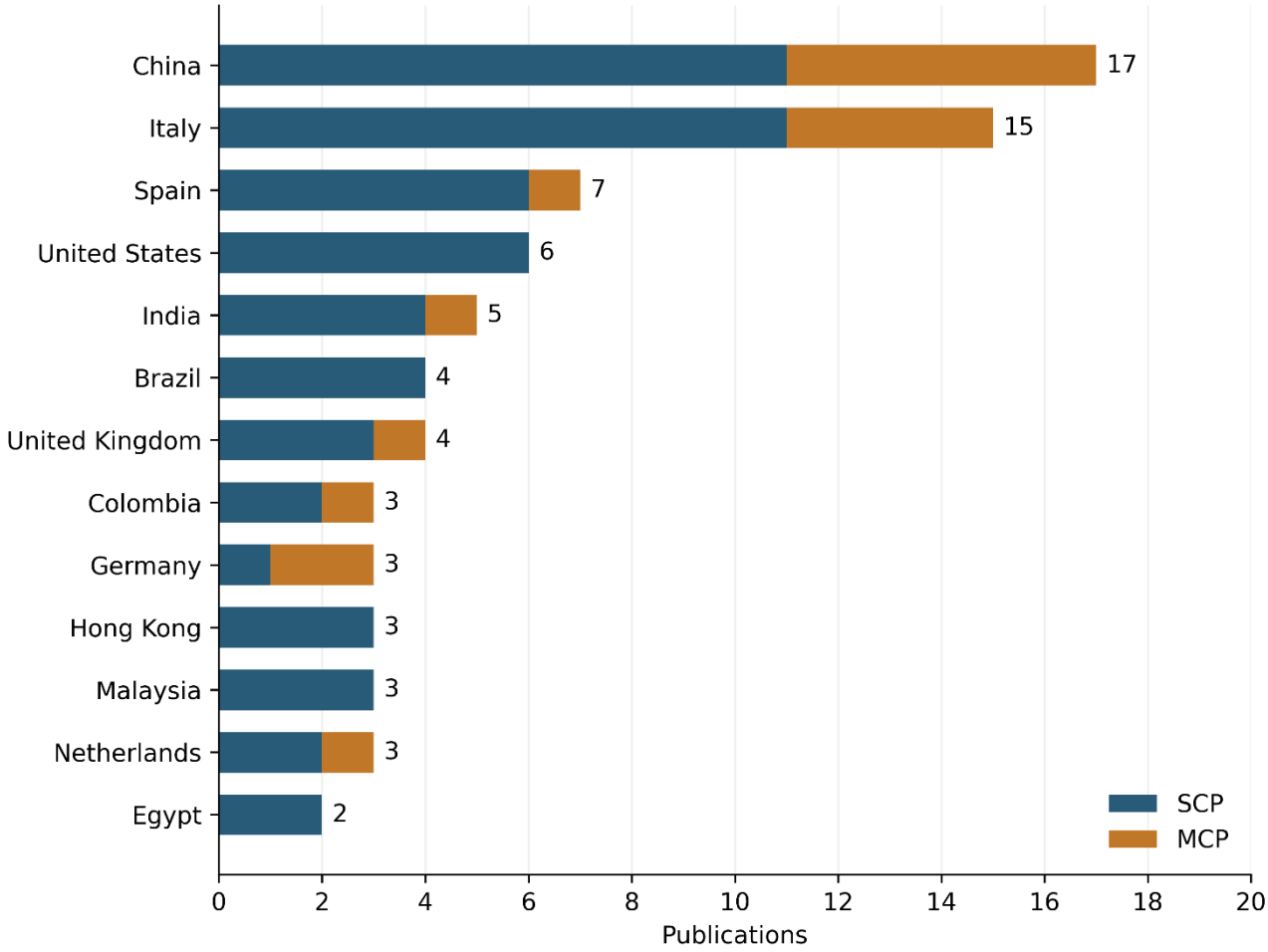


Fig 3: Corresponding-author countries or territories contributing at least two publications. All cutoff ties are retained (13 reporting units). Stacked bars show SCP and MCP, defined as affiliations in one versus multiple countries or territories. Corresponding geography was assigned to 85 publications; nine were unavailable. Hong Kong and Taiwan were treated as separate reporting units.

Citation Distribution

The most cited publication was the image-based planning and customized drill-guide study by Vrielinck et al. (2003), with 192 citations. It was followed by the immediate occlusal loading report by Chow et al. (2006; 92 citations) and the surgical robot pilot study

by Cao et al. (2020; 80 citations). The ten most cited publications accounted for 668 citations (51.9% of the corpus total) and covered image-based planning, guided placement, robotics, biomechanical analysis, and rehabilitation (Table 3). These counts represent citations recorded in Scopus at export and are not restricted to citations originating within the study corpus.

Table 3: Ten most cited publications.

Publication	Citations	DOI
Vrielinck L. et al. (2003). Image-based planning and clinical validation of zygoma and pterygoid implant placement in patients with severe bone atrophy using customized drill guides. Preliminary results from a prospective clinical follow-up study.	192	10.1054/ijom.2002.0337
Chow J. et al. (2006). Zygomatic Implants-Protocol for Immediate Occlusal Loading: A Preliminary Report.	92	10.1016/j.joms.2006.01.021
Cao Z. et al. (2020). Pilot study of a surgical robot system for zygomatic implant placement.	80	10.1016/j.medengphy.2019.07.020
Chrcanovic B.R. et al. (2010). Accuracy evaluation of computed tomography-derived stereolithographic surgical guides in zygomatic implant placement in human cadavers.	63	10.1563/AAID-JOI-D-09-00074
Schramm A. et al. (2000). Computer-assisted insertion of zygomatic implants (Brånemark system) after extensive tumor surgery.	59	10.1007/s100060000211
Ishak M.I. et al. (2012). Finite element analysis of different surgical approaches in various occlusal loading locations for zygomatic implant placement for the treatment of atrophic maxillae.	43	10.1016/j.ijom.2012.04.010
Hu Y.J. et al. (2007). Reconstruction of a palatomaxillary defect with vascularized iliac bone combined with a superficial inferior epigastric artery flap and zygomatic implants as anchorage.	36	10.1016/j.ijom.2007.04.011
Chow J. et al. (2016). A novel device for template-guided surgery of the zygomatic implants.	36	10.1016/j.ijom.2016.06.007
Zhou W. et al. (2021). A novel extraoral registration method for a dynamic navigation system guiding zygomatic implant placement in patients with maxillectomy defects.	34	10.1016/j.ijom.2020.03.018
Balshi T.J. et al. (2012). Zygomatic bone-to-implant contact in 77 patients with partially or completely edentulous maxillas.	33	10.1016/j.joms.2012.05.016

Citations are the Scopus counts captured in the supplied export. All publications tied at the cutoff would be retained; there was no cutoff tie in this ranking.

Author Keyword Networks and Temporal Overlay

At a minimum of two occurrences, the author-keyword network included 45 keywords, six clusters, and 236 links (Fig. 4). The sum of link weights was 428. Zygomatic implants was the most frequent author keyword (49 publications). The clusters included terms associated with atrophic-maxilla rehabilitation and digital workflows, guided surgery and dynamic navigation, dental implantation and robotics, augmented reality and navigation technologies, maxillectomy rehabilitation and virtual planning, and a small two-term group containing cone-beam computed tomography and static guided surgery. These are descriptions of the keyword groupings rather than independently validated clinical categories.

Increasing the minimum occurrence threshold to three yielded 33 keywords, five clusters, and 175 links, with a summed link weight of 347. Among the 33 shared keywords, cluster agreement between thresholds was high (adjusted Rand index = 0.899), supporting broad stability of the structure while showing sensitivity of smaller groups to the threshold.

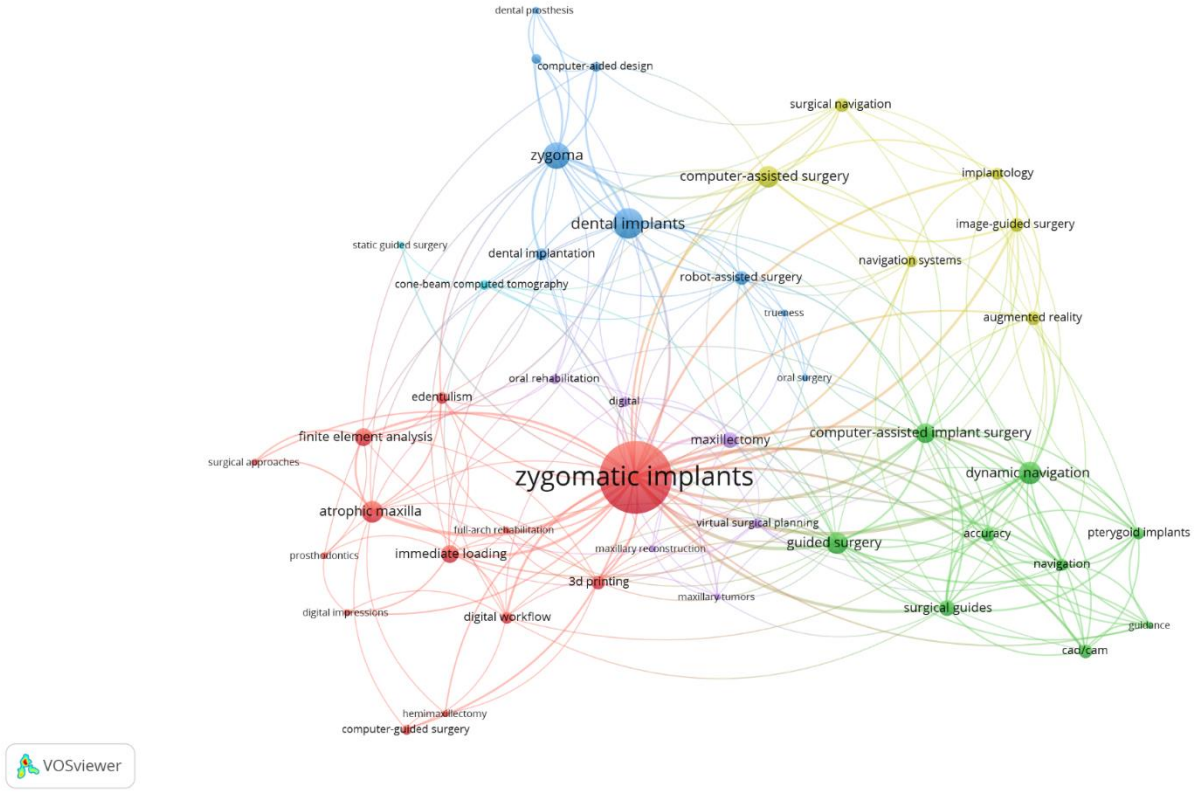


Fig 4: Author-keyword co-occurrence network for the 94-publication analysis corpus. Full counting and a minimum of two occurrences yielded 45 keywords, six clusters, and 236 links. Node size represents keyword occurrence frequency, colors indicate clusters, and links represent co-occurrence within publications. The sum of link weights was 428.

The publication-year overlay showed an average year of 2018.0 for finite element analysis, 2019.4 for CAD/CAM, and 2019.8 for surgical guides. Later average years were observed for digital workflow (2023.75), dynamic navigation (2024.1), augmented reality (2024.8), and robot-assisted surgery (2025.0) (Fig. 5). These values describe the dates of publications containing each keyword and do not establish the date of technological introduction or clinical adoption.

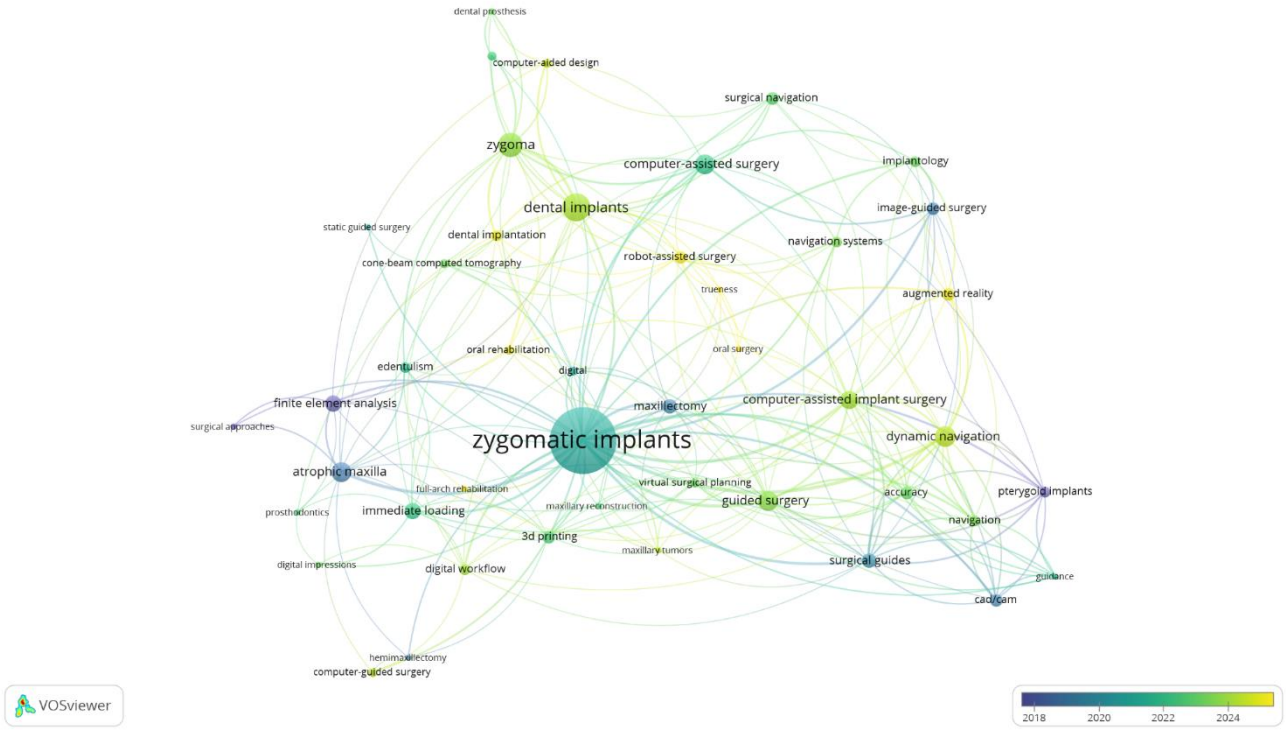


Fig 5: Average-publication-year overlay of the author-keyword network shown in Figure 1. Node size represents keyword occurrence frequency and color represents the average publication year of records containing each keyword. The keyword scores range from 2012.5 to 2025.5. Colors do not represent the year of first introduction or clinical adoption.

Indexed Keyword Network

Following synonym normalization, the indexed-keyword network at a minimum of three occurrences comprised 82 keywords, four clusters, and 1,573 links, with summed link weights of 3,852 (Fig. 6). The displayed groupings encompassed prosthetic and reconstructive rehabilitation, digital planning and fabrication, computer-assisted surgery and robotics, and biomechanical or outcome-related terms. This complementary network provided a broader indexing perspective on the author-keyword themes; its clusters were not treated as interchangeable with the six author-keyword clusters.

DISCUSSION

The present analysis depicts a growing and conceptually diverse literature on digital zygomatic implant rehabilitation. More than half of the provisional corpus was published during 2021–2025, and the highest output among completed years occurred in 2025. This pattern is consistent with the increasing use of digital technologies previously documented in maxillofacial prosthetics and the broader growth of zygomatic implant research reported in earlier bibliometric studies.[9-11] Our analysis extends those perspectives by examining a technology-focused corpus that encompasses surgical guidance, prosthetic workflows, and computational biomechanics. The six author-keyword clusters suggest that these applications form related but distinguishable research areas. However, publication growth indicates increasing research activity rather than greater treatment effectiveness or widespread clinical adoption. The partial 2026 output and future-dated 2027 record also preclude interpretation of the final years as a completed temporal trend.

The concentration of 38.3% of publications in five sources places this literature at the intersection of oral and maxillofacial surgery, prosthodontics, and broader dental research. China and Italy were the leading

corresponding-author locations, whereas earlier analyses of the general zygomatic implant literature identified the United States as the most productive country.[10,11] These findings should not be interpreted as a demonstrated geographic shift: the studies differ in database coverage, observation period, topic selection, and country-attribution method. Nevertheless, the prominence of Wu Yiqun and collaborators in our reviewed author ranking is consistent with their substantial clinical contribution to navigation research, including the study by Wu et al. involving 221 navigation-guided implants in 71 patients.[13] Only 17 publications involved international collaboration under the sovereign-country interpretation. This supports a case for multicenter validation, although neither corresponding-author geography nor coauthorship measures access to technology, training capacity, or routine clinical use.

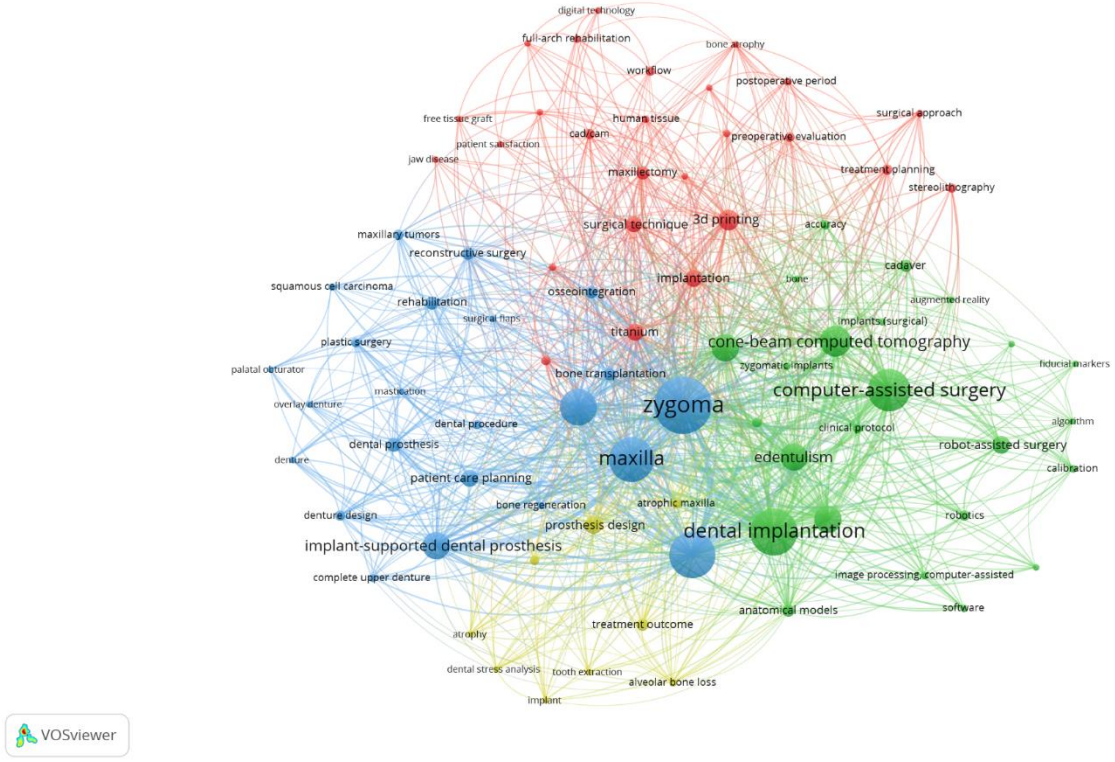


Fig 6: Indexed-keyword co-occurrence network following synonym normalization. Full counting and a minimum of three occurrences yielded 82 keywords, four clusters, and 1,573 links. Node size represents keyword occurrence frequency and colors indicate clusters. The sum of link weights was 3,852.

Citation concentration provides a complementary perspective on the field's development. The ten most cited publications accounted for 51.9% of all citations, and the leading studies linked image-based planning, immediate loading, and robotic placement. Vrielinck et al. established an early clinical framework for customized drill guides,[4] while Chow et al. combined virtual planning and rapid-prototyped guides with an immediate-loading protocol.[14] The computer-assisted insertion report by Schramm et al. further demonstrates that digitally assisted rehabilitation after maxillary resection has a longer history than the recent publication surge might suggest.[15] The prominence of these reports is compatible with their foundational role, but raw citation counts also reflect differences in citation windows and research context.[16] In particular, the highly cited robotic study by Cao et al. was conducted in phantom models;[6] its citation impact cannot establish clinical superiority or equivalence to patient-based evidence.

The author-keyword network emphasizes guided surgery and navigation as major components of the digital research landscape. Its broad structure remained similar after increasing the occurrence threshold, with an adjusted Rand index of 0.899 among the shared terms, although the loss of a small cluster illustrates the sensitivity of less frequent concepts. Clinical literature supports the relevance of these themes while tempering their interpretation. Fan et al. reported clinically acceptable average deviations across computer-assisted approaches,[5] and Traboulsi-Garet et al. subsequently found favorable accuracy estimates but substantial heterogeneity and only one included study with a freehand control.[17] Bhalerao et al.'s randomized trial compared flapless and flapped procedures, both using dynamic navigation, and therefore did not establish navigation's advantage over freehand surgery.[18] Device-related adverse events reported by Wu et al. further show that technical reliability remains consequential.[13] Keyword prominence should thus guide focused evidence appraisal rather than substitute for comparative clinical evaluation.

The temporal overlay places dynamic navigation, augmented reality, and robotic surgery among the more recently represented concepts. These average publication years describe the retrieved literature and do not identify when each technology originated: the robotic pilot by Cao et al. appeared in 2020,[6] while the clinical robot study by Deng et al., assigned to a 2025 journal issue, was published online in 2023.[19] Subsequent evidence remains promising but clinically limited. Deng et al. evaluated eight implants in six participants,[19] and the 2026 robotic meta-analysis by Fan et al. included seven in vitro studies, two clinical studies, and one hybrid study.[20] Although pooled accuracy favored robotics at selected endpoints, these data do not establish durable improvements in prosthetic outcomes or complication prevention. Similarly, the augmented-reality cadaver study by Heijtmeijer et al. demonstrated feasibility without outperforming surgical guides across all accuracy endpoints.[21] These findings support further clinical investigation of emerging technologies, with explicit attention to registration, technical failures, and learning requirements.

The presence of digital workflow, impressions, manufacturing, and maxillectomy-related terms is particularly relevant to maxillofacial prosthetics because surgical accuracy alone does not guarantee a usable prosthetic result. Wang et al.'s prospective case series integrated prosthetically driven navigation with computer-aided manufacture of a supporting bar in patients with extensive maxillary defects.[22] Mazzoni et al. addressed impression referencing for immediate loading,[7] while Nowicki and Osypko described a digital full-arch protocol incorporating scanning and printed interim restorations.[23] Elbashti et al.'s study of maxillectomy models with exposed zygomatic implants provides directly relevant evidence for digital acquisition, but its scanner-dependent findings require clinical validation.[8] Together, these publications contextualize the prosthetic themes in our maps without demonstrating a universally validated complete digital pathway. Future studies should evaluate the entire rehabilitation process, including prosthesis fit, hygiene, maintenance, patient-reported function, treatment time, and cost, and should distinguish acquired maxillary defects from atrophic but anatomically intact maxillae.

Several limitations constrain interpretation. Scopus coverage and the technology-focused eligibility criteria restrict generalization to the wider zygomatic implant literature; database choice can influence bibliometric findings.[24] The corpus remains provisional because eight original-search records have unresolved eligibility, and retained records were assessed using a mixture of title/abstract and available full-text evidence. Incomplete keyword coverage means that the maps do not represent all 94 publications equally. Author disambiguation reduced errors from abbreviated names but did not resolve every possible split profile. Likewise, corresponding-author location represents one address, whereas collaboration estimates depend on the declared geographic convention. The four-cluster indexed-keyword map provides a complementary indexing perspective, rather

than independent confirmation of the six author-keyword groups. Threshold sensitivity, bibliometric prominence, and overlay timing cannot validate clinical themes, quantify treatment effects, or establish adoption. Within these limits, the findings offer a structured view of research activity and indicate priorities for prospective multicenter studies, standardized outcome reporting, and evaluation of integrated surgical and prosthetic workflows.

CONCLUSION

The Scopus-indexed literature on digital zygomatic implant rehabilitation has expanded, with more than half of the provisional corpus published during 2021-2025. Research spans surgical guidance, navigation, robotics, computational biomechanics, and digital prosthetic procedures, while citation influence is concentrated in a small number of publications. The temporal overlay identifies navigation, augmented reality, and robotics as comparatively recent research themes, and the author-keyword sensitivity analysis supports the broad structure of the mapped relationships. These findings characterize research activity and priorities; they do not establish treatment superiority or routine clinical adoption. Future prospective multicenter studies should evaluate integrated surgical and prosthetic workflows using standardized measures of technical reliability, prosthesis performance, complications, patient-reported outcomes, and cost. The present conclusions remain provisional because eight retrieved records have unresolved eligibility and the analysis is restricted to Scopus.

Conflicts of Interest

The authors declare no conflicts of interest.

CRediT authorship contribution

Rohuma M: Conceptualization, Methodology, Investigation, Writing – Original Draft. **Shawi HK and Dokhan T:** Data Curation, Formal Analysis, Visualization, Writing – Review & Editing. **Abdesalam AM:** Supervision, Project Administration, Writing – Review & Editing.

All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

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