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Article

From robotic arms to AI-assisted: the evolution and interdisciplinary integration of robotic surgery technology based on bibliometron

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ABSTRACT

With medical technology innovation, robotic surgery has evolved from mechanical arm operations to AI-assisted decision-making, promoting deep integration of surgical medicine with engineering and computer science. This study employed CiteSpace software to conduct a bibliometric analysis of robotic surgical technology evolution literature from the Web of Science (2014-2024). Analysis of 520 publications revealed explosive growth from <5 annual papers (2014-2017) to 177 papers in 2024, representing a 3,540% increase. The dataset encompassed 2,968 authors, 1,957 institutions, and 266 journals across 77 countries/regions. The United States dominated with 191 publications (36.73%), followed by China (88, 16.92%) and the United Kingdom (71, 13.65%). The University of London emerged as the most productive institution (28 publications). Keyword burst analysis identified "artificial intelligence" (2019-2024) and "deep learning methods" (2022-2024) as dominant emerging themes. Computer science categories comprised >10% of publications, demonstrating strong interdisciplinary integration centered on surgery (31.54%) and biomedical engineering (12.31%). The field demonstrated clear evolution from basic instrument innovation to AI-driven, multi-disciplinary collaborative intelligent surgical systems, with Italy (centrality 0.18) and France (0.16) serving as critical knowledge brokers despite moderate publication volumes.

1. Introduction

Despite significant technological advances in robotic surgery and artificial intelligence, the research landscape lacks comprehensive quantitative analysis of their integration patterns and evolution trajectories. Current literature primarily focuses on isolated technical developments without providing systematic evidence of interdisciplinary collaboration trends, research hotspots, and knowledge diffusion mechanisms. This gap limits our understanding of how this field has evolved and where future research directions are heading. A bibliometric analysis is needed to objectively map the research landscape, identify influential contributors, and reveal emerging trends in the integration of robotic surgery with AI technologies. Since their emergence in the late 1980s, surgical robots have become increasingly fundamental to modern medical procedures [1,2]. In recent years, with the speedy improvement of cloud computing, big data analysis, artificial intelligence, and precision medicine, robotic surgical technology has developed from an important auxiliary tool in surgical operations to a smart surgical robot with autonomous perception, intelligent decision-making, and personalized operation capabilities [3]. This change no longer makes surgical operations increasingly specific and minimally invasive, but also promotes the mutual integration of surgical operations, engineering, and computer science [4]. Studies display that robotic surgical systems have substantially enhanced the safety and accessibility of complex surgical procedures. However, their limited ability to process complex information and make surgical decisions has not been effectively addressed [5]. However, most of the current literature focuses on a single technical field, such as human-machine assistance and the application of AI algorithms, lacking quantitative analysis of technological evolution [6]. Therefore, this study employs bibliometric analysis using the Web of Science Core Collection as the primary data source to systematically examine research literature on robotic surgery and artificial intelligence integration from 2014 to 2024. Using CiteSpace software, we constructed visual knowledge maps and applied co-occurrence analysis and cluster analysis to reveal research hotspots and evolutionary trends.

Abbreviations	
AI	Artificial Intelligence
CiteSpace	Citation Space
CV	Computer Vision
DL	Deep Learning
DOI	Digital Object Identifier
HRI	Human-Robot Interaction
MeSH	Medical Subject Headings
ML	Machine Learning
WoS	Web of Science
WoSCC	Web of Science Core Collection

This study aims to achieve four specific objectives: (a) map and analyze the characteristics of global collaboration networks in this interdisciplinary field; (b) identify influential authors and key research themes through highly cited publications and keyword frequency analysis; (c) trace the evolution paths and structural changes of major research categories over the past decade; (d) detect emerging research frontiers and predict future development directions in robotic surgery-AI integration.

2. Data acquisition and methods

2.1 Data collection

The data used in this study are all derived from the Web of Science Core Collection (WoSCC) database, which is an online academic citation index system developed by Thomson Reuters, and its literature indexing began in 1900 [7]. The content of WoSCC covers multiple disciplines, including natural sciences, social sciences, humanities, and arts, and includes over 12,000 high-impact journals, more than 150,000 conference papers, and a large amount of open access resources [8]. It has rich existing and historical data and supports in-depth interdisciplinary research. The literature data for this article were retrieved through a literature search in the WoSCC database. The search strategy was developed through a systematic approach to ensure comprehensive coverage. Keywords related to robotic surgery were selected based on: (1) a preliminary review of seminal papers in the field, (2) consultation with domain experts, and (3) analysis of Medical Subject Headings (MeSH) terms. The final keyword set included "robotic surgery" OR "robot-assisted surgery" OR "surgical robot" OR "da Vinci surgery" OR "minimally invasive robotic surgery" OR "computer-assisted surgery". To capture interdisciplinary integration, we included technology-related terms: "artificial intelligence" OR "AI" OR "machine learning" OR "deep learning" OR "computer vision" OR "neural networks" OR "interdisciplinary" OR "cross-disciplinary" OR "human-robot interaction". Alternative terms such as "laparoscopic robot", "surgical automation", and "intelligent surgery" were tested in pilot searches but yielded minimal additional relevant results. The time range (January 2014 to December 2024) was justified as it captures the period following the widespread adoption of da Vinci systems (post-2013) and the emergence of AI integration in surgical robotics, while including the most recent developments in the fieldA total of 520 articles were selected. To ensure data quality, the following procedures were applied: (1) author name standardization using CiteSpace's disambiguation function with manual verification for high-frequency authors; (2) institutional affiliation unification (e.g., consolidating department variations under parent institutions); (3) exclusion of non-peer-reviewed materials (editorials, letters, conference abstracts without full papers); (4) manual validation of a 10% random sample to verify relevance and metadata accuracy. While our search strategy aimed for comprehensiveness, certain limitations should be acknowledged. The focus on English-language publications may have excluded relevant research published in other languages. Additionally, conference proceedings and gray literature were not systematically included, which might have resulted in missing some cutting-edge developments that have not yet been published in peer-reviewed journals. Moreover, WoSCC has known indexing biases toward Western and English-language publications, potentially underrepresenting research contributions from non-English-speaking regions and limiting the global perspective of findings.

2.2 Bibliometric analysis and tools

CiteSpace is a visualization tool specifically designed for bibliometric analysis. It can be used to help answer questions related to knowledge domains and to study the relationships between academic references, authors, and journals [9]. This software can generate co-occurrence network diagrams of keywords, authors, countries/regions, and institutions under a specific research topic [10]. In this study, the parameters of CiteSpace were set as a time span from 2014 to 2024, with a time slice interval of 1 year. Based on different analysis requirements, this paper extracts literature data related to robotic surgery and its interdisciplinary technological integration from the WoSCC database, and conducts analysis from multiple perspectives, including keyword clustering, citation emergence detection, distribution of countries and regions, institution cooperation networks, and evolution of research topic categories.

3. Results and discussion

This paper conducts a two-stage study on the evolution of robotic surgery technology: Firstly, it performs descriptive statistics to summarize the development overview of this field in various aspects, including the distribution characteristics of countries/regions, research institutions, authors, co-cited authors, co-cited journals, and keywords; Secondly, using the bibliometric and visualization analysis tool CiteSpace, it deeply analyzes the evolution path of research topics, revealing the main features and development trends of the evolution of robotic surgery technology.

3.1 Descriptive analysis

3.1.1 Distribution of published literature on the evolution of robotic surgery technology

The number of documents reflects to a certain extent, the research level and development speed of the relevant field. As shown in Figure 1, the evolution of robotic surgery technology has shown different fluctuations across different years. The overall trend can be divided into three stages. The first stage is the initial exploration stage (2014-2017), during which the number of related literature was extremely small each year, with an average of less than 5 papers published annually, indicating that this research direction is still in its infancy and has relatively low academic attention. Secondly, the mid-term development stage (2018-2021): The number of literature in this stage has been increasing year by year, reaching 42 in 2020 and 69 in 2021, indicating that this field has gradually attracted attention, and the research enthusiasm for the evolution of robotic surgery technology has steadily risen. Finally, there is the explosive growth stage (2022-2024). As shown in Figure 1, research enthusiasm in this field has increased significantly since 2022. In 2022, there were 92 related papers, which rose to 177 in 2024, accounting for 34.23% of the total number of published papers. This publication surge is corroborated by keyword burst analysis (Figure 12), which shows the emergence of "deep learning methods" (2022-2024), "computer vision" (2022-2024), and "artificial intelligence" (2019-2024) as high-intensity burst terms. Additionally, the shift from early keywords like "laparoscopic surgery" (burst 2021-2022) to AI-focused terms supports the transition from traditional surgical robotics to intelligent surgical systems.

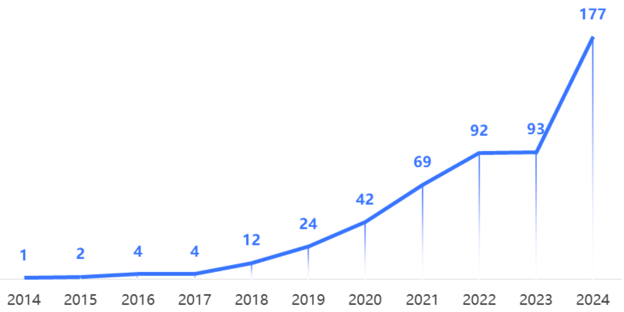

Figure 1. Annual distribution of literature related to the evolution of Robotic Surgical Techniques from 2014 to 2024

In the research field, a total of 520 articles were collected for analysis, revealing that research on the evolution of robotic surgery technology exhibits the characteristics of "clinical demand leading, engineering technology driving, and deep cross-integration of multiple disciplines." Its development trajectory has gradually evolved from early surgical clinical exploration to an intelligent development stage supported by cutting-edge technologies such as artificial intelligence and 5G communication, fully demonstrating the interdisciplinary collaborative paradigm of modern medical technological innovation. Based on the statistics of the Web of Science classification, a total of 80 subject categories were retrieved, covering medicine, engineering, computer science, and other fields. This interdisciplinary integration is evidenced by: (1) Computer Science categories accounting for >10% of publications (Table 1), compared to <5% in traditional surgical fields; (2) Co-occurrence analysis showing "artificial intelligence" and "machine learning" as central nodes with high connectivity (Figure 10); (3) The emergence of hybrid research clusters combining surgical and computational themes (Figure 11). As shown in Table 1, the top 15 subject categories collectively contributed over 70% of the literature, with a concentrated distribution in core technologies and application fields such as surgical procedures (31.54%), engineering biomedical (12.31%), and robotics (9.62%). Among them, Surgery ranked first, reflecting the medical dominance of robotic surgery research; while the high proportion of technical disciplines such as biomedical engineering and electrical and electronic engineering indicates that AI and engineering technologies are the key supports for the progress of this field.

In addition, clinical sub-sectors such as medicine general internal, oncology, urology, and general internal medicine also occupy significant shares, demonstrating the practical application value of robotic surgery in various medical departments. Computer science-related categories (such as artificial intelligence, information systems, and interdisciplinary applications) accounted for more than 10%, further indicating that the integration trend of AI in the medical field is increasingly strengthening.

Table 1. Top 15 Web of Science categories

Rank	Category	Count	Percentage (%)
1	Surgery	164	31.538
2	Engineering Biomedical	64	12.308
3	Robotics	50	9.615
4	Engineering Electrical Electronic	37	7.115
5	Medicine General Internal	32	6.154
6	Oncology	32	6.154
7	Urology Nephrology	32	6.154
8	Radiology, Nuclear Medicine, Medical Imaging	31	5.962
9	Computer Science Artificial Intelligence	20	3.846
10	Computer Science Interdisciplinary Applications	18	3.462
11	Automation Control Systems	17	3.269
12	Orthopedics	16	3.077
13	Computer Science Information Systems	14	2.692
14	Instruments Instrumentation	14	2.692
15	Health Care Sciences Services	12	2.308

3.1.2 Country and institution distribution

By analyzing the statistics of the countries/regions where the literature was published, it was found that a total of 77 countries/regions conducted research related to the evolution of robotic surgery techniques. As shown in Table 2, the United States ranked first with 191 papers, accounting for 36.73%, indicating that it holds a core position in the research on the evolution of robotic surgery techniques. China (88 , 16.92%), the United Kingdom (71, 13.65%), Italy (60, 11.54%), and Germany (40, 7.69%) followed. Figures 2 and Figure 3 are visual maps of the countries/regions and institutional collaboration networks in the field of robot surgery technology evolution in the Web of Science database. It is clearly observable that there is a highly interconnected research network. Among them, "centrality" is an important indicator for measuring the importance of a node in the network, reflecting its pivotal role in academic cooperation [11]. Values range from 0-1, where ≥0.10 indicates high influence: 0.01-0.09 (moderate), 0.10-0.19 (high), ≥0.20 (exceptional hub status). Centrality should be interpreted alongside publication volume, as high centrality with low output may indicate strategic rather than sustained research leadership. The data shows that the United States, with 191 publications and a centrality of 0.32, holds a core position in global research on robotic surgery technology. Meanwhile, Italy (0.18) and France (0.16), although having lower publication volumes (60 and 25, respectively), have a centrality higher than that of China (0.03) and the United Kingdom (0.13), ranking second and third, respectively. This suggests Italy and France serve as critical knowledge brokers, facilitating research exchange between different regional clusters despite moderate research output.

Table 2. The top 10 countries and institutions contributing

Rank	Count	Centrality	Country	Count	Centrality	Institution
1	191	0.32	USA	28	0.11	University of London
2	88	0.03	PEOPLES R CHINA	19	0.1	Imperial College London
3	71	0.13	ENGLAND	19	0.15	Johns Hopkins University
4	60	0.18	ITALY	18	0.02	University College London
5	40	0.13	GERMANY	16	0.03	Harvard University
6	28	0.11	INDIA	15	0.02	University of California System
7	28	0	SOUTH KOREA	15	0.03	Harvard University Medical Affiliates
8	25	0.16	FRANCE	14	0.01	King's College London
9	23	0.02	CANADA	10	0.05	Chinese Academy of Sciences
10	22	0.05	JAPAN	10	0	Roswell Park Comprehensive Cancer Center

Figure 2. Collaboration network map of countries/regions

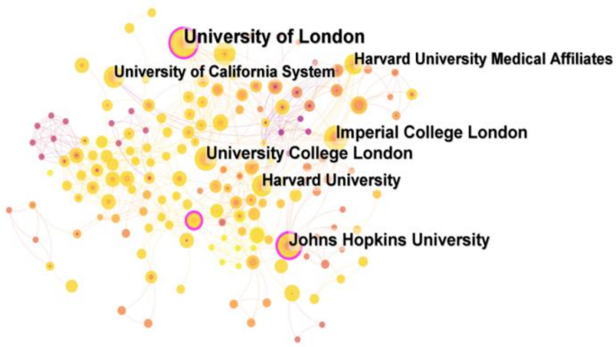

Figure 3. Collaboration network map of institutions

In contrast, China's low centrality (0.03), despite high output (88 papers), indicates more isolated or regionally-focused research networks. From the institutional perspective, the University of London ranked first with 28 publications, demonstrating a stable research output. Its centrality of 0.11 indicates a strong academic influence. Meanwhile, Johns Hopkins University, although having the same number of publications (19) as Imperial College London, has a centrality of 0.15, the highest among all institutions. This shows that it plays a crucial hub role in the global academic cooperation network in this field and has obvious knowledge-dissemination and cooperation organization capabilities. From 2014 to 2024, a total of 520 research papers on the evolution direction of robotic surgery technology were collected from the Web of Science Core Collection. The initial search yielded 547 records.

After manual screening for relevance and applying inclusion/exclusion criteria (English language publications, peer-reviewed articles, and direct relevance to robotic surgery technology evolution), 27 articles were excluded, resulting in 520 articles. Subsequently, the CiteSpace "delete duplicates" function was applied to identify potential duplicates based on DOI, title, and author matching. No additional duplicates were detected at this stage, confirming that the Web of Science database had already eliminated most duplicates during the initial search process. Therefore, the final dataset consisted of 520 unique articles for bibliometric analysis. Using the visualization trimming parameters, a country distribution map was generated. As shown in Figure 2, after running the software, an analysis network consisting of 77 nodes and 432 links emerged, with a network density of 0.1476.

As shown in Figure 3, this research field involves a total of 263 nodes, forming 696 cooperative links, with a network density of 0.0202. In this visualized network, each node represents an independent publishing institution, and its size is proportional to the number of publications of the institution. From the figure, it can be seen that although this field has formed a certain scale of institutional cooperation network, the overall connection density is relatively low, and the core institutions play an important regulatory role in the flow of knowledge. Among them, the University of London ranked first with 28 articles, distinguished by its pioneering work in AI-assisted surgical frameworks and ethical governance. Their most cited contribution (203 citations) established foundational principles for autonomous robotic surgery regulation, while their human-computer interaction research (170 citations) advanced deep learning applications in gesture recognition and multi-sensor fusion. This institution's leadership stems from its unique interdisciplinary approach, combining legal, technical, and clinical expertise. The most cited document among them received a total of 203 citations. It focused on the development paths of artificial intelligence (AI) and autonomous robotic surgeries within the legal, regulatory, and ethical frameworks, proposing that surgical robots can learn and perform routine operational tasks under the supervision of human surgeons. At the same time, another paper from this institution, which was cited 170 times, focused on human-computer interaction and remote operation technologies in the field of surgical robots, particularly in multi-sensor fusion and gesture recognition methods based on deep learning. Through these highly influential achievements, it can be seen that the University of London is at the forefront of the international community in promoting the multi-dimensional development of robotic surgery technology, especially in terms of technological innovation and institutional norms.

3.1.3 Distribution of authors and co-cited authors in the study on the evolution of robotic surgery technology

As shown in Figure 4, after adopting the Pathfinder/Binary Tree Network algorithm and setting pruning parameters, this study constructed an author collaboration network. This network consists of 312 nodes and 460 connection edges, with a network density of 0.0095. In the field of research on the development of robotic surgery technology, a total of 2,968 researchers have participated.

Table 3 presents the information of the top 10 authors in terms of the number of published papers, based on the number of publications and network centrality indicators, the most influential scholars are Stoyanov, Danail (7), Dasgupta, Prokar (6), Demomi, Elena (5), and Amparore, Daniele (5). Stoyanov, Danail's leadership (7 publications) centers on computer vision applications in surgical robotics, particularly real-time instrument tracking and surgical workflow analysis. Dasgupta, Prokar (6 publications) focuses on clinical validation of robotic systems in urological procedures, bridging the gap between technological innovation and clinical practice. Their complementary expertise—technical development and clinical validation—exemplifies the interdisciplinary collaboration driving this field. As shown in Figure 5, this study constructed a co-occurrence network graph of cited authors based on the evolution of robotic surgery technology. The network, consisting of 252 nodes and 439 connections, has a network density of 0.0139. To enhance the focus and representativeness of visualization, node selection adopts the g-index (k=10) as the pruning criterion. This parameter setting has been proven by multiple bibliometric studies to effectively balance information coverage and network simplicity.

Table 3. The top 10 authors and co-cited authors

Rank	Count	Centrality	Author	Count	Centrality	Co-Cited Author
1	7	0	Stoyanov, Danail	143	0.25	[ANONYMOUS]
2	6	0	Dasgupta, Prokar	57	0.15	HUNG AJ
3	5	0	De momi, Elena	47	0.06	HASHIMOTO DA
4	5	0	Amparore, Daniele	37	0.12	SHADEMAN A
5	4	0	Hung, Andrew J	36	0.09	HE KM
6	4	0	Porpiglia, Francesco	35	0.05	RONNEBERGER O
7	4	0	Shafiei, Somayeh B	33	0.21	ESTEVA A
8	4	0	Ma, Runzhuo	29	0.57	AHMIDI N
9	3	0	Ahn, Hanjong	29	0.03	YANG GZ
10	3	0	Kuchenbecker, Katherine J	28	0.03	CHEN J

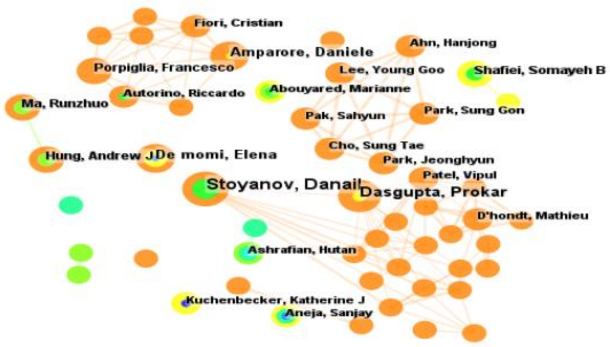

Figure 4. Collaboration network map of authors

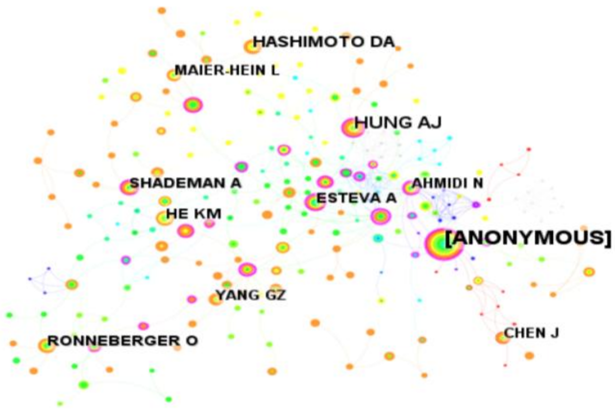

Figure 5. Co-citation network map of cited authors

The data in Table 3 shows that the most frequently cited one is [ANONYMOUS] (143), and its centrality is also ranked first. The document with the highest citation count is the review article published by Zhu et al. [21] in Nature Reviews Materials in 2021, which has been cited 211 times. This paper systematically elaborates on the cutting-edge progress of artificial intelligence-assisted 3D printing manufacturing technology in the field of multifunctional materials, especially the application prospects in personalized wearable devices, intelligent implants, and integration with surgical robots. Secondly, the paper that has been cited more than 203 times is the one published by O'Sullivan et al. [15], titled "Legal, Regulatory, and Ethical Frameworks for the Development of Standards in Artificial Intelligence and Autonomous Robotic Surgery". This article explores the legal, regulatory and ethical challenges faced by artificial intelligence and autonomous surgical robots during their development, and has significant theoretical and practical value for the construction of the medical AI governance system.

3.1.4 Distribution of cited journals in the study on the evolution of robotic surgery technology

As shown in Figure 6, the co-citation network constructed based on the field of robotic surgery technology in this study exhibits significant structural characteristics. This network consists of 275 nodes and 434 connection edges, with a network density of 0.115. Through the analysis of 266 core journals, Table 4 lists the 15 journals with the highest citation frequency and their centrality indicators. Among them, SURG ENDOSC ranked first with 228 citations (centrality 0.2), followed by INT J MED ROBOT COMP (187), ANN SURG (186), INT J COMPUT ASS RAD (174), and LECT NOTES COMPUT SC (143). It is worth noting that although LECT NOTES COMPUT SC ranked fifth in citation frequency, its centrality value reached 0.32, indicating the strongest network influence. These data results clearly reveal the core knowledge sources and dissemination paths in this research field.

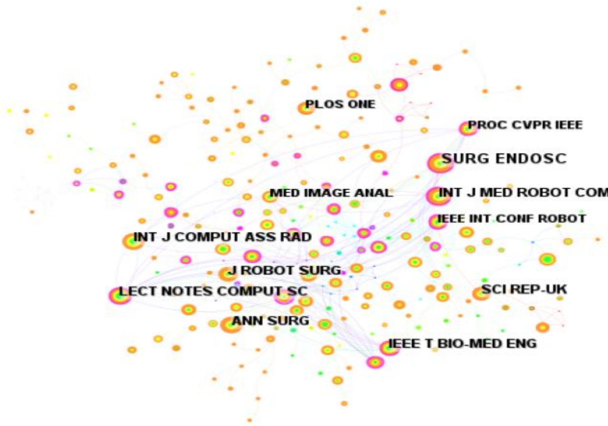

Figure 6. Network map of co-occurring journals

Through the analysis of 266 core journals, Table 4 lists the 15 most frequently cited journals and their centrality indicators. Among them, SURG ENDOSC ranks first with 228 citations (0.2), followed by INT J MED ROBOT COMP (187), ANN SURG (186), INT J COMPUT ASS RAD (174), and LECT NOTES COMPUT SC (143). It is worth noting that although LECT NOTES COMPUT SC ranks fifth in citation frequency, its centrality value reaches 0.32, indicating the strongest network influence. These data results clearly reveal the core knowledge sources and dissemination paths in this research field.

Table 4. The top 15 cited journals and the importance index (centrality value)

Rank	count	Centrality	Cited Journals
1	228	0.2	SURG ENDOSC
2	187	0.31	INT J MED ROBOT COMP
3	186	0.06	ANN SURG
4	174	0.02	INT J COMPUT ASS RAD
5	143	0.32	LECT NOTES COMPUT SC
6	137	0	J ROBOT SURG
7	130	0.1	SCI REP-UK
8	129	0.14	IEEE T BIO-MED ENG
9	107	0.26	IEEE INT CONF ROBOT
10	106	0	MED IMAGE ANAL
11	106	0.04	PLOS ONE
12	104	0.12	PROC CVPR IEEE
13	103	0.42	BJU INT
14	100	0	ARXIV
15	100	0.08	J UROLOGY

3.2 In-depth analysis

3.2.1 Distribution of category analysis in the evolution research of robotic surgery technology

Articles in the Internet of Technology (WoS) are commonly classified into one or more issue classes [12]. This study covers a total of 80 categories. As shown in Table 5, the "SURGERY" category has 164 documents and a centrality of 0.48, ranking first, indicating the considerable attention and central role of this technology within the surgical area. Following closely is the "ENGINEERING, BIOMEDICAL" category (64, 0.43) and the "ROBOTICS" category (50, 0.02), demonstrating the importance of the robotic surgery era now not only in scientific applications but additionally as a research hotspot in the fields of biomedical engineering and robotics. At the same time, we can also observe that categories such as "ENGINEERING, ELECTRICAL & ELECTRONIC" (37, centrality 0.29), "COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE" (20, centrality 0.05), and "AUTOMATION & CONTROL SYSTEMS" also account for a certain proportion, reflecting the integration and application trends of cutting-edge technologies such as artificial intelligence and automation control in this field.

Table 5. Top 10 research categories in the evolution of robotic surgery technology

Rank	Count	Centrality	Categories
1	164	0.48	SURGERY
2	64	0.43	ENGINEERING, BIOMEDICAL
3	50	0.02	ROBOTICS
4	37	0.29	ENGINEERING, ELECTRICAL & ELECTRONIC
5	32	0.35	MEDICINE, GENERAL & INTERNAL
6	32	0.09	ONCOLOGY
7	32	0.05	UROLOGY & NEPHROLOGY
8	31	0.21	RADIOLOGY, NUCLEAR MEDICINE & MEDICAL IMAGING
9	20	0.05	COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE
10	18	0.31	COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS

The citation burst intensity analysis of the disciplinary classes associated with the evolution of robotic surgical treatment era indicates, as depicted in determine 7, that the improvement of this discipline exhibits wonderful traits of interdisciplinary integration. "RADIOLOGY, NUCLEAR MEDICINE & MEDICAL IMAGING" (2016 - 2020, 4.06) and "ENGINEERING, BIOMEDICAL" (2016 - 2018, 3.47) rank at the top, indicating that those disciplinary categories have always been at the forefront of research in key technical factors consisting of image navigation, intraoperative imaging, and system integration in robotic surgery. Additionally, "MEDICINE, GENERAL & INTERNAL" began to experience a rapid burst in 2023 (2023 - 2024, 3.3), suggesting that as robotic-assisted surgery gradually becomes more widespread in the general medical system, its research focus has shifted from engineering development to clinical evaluation and wide medical adaptation.

In terms of the distribution of time, the years when the outbreaks began are concentrated from 2016 to 2020. During this period, there was a large-scale application transformation of technologies such as artificial intelligence, imaging technology, and remote operating systems in robotic surgery. For instance, fields like "MEDICAL INFORMATICS" and "TELECOMMUNICATIONS" experienced a synchronous outbreak in 2019, indicating that information processing and remote control systems are the core technical supports driving the intelligence and networking of robotic surgery.

At the same time, it is worth noting that the categories that experienced outbreaks later, such as "PHYSICS, APPLIED" (2021-2022), "HEALTH POLICY & SERVICES" (2022), and "MEDICINE, GENERAL & INTERNAL" (2023-2024), represent research hotspots that have gradually expanded from technology implementation to application optimization, policy evaluation, and clinical efficacy. This "evolution from the source of technology to its final implementation" trend reflects that the research on robotic surgery is gradually maturing and has a profound impact in multiple fields.

3.2.2 Distribution of commonly cited literature in the evolution study of robotic surgery technology

Table 6 presents the top 15 research papers with the highest citation frequency in the field of robotic surgery technology during the period from 2014 to 2024, along with their key indicators. From the data, it can be seen that the paper published by Hashimoto et al. [9] in "ANNALS OF SURGERY" ranked first with 24 citations. This paper comprehensively summarized the key technologies of artificial intelligence in surgical operations and their potential applications, emphasizing the core role of surgeons in the process of promoting the clinical transformation of AI, and providing an important theoretical basis and practical guidance for subsequent research in this field. Meanwhile, the paper published by Esteva et al. [8] in "Nature" (2017), although it was cited only 18 times and ranked fifth, demonstrated the centrality index (0.05). Esteva et al. [8] focused on the research of skin cancer classification using deep convolutional neural networks. It was the first to verify the diagnostic ability of artificial intelligence in medical image diagnosis at the level of dermatologists on a large-scale image dataset. Due to its bridging role in promoting the empowerment of artificial intelligence in precision medicine, it occupied a key intermediary position in the academic network. As shown in Figure 8, this study obtained the co-citation graph of the cited literature in the evolution research of robotic surgery techniques by setting the pruning parameter Pathfinder. This network consists of 481 nodes and 987 connections, with a network density of 0.0085. This indicates that the co-citation relationship is relatively sparse, but several significant clustering centers have been formed. The color of the nodes represents the time when the cited literature first appeared, ranging from purple (2014) to red (2025), reflecting the chronological development of the field. Larger nodes, such as Funke I (2019), Hashimoto DA [9], O'Sullivan S [15], Topol EJ (2019), etc., indicate that they have a high co-citation frequency and academic influence in this research field.

Figure7. Category burst detection based on WoS data

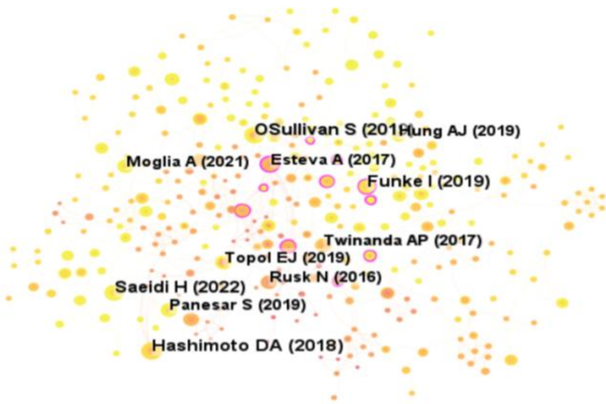

Figure 8. Co-citation network map of cited references

As shown in Figure 9, through the citation prominence analysis function of CiteSpace, the top 15 highly prominent references in the field of robot surgery technology evolution from 2014 to 2024 were identified. These papers saw a significant increase in citation volume during the specific period, indicating their core driving role in related research topics. Rusk [17] ranked first with a prominence strength of 6.33, indicating its significance in algorithm methods and basic model research. Secondly, Shademan et al. [18] research on the autonomous robotic surgical system also demonstrated a relatively high emergence intensity (5.76), with the emergence period spanning from 2019 to 2021.

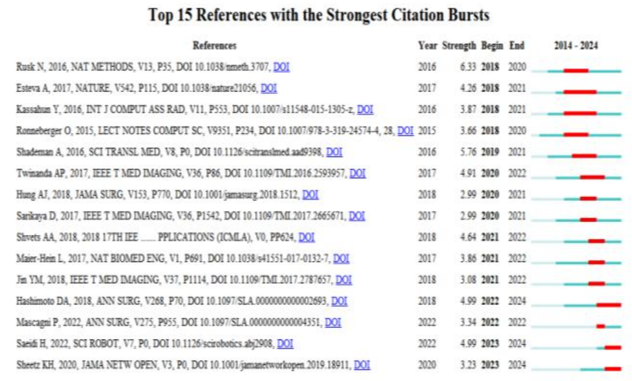

Figure 9. The top 15 co-cited references with the strongest citation burst

Table 6. Top 15 most-cited references from 2014 to 2024

Rank	count	Centrality	Year	Cited References
1	24	0.08	2018	Hashimoto DA, 2018, ANN SURG, V268, P70, DOI 10.1097/SLA.0000000000002693
2	23	0.08	2019	OSullivan S, 2019, INT J MED ROBOT COMP, V15, P0, DOI 10.1002/rcs.1968
3	20	0.01	2022	Saeidi H, 2022, SCI ROBOT, V7, P0, DOI 10.1126/scirobotics.abj2908
4	19	0.05	2019	Funke I, 2019, INT J COMPUT ASS RAD, V14, P1217, DOI 10.1007/s11548-019-01995-1
5	18	0.05	2017	Esteva A, 2017, NATURE, V542, P115, DOI 10.1038/nature21056
6	17	0.03	2017	Twinanda AP, 2017, IEEE T MED IMAGING, V36, P86, DOI 10.1109/TMI.2016.2593957
7	17	0.06	2021	Moglia A, 2021, INT J SURG, V95, P0, DOI 10.1016/j.ijsu.2021.106151
8	16	0.01	2019	Topol EJ, 2019, NAT MED, V25, P44, DOI 10.1038/s41591-018-0300-7
9	16	0.05	2019	Hung AJ, 2019, BJU INT, V124, P487, DOI 10.1111/bju.14735
10	16	0.05	2016	Rusk N, 2016, NAT METHODS, V13, P35, DOI 10.1038/nmeth.3707
11	16	0.03	2019	Panesar S, 2019, ANN SURG, V270, P223, DOI 10.1097/SLA.0000000000003262
12	15	0.03	2016	Shademan A, 2016, SCI TRANSL MED, V8, P0, DOI 10.1126/scitranslmed.aad9398
13	13	0.07	2018	Wang ZH, 2018, INT J COMPUT ASS RAD, V13, P1959, DOI 10.1007/s11548-018-1860-1
14	13	0.08	2020	Lee D, 2020, J CLIN MED, V9, P0, DOI 10.3390/jcm9061964
15	13	0	2020	Sheetz KH, 2020, JAMA NETW OPEN, V3, P0, DOI 10.1001/jamanetworkopen.2019.18911

The research focus was on constructing and verifying the application capability of the "Supervised Autonomous Robot System (STAR)" in soft tissue suturing surgeries. This research outcome represents a key breakthrough in the transformation of robotic surgical technology from "passive assistance" to "active execution", marking that surgical robots are entering a new stage of intelligence and autonomy. Furthermore, as can be seen from the figure, the recently emerged literature, such as Hashimoto et al. [8], Mascagni et al. [13], and Sheetz et al. [19], has attracted widespread attention from the academic community in the years 2022-2024. It is evident that the focus on robotic surgery in aspects such as clinical integration, safety standardization, and application efficiency assessment is gradually becoming an emerging research hotspot. The research emphasis is shifting from technological breakthroughs to clinical transformation and system optimization.

3.2.3 Keyword analysis

Keywords, as the key elements that reveal the core content of a paper, can accurately reflect the core elements and main research directions of the research topic [13]. By quantitatively studying the frequency distribution of keywords, the research hotspots and development trends in a specific academic field can be objectively presented [9]. This study utilized the keyword co-occurrence analysis function of the CiteSpace software to visually process the keyword data on the development of robotic surgery technology research in the Web of Science database from 2014 to 2024. Finally, the high-frequency keyword statistics results are shown in Table 7.

Table 7. Top 15 keywords in terms of citation counts and centrality

Rank	Count	Centrality	Year	keyword
1	179	0	2016	robotic surgery
2	170	0	2019	artificial intelligence
3	78	0.17	2015	machine learning
4	69	0	2018	deep learning
5	52	0	2018	surgery
6	44	0.02	2017	minimally invasive surgery
7	43	0.05	2016	system
8	42	0.02	2016	robot-assisted surgery
9	32	0.02	2018	outcm
10	31	0.1	2015	performance
11	31	0.11	2017	validation
12	24	0.14	2015	augmented reality
13	24	0.02	2017	laparoscopic surgery
14	20	0.05	2019	cancer
15	20	0.02	2017	tracking

Based on the keyword co-occurrence analysis results of CiteSpace, as shown in Table 7, a total of 15 keywords with high frequency of occurrence in the field of robot surgery technology evolution research were extracted, reflecting the research hotspots and evolution trends of this field. Among them, "robotic surgery" (179) and "artificial intelligence" (170 times) ranked as the top two, indicating that the deep integration of robotic surgery and artificial intelligence has become a core issue in recent years. High centrality keywords, such as "machine learning" (0.17), "augmented reality" (0.14), and "validation" (0.11), played a key bridging role in interdisciplinary research and method innovation. Overall, the research direction is gradually expanding from the application of a single technology to artificial intelligence-driven surgical assistance systems, intraoperative performance evaluation, and human-machine collaboration strategies, presenting an evolving trend of technological intelligence and clinical integration. As shown in Figure 10, it can be seen from the figure that keywords such as "augmented reality", "big data", and "surgical robotics" are located in the core area of the network, indicating their high attention and connectivity in this field, and forming the central themes of multiple research clusters. At the same time, keywords such as "machine learning", "design", "complications", and "manipulation" are distributed around the network, reflecting the diversity and refinement of research directions such as technical methods, intraoperative interaction, and postoperative evaluation. Particularly noteworthy is that keywords related to diseases such as "human papillomavirus" have also been included in the network, indicating that the application research of robotic surgery in specific disease treatment is expanding, and demonstrating the deep integration of medical practical problems with technological development. Overall, this graph reveals that the field of robotic surgery research is gradually shifting from equipment-centered engineering technology to comprehensive research oriented towards clinical application, data intelligence, and human-machine collaboration.

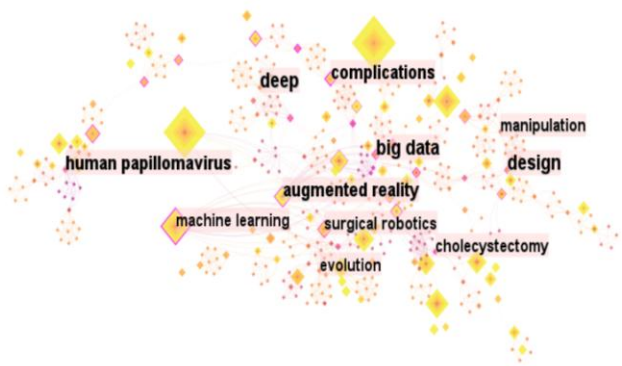

Figure10. Keyword co-occurrence visualization map

Furthermore, as shown in Figure 11, from the visualization results of the clustering network, it can be further observed that the current research on robotic surgery has formed several thematic clusters. Among them, clusters #0 "computer aided detection", #1 "minimally invasive surgery", #4 "design", and #6 "robot-assisted surgery" are relatively large in scale and closely related, representing the main directions of the integration of technology development and clinical practice in this field. At the same time, cluster #2 "transoral robotic surgery" and cluster #18 "surgical skill assessment" focus on specific surgical procedures and the evaluation of the surgeon's ability, demonstrating that the research is gradually expanding into more specialized areas such as disease-specific applications and quantitative assessment of surgical quality.

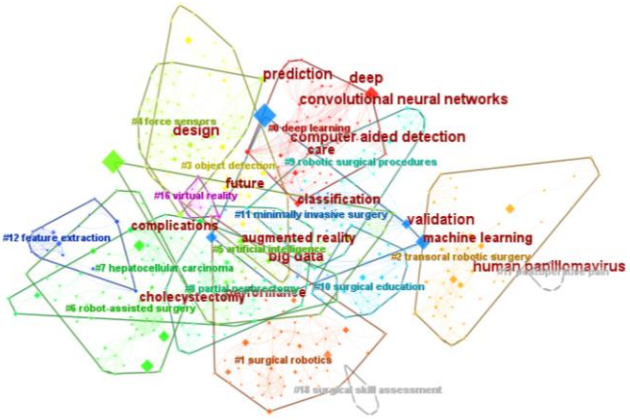

Figure 11. Cluster map of keywords

The sudden emergence of keywords serves as an important indicator for identifying emerging research trends and their evolution over time [9]. This study utilized CiteSpace to analyze the clustering of keywords, and Figure 12 presents the results of keyword burst detection. The intensity and duration of each burst keyword represent a significant increase in research attention for this topic during a specific period [10]. As shown in Figure 12, from the perspective of burst intensity, "laparoscopic surgery" (with a burst intensity of 5.52) ranks first, with the burst period concentrated in 2021-2022, indicating that traditional minimally invasive surgery remains a key focus of the academic community in the context of intelligence; secondly, keywords such as "resection" and "recognition" related to specific surgical tasks and intraoperative perception also showed a significant increase after 2021. At the same time, keywords like "robot-assisted surgery", "computer vision", "accuracy", and "task analysis" emerged in 2022-2023 and continued until 2024, reflecting that research in this field is gradually shifting towards intraoperative intelligent perception and automated execution performance.

Top 15 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2014 - 2024
medical robots and systems	2020	3.23	**2020**	2021	
laparoscopic surgery	2017	5.52	**2021**	2022	
resection	2021	3.67	**2021**	2022	
recognition	2018	3.43	**2021**	2022	
cancer	2019	2.48	**2021**	2022	
surgical robotics	2017	2.45	**2021**	2024	
deep learning methods	2021	2.34	**2021**	2021	
motion	2018	2.28	**2021**	2022	
robot-assisted surgery	2016	3.85	**2022**	2024	
computer vision	2022	3.49	**2022**	2024	
impact	2019	3.23	**2022**	2022	
model	2019	2.97	**2022**	2024	
medical robotics	2020	2.79	**2022**	2024	
accuracy	2018	3.34	**2023**	2024	
task analysis	2020	2.69	**2023**	2024	

Figure 12. The top 15 burst-detection keywords based on WoS data

Additionally, the emergence of terms such as "deep learning methods", "model", and "medical robots and systems" indicates that the embedding of AI technology in surgical systems and algorithm optimization has become a key research hotspot. Overall, the burst keywords have shifted from the early topics of "system application" and "minimally invasive surgery" to "intraoperative intelligent perception", "algorithm efficiency", and "precise operation", marking that robotic surgery technology is entering a new stage centered on data-driven intelligent perception and decision control.

4. Conclusion

In summary, this study analyzed the evolution of robotic surgery technology through a systematic analysis using the CiteSpace tool based on 520 articles from the Web of Science database between 2014 and 2024. It revealed the evolution trajectory of this field from early clinical exploration to intelligent development. The study found that this field has formed a new form of multi-disciplinary collaboration among surgery, biomedical engineering, and computer science. Through keyword analysis, it was discovered that intelligent sensing, precise execution, and disease-specific applications are becoming new research directions, indicating that robotic surgery technology is evolving from an auxiliary tool to an intelligent system. These conclusions are supported by convergent evidence from multiple bibliometric indicators: publication growth patterns (520% increase 2014-2024), keyword evolution (shift from mechanical to AI terms), citation bursts (AI-related papers dominating 2022-2024), and network centrality patterns (emergence of computational hubs). Firstly, the research on robotic surgery technology shows a significant phased growth characteristic. From the budding period of 2014-2017 to the explosive period of 2022-2024, the surge in the number of articles indicates that interdisciplinary technologies such as artificial intelligence and machine learning are driving this field into a high-speed development stage. The research topics have gradually shifted from early clinical exploration to intelligence, networking, and precision. Secondly, interdisciplinary integration has become the core paradigm of the development of robotic surgery technology. From the dominance of surgery, biomedical engineering, and robotics to the increasingly significant contributions of computer science and electronic engineering. Interdisciplinary cross-communication has not only been reflected in the technical development level but also extended to ethical norms and clinical evaluation dimensions, forming a new ecosystem of "technology - application - system" collaboration. Meanwhile, the national/regional and institutional collaboration network highlights the imbalance in the research landscape and the pivotal role of key hubs. Among them, the United States dominates with 36.73% of the publications, while Italy and France, with high centrality, become key hubs for academic cooperation. In terms of institutions, the University of London and Johns Hopkins University lead the global collaboration network with high output, focusing on AI legal frameworks, human-computer interaction, and remote operation technologies. Finally, keyword and emergent analysis further reveal emerging research directions. The frequent words "artificial intelligence" and "machine learning" indicate that the deep embedding of AI technology is the core of current research, while the emergent keywords "computer vision" and "deep learning methods" suggest that the future will focus on intelligent perception, algorithm optimization, and precise execution. At the same time, the incorporation of disease-related keywords such as "human papillomavirus" marks that the research on robotic surgery is shifting from general technology development to customized applications in specific clinical scenarios. Overall, robotic surgery technology is undergoing a transformation from an "auxiliary tool" to an "intelligent system". Based on the bibliometric analysis results of this study, future researchers can further precisely identify emerging research frontiers, provide data reference for interdisciplinary cooperation, and promote the further development of research in this field.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be provided upon a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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