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Force Sensing and Haptic Feedback in Robotic Surgery: A Bibliometric and Knowledge-Mapping Analysis of Technological Evolution and Translational Trajectories

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Abstract

Force sensing and haptic feedback are increasingly important for restoring information on instrument–tissue interaction during robotic surgery, yet the development and clinical translation of this field remain incompletely characterized. This study mapped its global research landscape, intellectual structure, technological evolution, and translational trajectory. Publications dated from January 2010 to July 30, 2026, were retrieved from the Web of Science Core Collection, Scopus, and PubMed. After deduplication, metadata quality control, and eligibility assessment, 2,872 publications from 960 sources were analyzed using bibliometric performance indicators, science mapping, citation-burst detection, logistic growth modeling, and exploratory topic modeling. Annual output increased from 56 publications in 2010 to 393 in 2025, with 54.46% of the corpus published during 2020–2025. The field was positioned within a rapid-growth phase, although recent output exceeded the smoothed logistic trajectory. China led publication volume, whereas the United States had the highest cumulative citation impact; international co-authorship remained limited at 11.98%. The knowledge structure evolved from master–slave teleoperation and bilateral control toward miniaturized force sensing, sensorized instruments, robotic palpation, sensorless force estimation, and force-aware intelligent assistance. Exploratory topic modeling did not yield sufficiently coherent or stable themes for definitive classification. Force sensing and haptic feedback are progressing from component-level engineering toward integrated systems and early clinical evaluation. Future research should prioritize standardized reporting, task- and tissue-specific force thresholds, independent validation, human-factor assessment, and prospective multicenter studies.

Introduction

Robot-assisted surgery (RAS) has expanded the capabilities of minimally invasive surgery through articulated instrumentation, motion scaling, tremor filtration, three-dimensional visualization, and improved surgeon ergonomics [1, 2]. Nevertheless, many established robotic platforms have historically relied predominantly on visual information and have provided limited direct perception of instrument–tissue interactions. This sensory deficit is particularly relevant during grasping, dissection, suturing, and palpation, where the magnitude and distribution of applied forces may influence tissue handling and technical performance [3].

Force sensing and haptic feedback address distinct but complementary components of this limitation. Force sensing refers to the direct measurement or model-based estimation of instrument–tissue interaction forces, whereas haptic feedback conveys sensory information to the operator through kinesthetic force cues, cutaneous stimulation, or sensory-substitution interfaces [3–5]. Miniaturized electrical, capacitive, optical, and microelectromechanical sensors have enabled multidirectional force measurement and integration within robotic surgical instruments [4–6]. In parallel, fingertip deformation, vibration, and multimodal feedback interfaces have been investigated as methods of communicating contact forces and tissue characteristics to the surgeon [7–9]. Experimental evidence indicates that haptic augmentation can reduce average and peak forces and improve selected task-level measures of

accuracy, completion time, and success; however, the magnitude of benefit varies across tasks, feedback modalities, and operator experience, and direct evidence of improved patient outcomes remains limited [10].

The field has subsequently progressed from isolated sensor prototypes toward integrated sensing and feedback systems. Contemporary approaches encompass distal and shaft-mounted sensors, tactile arrays, optical and fiber-based devices, sensorless force estimation, multimodal sensor fusion, and closed-loop robotic control [11, 12]. These technologies may also contribute to objective skills assessment, robotic palpation, and higher levels of surgical autonomy by providing information required for environmental perception and safe interaction control [13]. Nevertheless, clinical translation remains constrained by sensor miniaturization, sterilizability, robustness, mechanical decoupling, signal drift, latency, compatibility with surgical workflows, and the absence of standardized evaluation frameworks [14, 15]. Recent preclinical studies of integrated force-feedback systems have demonstrated reductions in applied forces and improvements in selected suturing-performance measures, particularly among novice users, but their influence on operative safety and patient-level outcomes requires prospective clinical validation [16, 17].

Existing reviews have provided valuable classifications of force-sensing mechanisms, tactile sensors, feedback interfaces, and engineering requirements [5, 11, 12, 14, 15]. However, these technology-focused syntheses do not quantify the broader development of the field, including its publication growth, collaborative structure, intellectual foundations, thematic transitions, and progression from sensor innovation toward integrated systems and clinically oriented validation. Bibliometric analysis and science mapping can complement conventional reviews by examining scientific productivity, citation relationships, collaboration networks, conceptual structures, and temporal changes across a large multidisciplinary literature [18, 19].

Accordingly, this study conducted a multidatabase bibliometric and knowledge-mapping analysis of force sensing and haptic feedback in robotic surgery from 2010 to 2026. We aimed to characterize global scientific production and collaboration, identify influential authors, institutions, countries, sources, and publications, delineate the intellectual and conceptual structure of the field, and examine emerging technological directions. In this study, translational trajectories refer to literature-level transitions from sensing principles and device development to system integration, task-based evaluation, and clinically oriented validation, rather than direct evidence of clinical effectiveness. By clarifying these developmental patterns, this study seeks to identify priorities for technological standardization, interdisciplinary collaboration, and future clinical evaluation.

Materials and methods

Study design and reporting framework

This study combined bibliometric performance analysis with science mapping to characterize the scientific development, collaboration patterns, intellectual foundations, conceptual evolution, and literature-level translational trajectories of force sensing and haptic feedback in robotic surgery [18, 19]. The identification and selection of records were documented using a PRISMA 2020-inspired flow diagram, while reporting of the database searches was informed by PRISMA-S [20, 21]. These frameworks were applied to improve reporting transparency and reproducibility rather than to classify the study as a systematic review or meta-analysis; therefore, no study-level risk-of-bias or certainty-of-evidence assessment was performed.

Data sources and search strategy

The Web of Science Core Collection, Scopus, and PubMed were searched on July 30, 2026, for publications dated from January 1, 2010, to July 30, 2026. The search strategy comprised two concept blocks combined using the Boolean operator AND. The first block included terms related to robotic surgery, robot-assisted procedures, surgical robots, robotic microsurgery, telesurgery, and robot-assisted interventions. The second block included terms related to haptics, force sensing or estimation, tactile sensing, force or tactile feedback, sensory substitution, instrument-tissue interaction, tissue stiffness, and robotic palpation. Searches were conducted in the Topic field of the Web of Science Core Collection, the title-abstract-keyword fields of Scopus, and Medical Subject Headings combined with title and abstract terms in PubMed. Database-specific syntax and wildcard conventions were adapted while maintaining equivalent conceptual coverage. The complete database-specific search strategies are provided in Supplementary Table S1.The search was restricted to English-language original research articles, reviews, and full-length conference papers. A total of 5,105 records were retrieved, including 1,351 from the Web of Science Core Collection, 3,436 from Scopus, and 318 from PubMed.

Eligibility criteria and record selection

Publications were eligible when force sensing, tactile sensing, force measurement or estimation, haptic or tactile feedback, sensory substitution, instrument-tissue interaction, stiffness assessment, or robotic palpation constituted a substantive component of a robotic surgical, robot-assisted interventional, or telesurgical system. Records were excluded if they fell outside the prespecified publication period, were not published in English, or were classified as editorials, letters, corrections, meeting abstracts, book reviews, news items, or other ineligible document types. Studies focusing on industrial, rehabilitation, assistive, or other non-surgical robots, as well as conventional minimally invasive surgery without a robotic component, were also excluded. Additional exclusion criteria included only incidental mention of the target technologies, absence of one or more mandatory metadata fields, formal retraction, or thematic irrelevance identified through examination of the title, abstract, keywords, source information, and publication status. Screening was conducted against predefined eligibility criteria, and exclusion reasons were documented during record assessment. The numbers of records retained or excluded at each stage are presented in Fig. 1.

Data merging, deduplication, and metadata quality control

Records from the three databases were converted into a common bibliographic structure and merged using the bibliometrix package in R [19]. Duplicate identification was performed hierarchically using standardized DOI strings, normalized titles, publication years, and author information. DOI strings were converted to lowercase and stripped of URL prefixes and extraneous spaces, while titles were normalized for capitalization, punctuation, and spacing. Potential duplicates with minor discrepancies were resolved by comparing the available bibliographic fields, and the most complete record was retained.

Removal of 1,465 duplicate records yielded 3,640 unique publications. To establish a consistent dataset for descriptive, citation, keyword, source, and network analyses, each record was required to contain title (TI), authors (AU), publication year (PY), source title (SO), author keywords (DE), abstract (AB), digital object identifier (DI), and total citation count (TC). This completeness criterion was applied for analytical consistency and was not considered an assessment of scientific quality. A citation count of zero was treated as valid; only an absent or non-interpretable citation field was classified as incomplete. The metadata-completeness assessment excluded 758 records, leaving 2,882 records. Subsequent thematic and publication-status screening excluded 10 retracted or irrelevant records, resulting in a final analytical corpus of 2,872 publications.

Data cleaning and bibliometric performance analysis

Bibliographic metadata, including source titles, author names, affiliations, countries, funding agencies, and keywords, were standardized before analysis. Unambiguous spelling, abbreviation, hyphenation, and singular-plural variants were merged, whereas technically distinct concepts such as force sensing, tactile sensing, force feedback, tactile feedback, and haptic feedback were retained separately. Descriptive and performance indicators included annual publication output, source and author productivity, global and local citations, h-index, g-index, m-index, co-authorship, and international collaboration. Database-specific citation counts were not summed. For duplicate records, the citation value associated with the retained bibliographic record was used, whereas local citations were calculated from citation relationships within the final corpus. Citation indicators were interpreted as measures of scholarly visibility rather than scientific quality or clinical value.Full counting was used for source, institution, country, and funding analyses, with fractionalized counts additionally calculated for authorship. Country output was evaluated using corresponding-author countries and all-author affiliations, and corresponding-author publications were classified as single-country or multiple-country contributions. Because the search ended on July 30, 2026, publication data for 2026 were treated as incomplete.

Science mapping and thematic analysis

Co-authorship, keyword co-occurrence, co-citation, and bibliographic-coupling networks were constructed and visualized using VOSviewer [22]. Science mapping was used to examine the social, intellectual, and conceptual structures of the field [18, 23].Node size, link thickness, and spatial proximity represented entity weight, link strength, and relatedness, respectively, while clusters were generated using the clustering procedure implemented in VOSviewer. Co-citation and bibliographic-coupling analyses were used to identify the historical intellectual base and contemporary research groupings, respectively. Reference-based analyses were restricted to records containing usable cited-reference metadata. Keyword networks, thematic maps, trend-topic analyses, thematic-evolution diagrams, three-field plots, and historiographic maps were used to characterize conceptual and temporal development.CiteSpace was used to detect citation bursts in keywords, cited references, and cited authors [24] using Kleinberg's burst-detection framework [25]. Burst strength represented the magnitude of a temporary increase in attention, whereas burst duration represented the corresponding active interval. Bursts extending to 2026 were interpreted cautiously because the final publication year was incomplete.

Growth modeling, exploratory topic analysis, and translational trajectories

Annual publication trends were summarized for 2010-2026, while lifecycle modeling was restricted to the complete years 2010-2025. Cumulative publication output was fitted by nonlinear logistic regression using

$$C(t) = K / \{1 + \exp[-r(t - tm)]\}$$

where K represents the estimated saturation level, r the intrinsic growth rate, and t_m the developmental midpoint. Model fit was assessed using R^2, root-mean-square error, Akaike information criterion, and Bayesian information criterion. All lifecycle estimates were interpreted as exploratory rather than deterministic forecasts.

Latent Dirichlet allocation was applied to publication titles and abstracts as a supplementary analysis of thematic heterogeneity [26] and was implemented using the topicmodels package in R [27]. A 20-topic model was prespecified for exploratory analysis, with a document-topic prior of $\alpha = 0.01$ and a topic-term prior of $\delta = 0.05$. Annual topic prevalence was calculated from mean document-level topic probabilities, and principal component analysis was used to visualize relationships among topics. Model adequacy was examined using perplexity, semantic coherence, and bootstrap stability. Because results may vary according to text preprocessing, model initialization, hyperparameter specification, and the number of topics, the LDA and principal-component findings were interpreted as exploratory rather than definitive classifications.

Translational trajectories were defined as literature-level progression from sensing principles and component development to instrument integration, task-based evaluation, preclinical validation, and

clinically oriented applications. These trajectories were evaluated through convergent temporal, thematic, bibliographic-coupling, and citation-burst patterns and did not imply established clinical effectiveness or improved patient outcomes.

Software, reproducibility, and ethics

Data conversion, cleaning, descriptive bibliometric analysis, thematic mapping, and publication-growth modeling were performed in R version 4.6.1 using bibliometrix version 5.4.1 and its integrated Biblioshiny interface [19]. Network construction and visualization were conducted using VOSviewer version 1.6.21 [22], temporal mapping and citation-burst analyses were performed using CiteSpace version 7.0.1 [24], and topic modeling was implemented using topicmodels version 0.2-17 [27].The complete search strategies, thesaurus files, data-cleaning rules, network settings, and topic-modeling parameters are provided in the supplementary materials. The cleaned bibliographic dataset and analytical scripts are available from the corresponding author upon reasonable request.This study used publicly available bibliographic metadata and did not involve human participants, identifiable patient-level information, biological specimens, or clinical interventions. Institutional review-board approval and informed consent were therefore not required.

Results

3.1 Bibliometric Profile, Growth Dynamics, Citation Impact, and Source Structure

After database merging, deduplication, metadata screening, and eligibility assessment, 2,872 publications from 960 sources were included. The corpus comprised 1,885 original journal articles (65.63%), 684 conference papers (23.82%), and 303 reviews, systematic reviews, or meta-analyses (10.55%). The publications had a mean age of 5.73 years and received an average of 16.48 citations, with 139,770 cited references, 11,364 Keywords Plus, and 7,098 author keywords. A total of 7,779 authors contributed to the field, with 5.22 co-authors per document on average; only 60 publications were single-authored, and international co-authorship accounted for 11.98% of the corpus.Annual output increased from 56 publications in 2010 to 393 in 2025. More than half of the corpus was published during 2020–2025 (n = 1,564, 54.46%), with particularly rapid growth in 2024 and 2025. The 207 records indexed in 2026 were treated as incomplete-year data rather than evidence of declining activity. Citation impact varied by publication year and available citation window. The 2016 cohort achieved the highest mean total citation count (30.78 citations per article), whereas the 2021 cohort showed the highest mean annual citation rate (3.81 citations per article per year). Lower citation counts among the most recent publications were interpreted primarily as citation-delay effects.Logistic lifecycle modeling estimated a saturation level of 7,139 publications, with approximately 40.2% of the projected cumulative output reached by the end of the observation period. The field was therefore positioned within a rapid-growth stage, with the midpoint estimated around 2027.8. Model fit was acceptable (R^2 = 0.797, RMSE = 39.74, AIC = 131.2, and BIC = 133.7), although the observed 2025 output exceeded the model-derived

maximum annual increment, indicating that the recent acceleration was not fully captured by the smoothed logistic trajectory. Accordingly, lifecycle estimates were interpreted as exploratory.IEEE Robotics and Automation Letters was the most productive source (n = 135), followed by the International Journal of Medical Robotics and Computer Assisted Surgery (n = 106), Journal of Robotic Surgery (n = 78), Sensors (n = 70), and International Journal of Computer Assisted Radiology and Surgery (n = 64). These five sources contributed 15.77% of the corpus. Bradford's Law identified 19 core sources that published 966 documents, indicating that approximately one-third of the literature was concentrated in only 1.98% of all sources. Surgical Endoscopy was the most locally cited source (1,835 citations), while IEEE Robotics and Automation Letters showed the strongest overall source-level performance, with the highest h-index (32), g-index (50), m-index (2.909), and total citation count (3,172)(Fig. 2).

3.2 Authorship, Institutional and Geographic Distribution, and Funding Support

Authorship was highly dispersed, with 5,578 of 7,779 authors (71.70%) contributing to only one publication and 90.86% publishing no more than three. Only 167 authors (2.15%) contributed at least ten publications, indicating a large peripheral population of occasional contributors. Guo S was the most productive and influential author-name record, with 85 publications, a fractionalized count of 18.98, an h-index of 25, and 2,140 total citations. Wang Y ranked second in productivity (n = 68; h = 18), while Choi H and Kim U received the highest local citation counts. Differences between full and fractional counting indicated that ranking was partly influenced by team size and co-authorship structure.Johns Hopkins University was the most productive institution (n = 136), followed by Shanghai Jiao Tong University (n = 132), Imperial College London (n = 122), Tianjin University (n = 101), and King's College London and the National University of Singapore (n = 93 each). China led affiliation-based output (n = 1,304) and corresponding-author publications (n = 660), followed by the United States (n = 926 and 390, respectively). China's rapid expansion after 2020 shifted the geographic center of publication growth, whereas the United States retained the highest cumulative citation impact (8,655 citations), followed closely by China (8,210). The United Kingdom and Singapore showed comparatively high mean citation rates, although country-level averages for lower-output nations were interpreted cautiously because of small sample sizes. International collaboration remained limited overall, with most corresponding-author publications classified as single-country studies; among countries with at least 40 publications, Singapore showed the highest multiple-country publication proportion (31.3%).Funding was dominated by national science agencies and government research programs. The National Natural Science Foundation of China was the most frequently acknowledged funder, followed by the Fundamental Research Funds for the Central Universities, the US National Science Foundation, the National Key Research and Development Program of China, and the National Research Foundation of Korea. Because individual publications could acknowledge multiple agencies, funding counts were not mutually exclusive(Fig. 3).

3.3 Document-Level Citation Performance, Intellectual Foundations, and Author Citation Bursts

Document-level analysis showed that global citation visibility and within-corpus influence reflected different dimensions of scholarly impact. The 2022 article by Heng W in Advanced Materials had the highest global citation performance, with 558 citations, 111.60 citations per citable year, and the highest normalized global citation score. Other highly cited contributions included publications by Jacofsky D, Abbott J, Bowyer S, Xu R, and Makhataeva Z. After adjustment for publication year, several recent studies also showed strong citation performance, indicating that normalized and annualized indicators were useful for comparing publications with unequal citation windows.Local citation analysis identified the works most central to the development of the analyzed field. Kim U's 2015 article in IEEE Transactions on Robotics ranked first with 65 local citations, followed by related publications by Kim U and Pacchierotti C. The principal intellectual foundations extended beyond the final corpus: Okamura AM's 2009 review was the most frequently cited reference, followed by the studies of Van der Meijden OAJ and Puangmali P. The recurrence of several publications in both the local-document and cited-reference rankings indicated that these studies functioned as important bridges between foundational sensing research and subsequent developments in robot-assisted surgery.Author citation-burst analysis identified periods of rapidly increasing scholarly attention. Guo S exhibited the strongest burst from 2016 to 2023, while Wang Y, Liu Y, Zhang J, Li Y, and Zhang Y showed prominent bursts extending to 2026. These ongoing bursts suggest sustained recent interest in the research programs associated with these author-name records, although interpretation should account for possible author-name ambiguity((Fig. 4).

3.4 Conceptual Structure, Thematic Evolution, and Collaboration Networks

The conceptual structure of the field was centred on robotic surgery, minimally invasive intervention, and sensory-feedback technologies. "Robotic surgery" was the most frequent term (n = 1,003), followed by "surgery" (n = 607), "robotics" (n = 560), and "surgical equipment" (n = 491), while force feedback, haptic feedback, tactile feedback, and haptic interfaces constituted the principal technical domain. Cumulative term trajectories showed sustained growth throughout 2010–2026, with particularly rapid increases after 2020 in medical robotics, robot-assisted surgery, and feedback-related research. Trend-topic analysis indicated a chronological transition from teleoperation, master–slave architectures, and bilateral control toward minimally invasive surgery, force sensing, human–robot interaction, intelligent robots, artificial intelligence, and sensor arrays. Consistently, "robot-assisted surgery" showed the strongest keyword burst (strength = 61.45; 2021–2026), while ongoing bursts for force, force sensing, robot sensing systems, intelligent robots, and artificial intelligence identified sensing integration and intelligent robotic assistance as current research frontiers. Bibliographic coupling analysis revealed two major literature clusters sharing a common foundation in minimally invasive surgery and haptic feedback: a larger force-feedback-oriented cluster comprising 180 records and a smaller surgical-robotics-oriented cluster comprising 70 records, the latter showing a higher reported impact score. The keyword co-occurrence network formed a single interconnected structure in which surgery, robotic surgery, and robotics occupied the principal bridging and PageRank positions, while minimally invasive surgery and feedback connected the clinical context with force control, teleoperation, haptic interfaces, and tissue interaction. In the co-citation network, author-level comparisons identified Taylor R.H.,

Okamura A.M., Dankelman J., Menciassi A., and Kazanzides P. as major bridging nodes, delineating an intellectual base spanning surgical robotics, tactile and force sensing, and computer-assisted intervention; complete cited-reference nodes were not directly compared with author nodes because of their different representation. The historiographic map further traced a developmental pathway from optical-fiber tactile sensors and direct force measurement to multiaxis sensing, sensory substitution, robotic palpation, sensorized instruments, learning-based force estimation, and surgical autonomy. Finally, the author collaboration network comprised six communities: Ren H showed the strongest intercommunity bridging role, Guo S had the highest PageRank prominence, and Wang Y combined high betweenness, closeness, and PageRank values(Fig. 5).

3.5 Exploratory Topic Modeling and Latent Thematic Heterogeneity

Exploratory latent Dirichlet allocation identified a broadly distributed 20-topic structure, with topic prevalence ranging from 0.0438 to 0.0576 and no single topic dominating the corpus. However, the model showed limited semantic coherence and bootstrap stability, indicating that the derived topics were not sufficiently robust for definitive labeling. The LDA findings were therefore used only as supplementary evidence of thematic heterogeneity, while the principal knowledge domains and emerging research directions were interpreted primarily from keyword co-occurrence, trend-topic, citation-burst, and bibliographic-coupling analyses (Fig. 6).

Discussion

Principal findings and development of the field

This study demonstrates that force sensing and haptic feedback in robotic surgery have evolved into a rapidly expanding and multidisciplinary field. More than half of the included publications appeared during 2020–2025, with pronounced growth in 2024 and 2025. Logistic modeling likewise positioned the field within a rapid-growth phase; however, the observed publication output in 2025 exceeded the model-derived annual maximum. The estimated saturation level and developmental midpoint should therefore be interpreted as exploratory descriptions of publication dynamics rather than reliable long-term forecasts.The distribution of publications across robotics, biomedical engineering, sensing, computer-assisted intervention, and clinical surgery reflects the translational structure of the field. Engineering sources primarily supported the development of sensors, control systems, and instrument prototypes, whereas clinically oriented journals increasingly addressed training, tissue interaction, usability, and early clinical evaluation. Differences between global and local citation rankings further indicated that publications with broad interdisciplinary visibility were not necessarily those most central to the subsequent development of force-aware robotic surgery.

China showed the fastest recent growth and led publication volume, whereas the United States retained the highest cumulative citation impact. These measures reflect research productivity and scholarly visibility rather than technological or clinical superiority. International co-authorship accounted for only

11.98% of the corpus, indicating that cross-national and multicenter collaboration remains comparatively limited.

From engineering feasibility to early clinical evaluation

The conceptual and historiographic findings indicate a transition from master–slave teleoperation and bilateral control toward miniaturized sensing, sensorized instruments, robotic palpation, learning-based force estimation, and force-informed assistance. The central research question is consequently shifting from whether force information can be measured and transmitted to whether it can improve operator behavior, training, tissue handling, and surgical safety.

Haptic training studies suggest that wrist-squeezing force feedback can reduce applied force and improve technical accuracy without compromising task speed [28]. In a large observational analysis of robotic thoracic procedures, higher feedback settings were associated with lower median and peak instrument-tip forces and less time above a predefined high-force threshold [29]. These measurements represented translational forces at the instrument tip rather than grasping forces and were not directly linked to patient outcomes.A colorectal pilot study similarly reported reduced instrument forces but found no clear improvement in postoperative bowel recovery or hospital stay [30]. A subsequent small study of robotic rectal surgery suggested that the effect of feedback varied by operative task, with reductions in sustained force during static retraction and peak force during dynamic manipulation [31]. However, the single-surgeon design, limited sample size, and chronological comparison of feedback settings restrict causal interpretation.Early experience with the Saroa platform also showed lower grasping forces when tactile feedback was activated, although the small number of procedures and possible platform-learning effects limit generalizability [32]. In vivo experiments further demonstrated that susceptibility to force-related injury differed among organs, with lung and liver tissues showing greater damage as grasping force increased [33]. These findings support the development of tissue-, instrument-, and task-specific operating ranges rather than a universal force threshold.Collectively, the available evidence indicates that force feedback can modify instrument–tissue interaction, but reductions in measured force should be regarded as mechanistic or surrogate outcomes rather than proof of clinical benefit. Prospective studies are required to determine whether these changes reduce bleeding, tissue injury, anastomotic failure, postoperative morbidity, or delayed functional recovery. Comparisons across platforms should also account for differences in sensing location and force components, particularly the distinction between grasping forces and translational instrument-tip forces.

Convergence of direct sensing, sensorless estimation, and intelligent assistance

The thematic evolution identified complementary pathways involving direct force measurement, sensorless estimation, and multimodal integration with visual, kinematic, and control data. Sensorless approaches may provide force information without modifying the instrument tip, thereby reducing challenges related to miniaturization and sterilization. A recent telesurgical study showed that sensorless haptic feedback improved target detection and reduced unintended interaction forces,

although it also increased free-motion resistance and operator effort [34]. Such methods remain sensitive to changes in robot dynamics, cable friction, trocar position, instrument wear, and tissue properties.Direct sensing offers physically interpretable measurements close to the instrument–tissue interface but faces constraints related to wiring, packaging, durability, sterilization, and preservation of instrument function. Recent developments include a three-axis MEMS tactile sensor integrated into gastrointestinal endoscopic forceps [35], a six-axis force-sensing robotic forceps developed for cochlear implantation [36], and compliant microfluidic sensors incorporated into laparoscopic graspers [37]. These technologies demonstrate progress toward compact and application-specific force measurement, but they should not yet be interpreted as evidence of routine clinical deployment.The increasing prominence of artificial intelligence and intelligent-robot terminology therefore reflects technological convergence rather than established clinical autonomy. Before force data can support automated safety constraints or shared control, systems must demonstrate generalizability, uncertainty estimation, failure detection, control stability, and immediate surgeon override.

Translational and standardization priorities

The clinical value of force feedback depends on both measurement performance and human–machine interaction. Feedback that is delayed, noisy, excessively strong, or poorly matched to the operative task may increase workload or impair precision. Optimal settings are therefore unlikely to be identical for retraction, dissection, palpation, suturing, and needle manipulation. Interviews with early users of the da Vinci 5 system suggested perceived value for training, ergonomics, and tissue handling, but surgeons remained uncertain about patient-level clinical benefits [38].Future studies should distinguish clearly among tactile, kinesthetic, visual, auditory, and multimodal feedback. Technical reporting should include sensing location, measured force components, range, resolution, accuracy, bandwidth, latency, calibration, drift, cross-axis interference, sterilization compatibility, and feedback gain. Clinical evaluations should combine mean, peak, and cumulative force metrics with operative errors, tissue injury, surgeon workload, learning effects, complications, recovery, and patient-reported outcomes.Several early studies used manufacturer-derived datasets or included investigators with industry affiliations. These relationships do not invalidate the reported findings, but they reinforce the need for independent replication, transparent data governance, and externally validated analytical methods. The IDEAL Robotics framework provides an appropriate pathway for staged evaluation, progressing from technical development and early clinical exploration to comparative assessment and long-term surveillance [39]. Multicenter studies will be particularly important for determining whether sensing and feedback systems generalize across robotic platforms, institutions, procedures, and surgeon-experience levels.

Strengths and limitations

This study integrated three major bibliographic databases and included full-length conference papers, which represent an important channel for technical innovation in robotics. The combined use of performance indicators, collaboration networks, co-citation, bibliographic coupling, keyword evolution, citation bursts, historiography, lifecycle modeling, and exploratory topic analysis enabled the field to be

examined from complementary social, intellectual, conceptual, and temporal perspectives. Distinguishing global from local citations also helped separate broad scholarly visibility from influence within the analyzed corpus.Several limitations should be acknowledged. Restriction to English-language records indexed in the Web of Science Core Collection, Scopus, and PubMed may have excluded relevant regional publications, patents, standards, preprints, and non-indexed conference proceedings. The requirement for complete metadata led to the exclusion of 758 records and may have disproportionately removed older or incompletely indexed studies.Citation indicators were influenced by publication age, database coverage, and disciplinary citation practices. Author and institutional analyses remained susceptible to name ambiguity and affiliation variants, while keyword analyses depended on author terminology and database indexing. The poor stability of the LDA model prevented definitive topic classification, and the logistic model could not fully represent abrupt technological changes, commercial platform releases, or changes in database coverage.

Finally, bibliometric analysis evaluates the structure and visibility of the literature rather than the technical performance or clinical effectiveness of individual technologies. The discussion of recent translational studies was contextual rather than a systematic evidence synthesis, and these studies were not subjected to formal risk-of-bias or certainty-of-evidence assessment. Consequently, neither citation prominence nor identification as a research frontier should be interpreted as evidence of clinical readiness.

Conclusions

Force sensing and haptic feedback in robotic surgery are progressing from isolated sensor development and bilateral teleoperation toward integrated instruments, sensorless estimation, force-aware training, and early clinical evaluation. Current evidence suggests that force feedback can reduce selected measures of instrument–tissue loading and modify operative behavior, but convincing evidence of improved patient outcomes remains insufficient.Future research should prioritize standardized terminology and reporting, task- and tissue-specific force thresholds, independent external validation, multicenter comparative studies, human-factor assessment, and long-term clinical monitoring. The clinical value of force sensing will ultimately depend on whether technically accurate measurements can be translated into reproducible, interpretable, and patient-relevant improvements in robotic surgery.

Declarations

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Not applicable

Author Contributions

All authors contributed to the conception and design of the study. Conceptualization: Xue Zhang, Zhichao Fu, and Feng Xin. Methodology: Xue Zhang and Zhichao Fu. Data curation and literature

screening: Xue Zhang and Zhichao Fu. Formal analysis and visualization: Xue Zhang and Zhichao Fu. Writing—original draft preparation: Xue Zhang. Writing—review and editing: Zhichao Fu and Feng Xin. Supervision: Feng Xin. All authors commented on previous versions of the manuscript, read and approved the final manuscript, and agreed to be accountable for the content of the work.

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Data availability

No datasets were generated or analysed during the current study.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval and consent to participate

Not applicable. This study analyzed publicly available bibliographic metadata and did not involve human participants, identifiable personal data, biological specimens, or clinical interventions.

Consent for publication

Not applicable.

References

1. Lanfranco AR, Castellanos AE, Desai JP, Meyers WC (2004) Robotic surgery: a current perspective. Ann Surg 239:14–21. https://doi.org/10.1097/01.SLA.0000103020.19595.7D
2. Taylor RH, Menciassi A, Fichtinger G, Fiorini P, Dario P (2016) Medical robotics and computer-integrated surgery. In: Siciliano B, Khatib O (eds) Springer handbook of robotics, 2nd edn. Springer, Cham, pp 1657–1684. https://doi.org/10.1007/978-3-319-32552-1_63
3. Okamura AM (2009) Haptic feedback in robot-assisted minimally invasive surgery. Curr Opin Urol 19:102–107. https://doi.org/10.1097/MOU.0b013e32831a478c
4. Puangmali P, Althoefer K, Seneviratne LD, Murphy D, Dasgupta P (2008) State-of-the-art in force and tactile sensing for minimally invasive surgery. IEEE Sens J 8:371–381. https://doi.org/10.1109/JSEN.2008.917481
5. Bandari N, Dargahi J, Packirisamy M (2020) Tactile sensors for minimally invasive surgery: a review of the state-of-the-art, applications, and perspectives. IEEE Access 8:7682–7708. https://doi.org/10.1109/ACCESS.2019.2962636

6. Kim U, Lee DH, Yoon WJ, Hannaford B, Choi HR (2015) Force sensor integrated surgical forceps for minimally invasive robotic surgery. IEEE Trans Robot 31:1214–1224. https://doi.org/10.1109/TRO.2015.2473515
7. Pacchierotti C, Prattichizzo D, Kuchenbecker KJ (2016) Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery. IEEE Trans Biomed Eng 63:278–287. https://doi.org/10.1109/TBME.2015.2455932
8. Meli L, Pacchierotti C, Prattichizzo D (2014) Sensory subtraction in robot-assisted surgery: fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction. IEEE Trans Biomed Eng 61:1318–1327. https://doi.org/10.1109/TBME.2014.2303052
9. Abiri A, Juo YY, Tao A et al (2019) Artificial palpation in robotic surgery using haptic feedback. Surg Endosc 33:1252–1259. https://doi.org/10.1007/s00464-018-6405-8
10. Bergholz M, Ferle M, Weber BM (2023) The benefits of haptic feedback in robot assisted surgery and their moderators: a meta-analysis. Sci Rep 13:19215. https://doi.org/10.1038/s41598-023-46641-8
11. Wang W, Wang J, Luo Y, Wang X, Song H (2023) A survey on force sensing techniques in robot-assisted minimally invasive surgery. IEEE Trans Haptics 16:702–718. https://doi.org/10.1109/TOH.2023.3329172
12. Hao Y, Zhang H, Zhang Z, Hu C, Shi C (2024) Development of force sensing techniques for robot-assisted laparoscopic surgery: a review. IEEE Trans Med Robot Bionics 6:868–887. https://doi.org/10.1109/TMRB.2024.3407238
13. Attanasio A, Scaglioni B, De Momi E, Fiorini P, Valdastri P (2021) Autonomy in surgical robotics. Annu Rev Control Robot Auton Syst 4:651–679. https://doi.org/10.1146/annurev-control-062420-090543
14. Colan J, Davila A, Hasegawa Y (2024) Tactile feedback in robot-assisted minimally invasive surgery: a systematic review. Int J Med Robot 20:e70019. https://doi.org/10.1002/rcs.70019
15. Friebe MH (2026) Haptic and palpation sensing for robotic surgery: engineering perspectives on design and integration. Sens (Basel) 26:1126. https://doi.org/10.3390/s26041126
16. Awad MM, Raynor MC, Padmanabhan-Kabana M, Schumacher LY, Blatnik JA (2024) Evaluation of forces applied to tissues during robotic-assisted surgical tasks using a novel force feedback technology. Surg Endosc 38:6193–6202. https://doi.org/10.1007/s00464-024-11131-z
17. Servais EL, Rashidi L, Porwal P, Garibaldi M, Hung AJ (2025) Novel force feedback technology improves suturing in robotic-assisted surgery: a pre-clinical study. Surg Endosc 39:1217–1226. https://doi.org/10.1007/s00464-024-11472-9
18. Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM (2021) How to conduct a bibliometric analysis: an overview and guidelines. J Bus Res 133:285–296. https://doi.org/10.1016/j.jbusres.2021.04.070
19. Aria M, Cuccurullo C (2017) bibliometrix: an R-tool for comprehensive science mapping analysis. J Informetr 11:959–975. https://doi.org/10.1016/j.joi.2017.08.007
20. Page MJ, McKenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71. https://doi.org/10.1136/bmj.n71

21. Rethlefsen ML, Kirtley S, Waffenschmidt S et al (2021) PRISMA-S: an extension to the PRISMA statement for reporting literature searches in systematic reviews. Syst Rev 10:39. https://doi.org/10.1186/s13643-020-01542-z
22. van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84:523–538. https://doi.org/10.1007/s11192-009-0146-3
23. Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F (2011) Science mapping software tools: review, analysis, and cooperative study among tools. J Am Soc Inf Sci Technol 62:1382–1402. https://doi.org/10.1002/asi.21525
24. Chen C (2006) CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. J Am Soc Inf Sci Technol 57:359–377. https://doi.org/10.1002/asi.20317
25. Kleinberg J (2003) Bursty and hierarchical structure in streams. Data Min Knowl Discov 7:373–397. https://doi.org/10.1023/A:1024940629314
26. Blei DM, Ng AY, Jordan MI (2003) Latent Dirichlet allocation. J Mach Learn Res 3:993–1022
27. Grün B, Hornik K (2011) topicmodels: an R package for fitting topic models. J Stat Softw 40(13):1–30. https://doi.org/10.18637/jss.v040.i13
28. Machaca S, Cao E, Chi A, Adrales GL, Kuchenbecker KJ, Brown JD (2022) Wrist-squeezing force feedback improves accuracy and speed in robotic surgery training. In: 2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob), Seoul, Republic of Korea. IEEE, pp 1–8. https://doi.org/10.1109/BioRob52689.2022.9925306
29. Kneuertz PJ, Mostellar R, Merritt RE et al (2025) Force in robotic thoracic surgery—a one year analysis of DaVinci 5 force feedback. J Robot Surg 19:632. https://doi.org/10.1007/s11701-025-02781-9
30. Chang GC, Sidhu U, Lai D, Vargas G, Shah S, Rashidi L (2025) A pilot study on the impact of da Vinci 5's force feedback on clinical outcomes: does it lead to less tissue trauma in colorectal surgery? Am J Surg 248:116518. https://doi.org/10.1016/j.amjsurg.2025.116518
31. Nishi Y, Hirano Y, Ishiyama Y (2026) Quantitative analysis of da Vinci 5 force feedback technology in robotic rectal surgery: a preliminary pilot study. Surg Endosc 40:6350–6354. https://doi.org/10.1007/s00464-026-12842-1
32. Iwatani K, Urabe F, Saito S et al (2024) Initial experience of a novel surgical assist robot Saroa featuring tactile feedback and a roll-clutch system in radical prostatectomy. Sci Rep 14:31727. https://doi.org/10.1038/s41598-024-82531-3
33. Nakashima H, Ueda Y, Miyanari Y et al (2025) In vivo evaluation of tissue damage from varying grasping forces using the Saroa surgical system. Sci Rep 15:10043. https://doi.org/10.1038/s41598-025-95310-5
34. Yilmaz N, Burkhart B, Deguet A, Kazanzides P, Tumerdem U (2024) Enhancing robotic telesurgery with sensorless haptic feedback. Int J Comput Assist Radiol Surg 19:1147–1155. https://doi.org/10.1007/s11548-024-03117-y

35. Hou C, Gao H, Yang X et al (2024) A piezoresistive-based 3-axial MEMS tactile sensor and integrated surgical forceps for gastrointestinal endoscopic minimally invasive surgery. Microsyst Nanoeng 10:141. https://doi.org/10.1038/s41378-024-00774-6
36. Gao H, Liu H, Jia H et al (2025) Multi-axis robotic forceps with decoupled pneumatic actuation and force sensing for cochlear implantation. Nat Commun 16:1648. https://doi.org/10.1038/s41467-025-56958-9
37. Othman W, Qasaimeh MA (2026) Multichannel soft microfluidic force sensors: design, characterization, and application in laparoscopy. Microsyst Nanoeng 12:138. https://doi.org/10.1038/s41378-026-01263-8
38. Erstad DJ, Fazal ZA, Draulis K, Zheng F, Jackson G, Chai CY (2026) Qualitative perspectives of early surgeon users on the value of the daVinci 5 surgical system. J Robot Surg 20:520. https://doi.org/10.1007/s11701-026-03366-w
39. Marcus HJ, Ramirez PT, Khan DZ et al (2024) The IDEAL framework for surgical robotics: development, comparative evaluation and long-term monitoring. Nat Med 30:61–75. https://doi.org/10.1038/s41591-023-02732-7

Figures

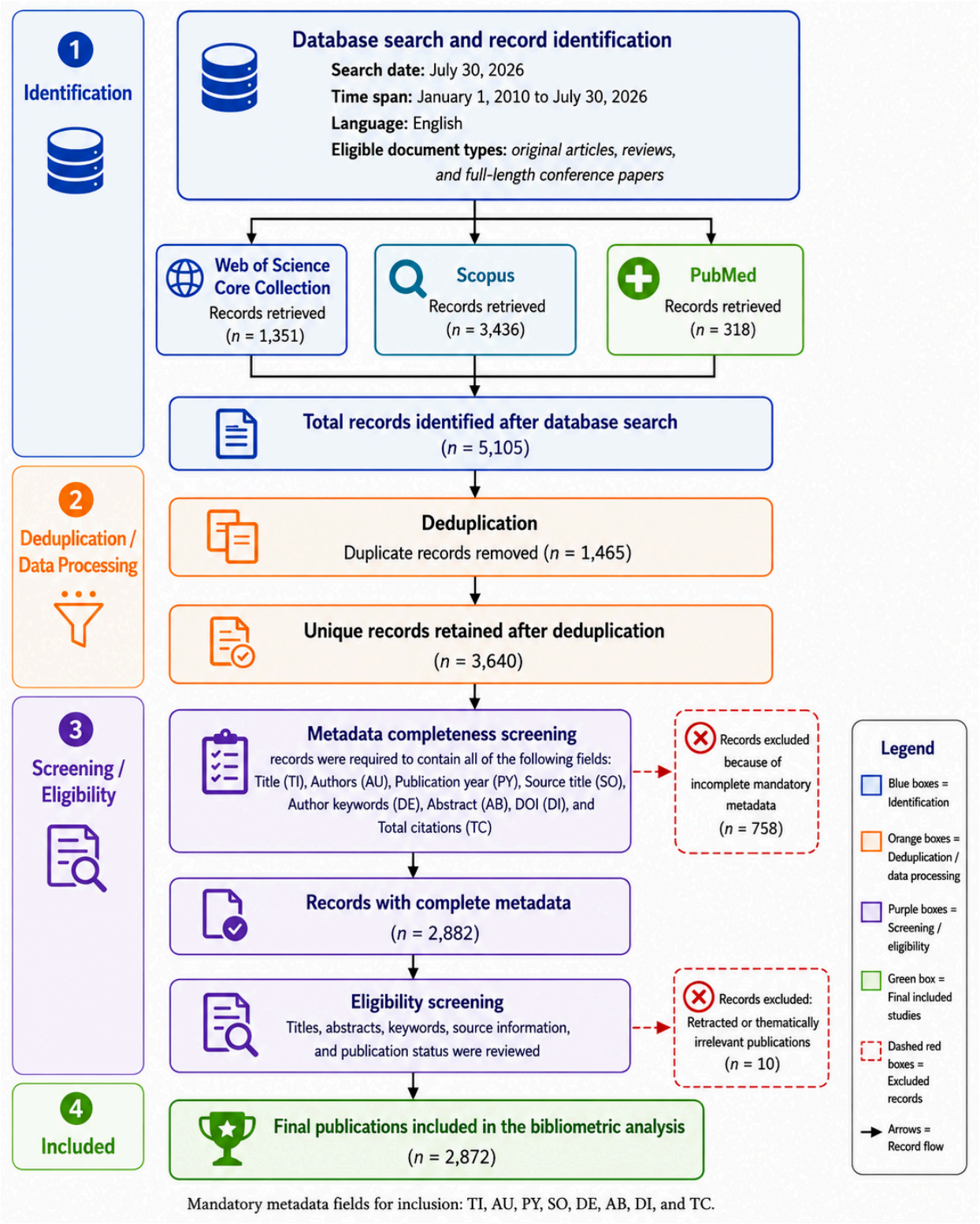


Figure 1

PRISMA flow diagram of the literature identification, screening, and inclusion process for the bibliometric analysis.

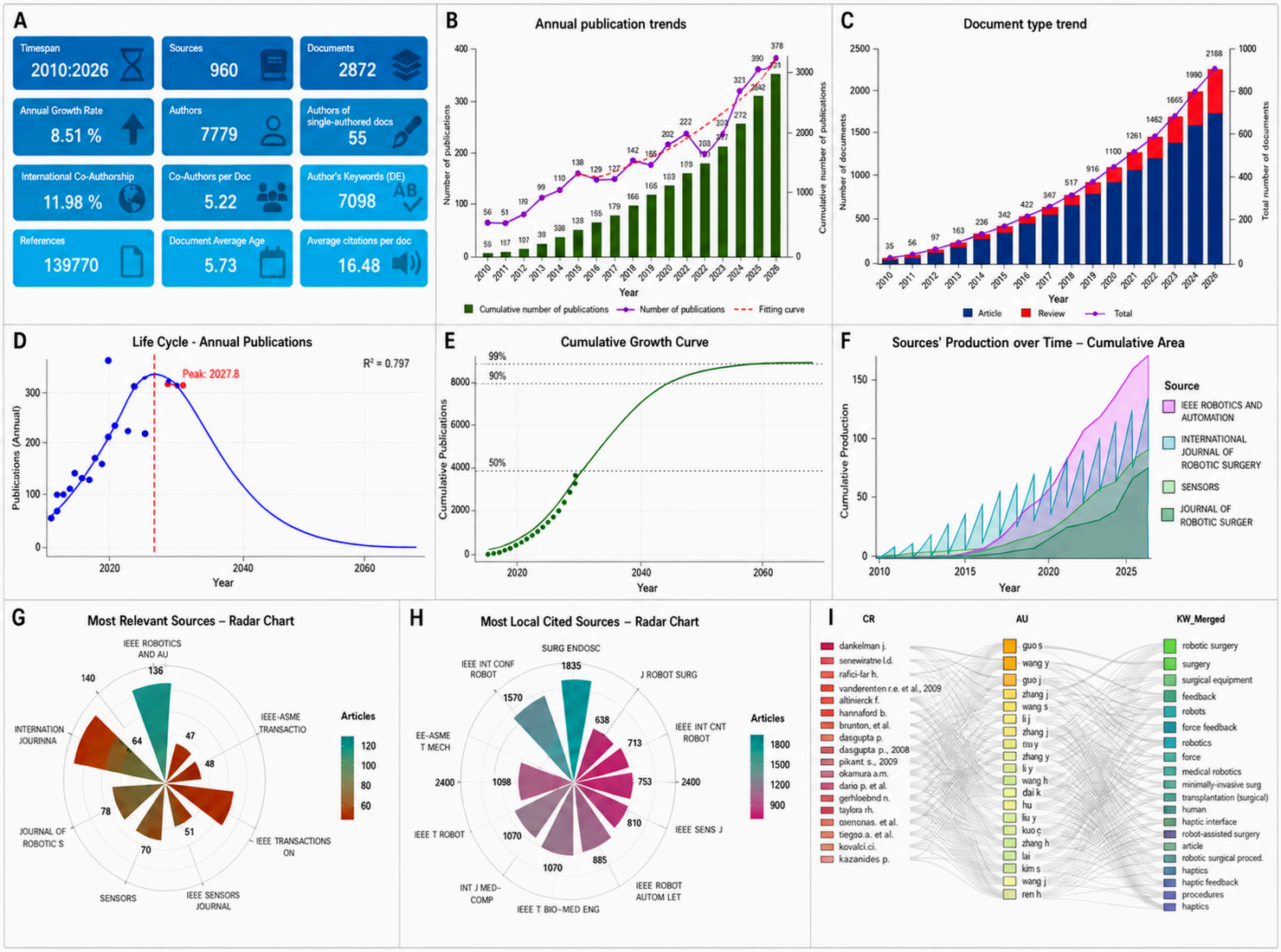


Figure 2

Bibliometric profile, publication dynamics, source structure, and knowledge linkages of force sensing and haptic feedback in robotic surgery, 2010–2026. (A) Main characteristics of the corpus. (B) Annual and cumulative publication trends with the fitted growth curve. (C) Temporal distribution of articles and reviews. (D) Modeled lifecycle of annual scientific production, including the estimated peak. (E) Fitted cumulative growth trajectory and the 50%, 90%, and 99% development thresholds. (F) Cumulative publication trajectories of the leading sources. (G) Most productive sources by number of included publications. (H) Most locally cited sources within the analyzed corpus. (I) Three-field plot linking cited references (CR), authors (AU), and merged keywords (KW_Merged).



Figure 3

Author, institutional, national, and funding profiles of force-sensing and haptic-feedback research in robotic surgery. (A) Most productive authors ranked by publication count. (B) Authors receiving the highest numbers of local citations within the analyzed corpus. (C) Local scholarly impact of leading authors based on the h-index. (D) Most productive affiliations ranked by the number of included publications. (E) Cumulative publication trajectories of the leading affiliations from 2010 to 2026. (F) Distribution of publications according to the corresponding author's country. (G) Annual publication output of the five most productive countries. (H) Temporal distribution of scientific production among the ten leading countries, with bubble size proportional to annual publication volume. (I) Comparative national performance based on publication count, total citations scaled by 0.01, citations per article, and h-index. (J) Major funding sources ranked by the number of supported publications.

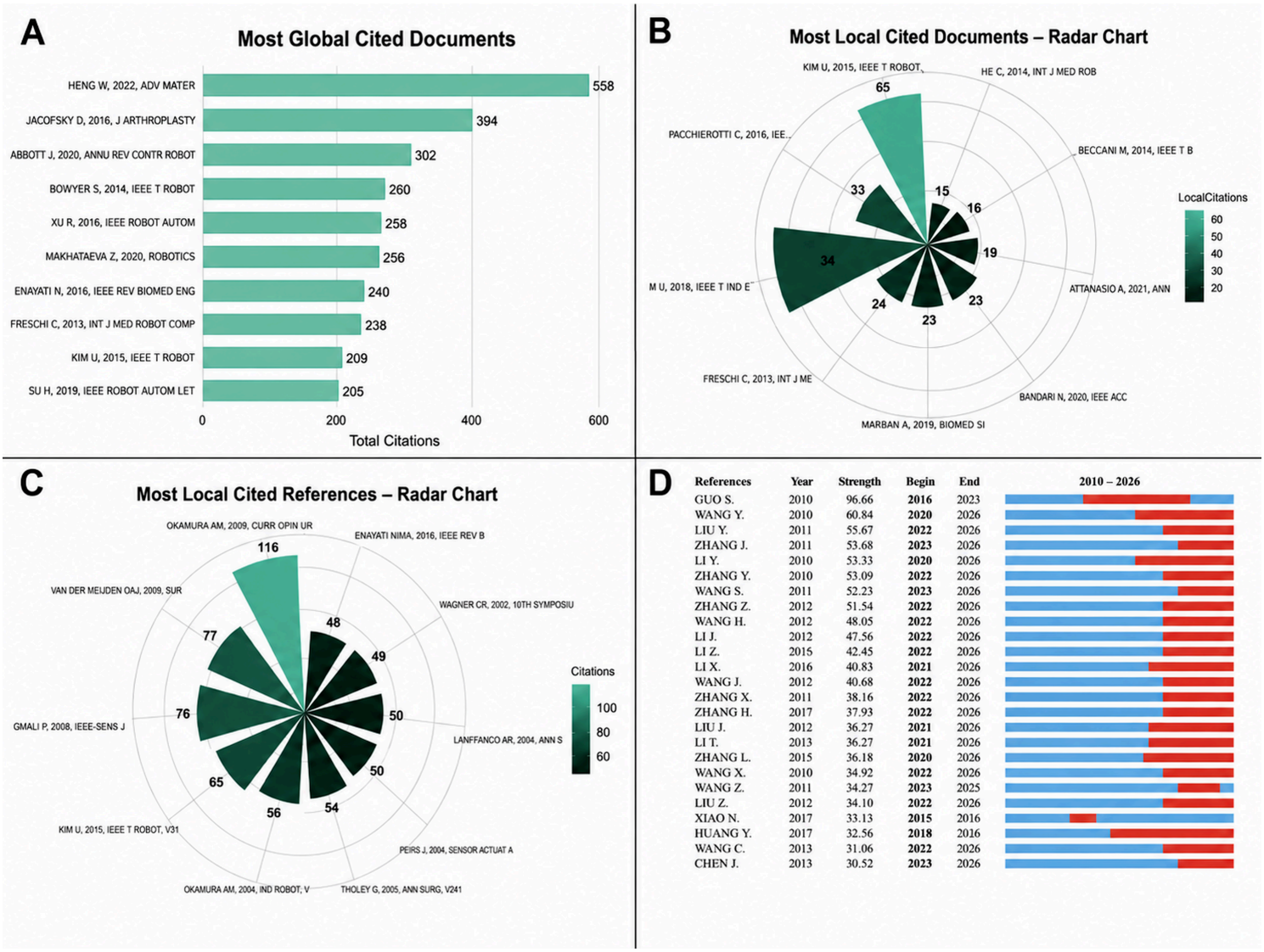


Figure 4

Document-level citation performance, intellectual foundations, and author citation bursts in force-sensing and haptic-feedback research. (A) Ten globally most cited documents ranked by total citations. (B) Most locally cited documents, where local citations denote citations received from publications within the analyzed corpus. (C) Most frequently cited references within the corpus, representing the principal intellectual foundations of the field. (D) Top 25 author-name records with the strongest citation bursts from 2010 to 2026

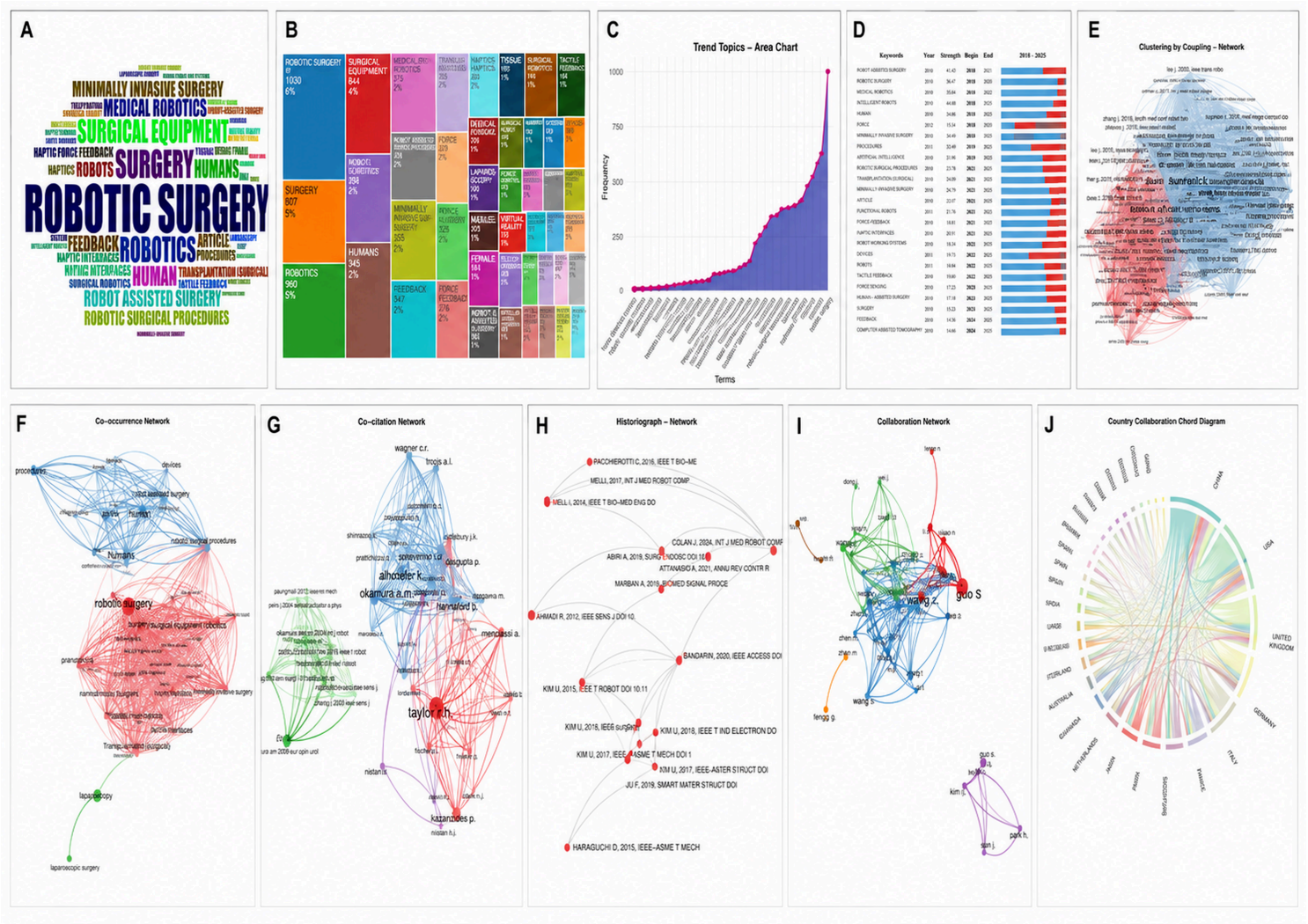


Figure 5

Conceptual structure, thematic evolution, intellectual linkages, and collaboration patterns in force-sensing and haptic-feedback research in robotic surgery. (A) Word cloud of high-frequency terms, with font size proportional to term frequency. (B) Treemap of the most frequent terms, with rectangle area representing relative occurrence. (C) Frequency distribution of trend topics across the corpus. (D) Keywords with the strongest citation bursts from 2010 to 2026; red segments indicate periods of intensified attention. (E) Bibliographic-coupling network of the included publications, illustrating contemporary thematic groupings based on shared references. (F) Keyword co-occurrence network showing the conceptual relationships among major research terms. (G) Co-citation network depicting the principal intellectual communities and frequently co-cited knowledge sources. (H) Historiographic network tracing the citation-linked development of representative publications. (I) Author collaboration network, in which links represent co-authorship relationships and colors distinguish collaboration communities. (J) Country collaboration chord diagram showing international research connections; wider sectors and ribbons indicate greater publication participation and stronger collaborative links, respectively.

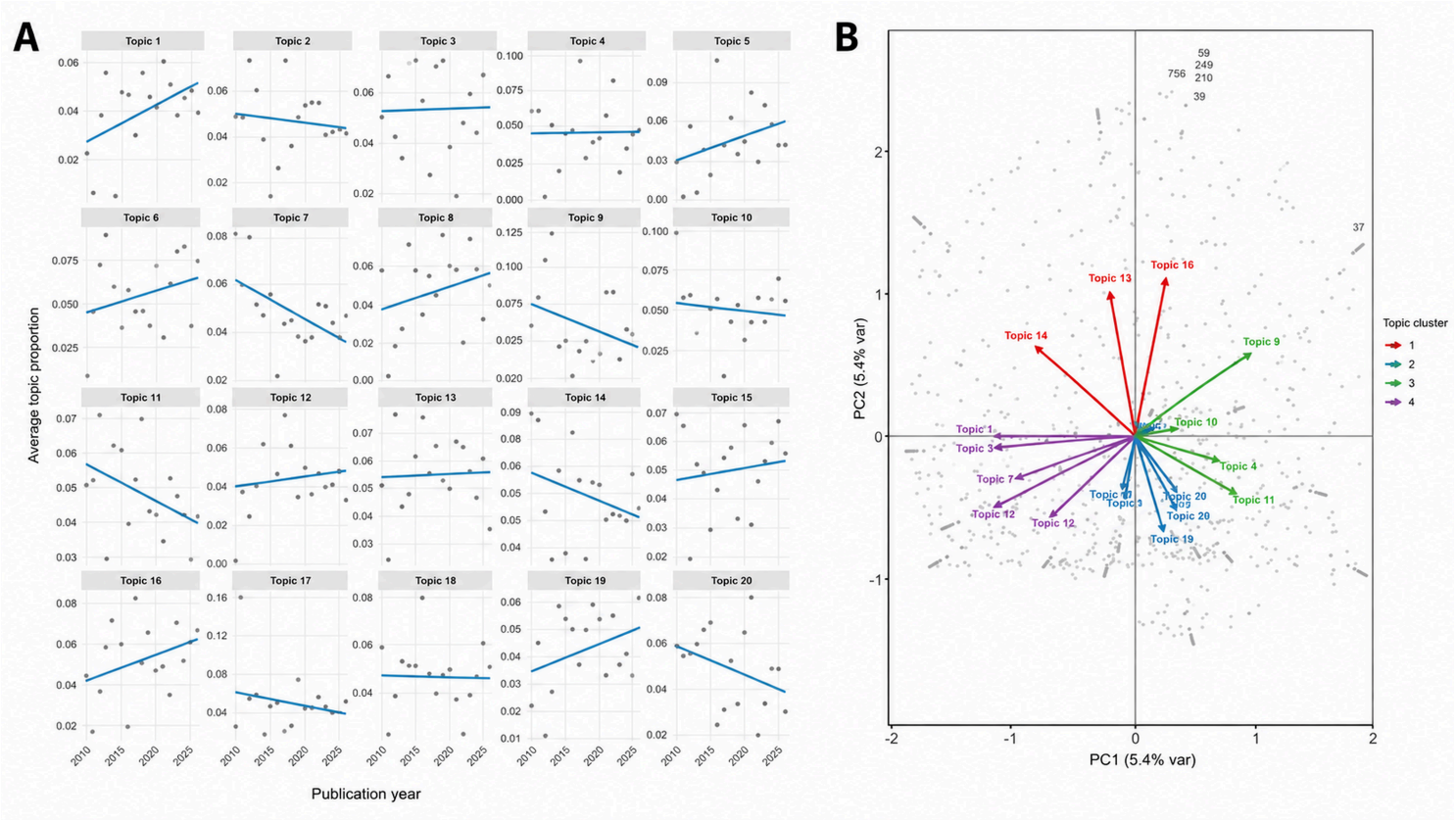


Figure 6

Exploratory temporal and multivariate structure of the 20-topic latent Dirichlet allocation model. (A) Temporal variation in the mean annual prevalence of Topics 1–20 from 2010 to 2026. Gray points represent yearly average topic proportions, and blue lines indicate fitted linear trends over publication year. (B) Principal component analysis of document-level topic distributions.

Supplementary Files

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- SupplementaryTableS1.docx