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Research article

The bibliometric analysis of extended reality in surgical training: Global and Chinese perspective

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ABSTRACT

Objectives: The prospect of extended reality (XR) being integrated with surgical training curriculum has attracted scholars. However, there is a lack of bibliometric analysis to help them better understand this field. Our aim is to analyze relevant literature focusing on development trajectory and research directions since the 21st century to provide valuable insights.
Methods: Papers were retrieved from the Web of Science Core Collection. Microsoft Excel, VOSviewer, and CiteSpace were used for bibliometric analysis.
Results: Of the 3337 papers published worldwide, China contributed 204, ranking fifth. The world's enthusiasm for this field has been growing since 2000, whereas China has been gradually entering since 2001. Although China had a late start, its growth has accelerated since around 2016 due to the reform of the medical postgraduate education system and the rapid development of Chinese information technology, despite no research explosive period has been yet noted. International institutions, notably the University of Toronto, worked closely with others, while Chinese institutions lacked of international and domestic cooperation. Sixteen stable cooperation clusters of international scholars were formed, while the collaboration between Chinese scholars was not yet stable. XR has been primarily applied in orthopedic surgery, cataract surgery, laparoscopic training and intraoperative use in neurosurgery worldwide.
Conclusions: There is strong enthusiasm and cooperation in the international research on the XR-based surgical training. Chinese scholars are making steady progress and have great potential in this area. There has not been noted an explosive research phase yet in the Chinese pace. The research on several surgical specialties has been summarized at the very first time. AR will gradually to be more involved and take important role of the research.

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1. Introduction

Under the multiple pressures of ethics, finance, strained doctor-patient relationship and limited medical and educational resources, the traditional apprenticeship model of "see one, do one, teach one" no longer ensures that novice surgeons receive adequate training and professional development within a limited period of time, especially during residency training [1,2]. In such case, establishing a more comprehensive, effective and diversified surgical training model has become a consensus. At present, modern surgical training model is still in the exploratory stage, and has not yet been fully established and standardized. Nevertheless, many attempts have been made worldwide, most of which have constructively considered the diverse, multi-level and different needs of trainees, which are more in line with the current training status and medical needs [2–4].

The rapid development of information society has provided many promising means and directions for modern surgical training model, among which high-fidelity virtual trainers have received great attention [1]. The virtual trainers currently used or under development for surgical training mainly include virtual reality (VR), augmented reality (AR) and mixed reality (MR), which are collectively known as extended reality (XR) [5]. These different types of XR are all capable of creating a reality-based, computer--generated virtual environment and realizing human-machine interaction with the help of wearable and remote controllers, but they each have their own characteristics [5]. Invented in the late 20th century, VR simulators have gained widespread recognition for their value in the field of surgical training due to their advantages over traditional training, such as multi-sensory simulation, timely feedback, and preoperative and repetitive practice [2,6]. Compared to VR, AR further enhances the immersion by attaching digital elements to the real world [7]. According to the analysis results of Han et al., AR has become increasingly important in surgical training in recent decades because of its ability to construct virtual environment based on a real patient anatomy and allow surgeons to use them in their clinical work. However, although the application of AR is more flexible than VR, its application areas are slightly different from VR, which means that AR is unlikely to replace the role of VR, but more likely to co-exist with it, namely MR [7–9].

Bibliometric analysis can comprehensively and detailed analyze the intellectual landscape of a specific field. Currently, there is only one bibliometric article on the application of XR in surgical training [7,10,11], and it only discusses the evolutionary dynamic of keywords, lacking analysis of co-citation, co-authorship and burst detection that could provide a more detailed intellectual base and milestone events in this field. In order to make up for this deficiency, we conducted this study to accurately capture the development, important events and future direction of XR in surgical training. In addition, noting the different rates and characteristics of technological development in different countries, we analyzed the development of XR in surgical training from both world and Chinese perspectives, so as to provide guidance to scholars in different regions of the world and to provide suggestions for scholars in China on regional development.

2. Methods

2.1. Search strategies and data collection

Web of Science Core Collection (WoSCC) was chosen as the search platform because the publications on it are peer-reviewed and the quality of the publications is authoritative. Retrieval and download of data were completed on the same day, September 28, 2022. The queries were as follows: ((virtual reality) OR (augmented reality) OR (mixed reality)) AND surg* AND (train* OR educat*). All publications to be retrieved were articles or reviews, from January 1, 2000 to June 30, 2022. When analyzing Chinese data, there was one more searching restriction: the country/region was Peoples R China or Taiwan.

All data to be analyzed, including the annual number of publications, the number of papers published by countries/regions, institutions, journals and authors were downloaded as the plain text version. Microsoft Excel, VOSviewer, and CiteSpace were used for analysis.

2.2. Data analysis

VOSviewer software (www.vosviewer.com, VOSviewer version 1.6.13) was applied to visualize the collaborative map between countries/regions, between institutions and between authors. The size of the circle of an item was proportional to its number of publications, while the width of the line between two items was proportional to the magnitude of their collaboration. Items of the same color belonged to the same cluster, indicating that they cooperated closely in this field.

Using CiteSpace (Drexel University, Philadelphia, PA, USA) for co-citation analysis and burst detection is an important step to explore the research base and frontier of a specific research field [12]. References with strong co-citation relationships formed a certain cluster to reflect the same research topic or direction. The nodes and links shown in the co-citation map were color-coded. Different colors represented different years, and the nodes presented by the "tree ring" were surrounded by rings of different colors with a certain thickness, meaning that this reference was cited in different year with certain cited number. The color of the link between nodes reflected the year that these two references were first co-cited. References or keywords with the strongest citation bursts were identified to explore the most active topics in the research field. We selected the top 25 references and top 50 keywords with the strongest citation bursts in this paper to explore the research hot-spots worldwide. As for the setting of CiteSpace V in this study, the "time slicing" was set from 2000 to 2022, while "years per slice" and "top N per slice" were set at 1 and 50, respectively [13].

3. Results

3.1. The overall landscape of the publications

Using our search strategy, a total of 3337 papers were retrieved worldwide, 204 of which involved Chinese institutions. The annual number of publications worldwide was shown in Fig. 1, with the number of publications per year in China in green. Based on the amount of increase each year over the previous year (Table 1), we divided the development of field into the following periods and determined several milestone time points.

Emergence period: From the global perspective, the number of papers published worldwide has been rising since 21st century, and it is assumed that the emergence period of world should be earlier in 1990's. The first paper on Chinese institutional participation appeared in 2001, and the number of Chinese institutional participation was approximately 5 papers per year until 2011, therefore we classified the period from 2001 to 2011 as the emergence period of China in this field.

Growth period: Since 2012, the number of publications involving Chinese institutions has started to increase, and China's development in this field has thus entered a growth period, and is still in the growth phase. The global annual volume of publications has been rising since the beginning of the 21st century and continue on the rise.

Explosive period: From a global perspective, the first explosive period of research with significant annual increases occurred from 2003 to 2006, the second explosive period took place between 2010 and 2011, and the third explosive period was noted between 2020 and 2021. Despite the large increase ratio of annual variation in the number of publications in China, considering the small base per year, we did not consider the growth as an explosive period for the time being.

Milestone points: Based on the number of publications, there were two milestone time points appeared in the field worldwide: they are 2008 (breakthrough of 100 papers) and 2017 (breakthrough of 200 papers, approximately doubling from 2008). China has three milestone time points in this field in the past 22 years: they are 2001 (zero breakthrough); 2014 (small leap in the numbers of publications), and 2017 (nearly double the number of publications compared to 2014).

3.2. The top 10 productive entities worldwide

The top 10 productive countries/regions in terms of the number of publications in this field were listed in Table 2. The USA accounted for almost a third of the papers written in the field of XR applications in surgical training, while the top five countries together contributed about 70 percent of the papers (2,407, 72.1%). China was the fifth productive country with a total of 204 relevant publications.

The top 10 productive institutions in terms of the number of publications in this field worldwide were listed in Table 3. Across the world, Imperial College London in the UK published the most in this field (181 papers), followed by University of London in the UK (139 papers), University of Toronto in Canada (130 papers), University of Copenhagen in Denmark (106 papers) and Harvard University in the USA (103 papers). Six of the top 10 productive institutions are in Europe, four in North America and no Asian Institutions

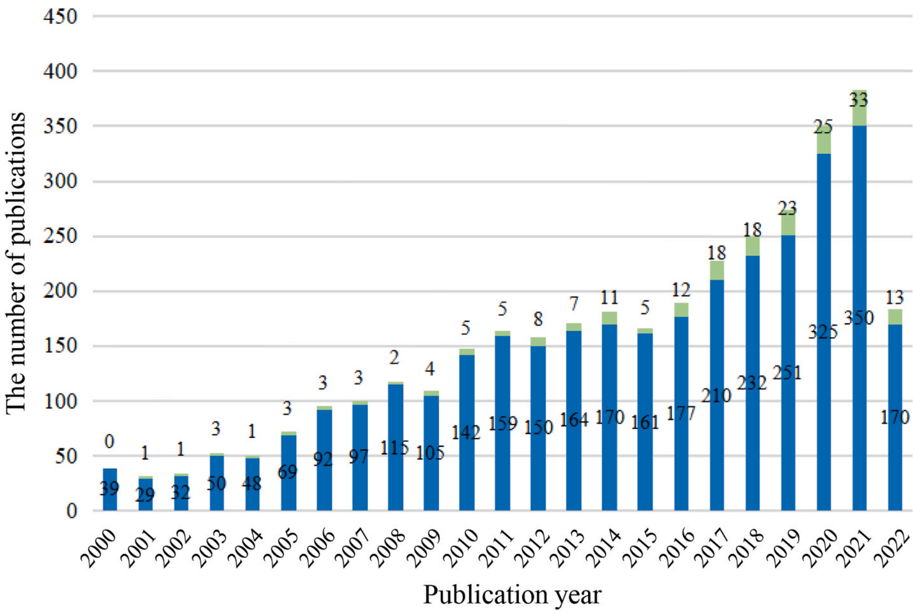

Fig. 1. The annual number of publications worldwide or in China between January 1, 2000 and June 30, 2022. The blue and green modules added up to the number of world publications in the corresponding year (the total was marked on the blue module), and the green module was the number of publications in which Chinese institutions were involved in the corresponding year.

Table 1
The annual publication volume change of world and China.

Publication year	World	Compared to last year	China	Compared to last year	Percentage of overall global publications	Compared to last year
2000	39	–	0	–	0.0%	–
2001	29	−25.6%	1	100.0%	3.4%	3.40%
2002	32	10.3%	1	0.0%	3.1%	−0.30%
2003	50	56.3%	3	200.0%	6.0%	2.90%
2004	48	−4.0%	1	−66.7%	2.1%	−3.90%
2005	69	43.8%	3	200.0%	4.3%	2.20%
2006	92	33.3%	3	0.0%	3.3%	−1%
2007	97	5.4%	3	0.0%	3.1%	−0.20%
2008	115	18.6%	2	−33.3%	1.7%	−1.40%
2009	105	−8.7%	4	100.0%	3.8%	2.10%
2010	142	35.2%	5	25.0%	3.5%	−0.30%
2011	159	12.0%	5	0.0%	3.1%	−0.40%
2012	150	−5.7%	8	60.0%	5.3%	2.20%
2013	164	9.3%	7	−12.5%	4.3%	−1%
2014	170	3.7%	11	57.1%	6.5%	2.20%
2015	161	−5.3%	5	−54.5%	3.1%	−3.40%
2016	177	10.0%	12	140.0%	6.8%	3.70%
2017	210	18.6%	18	50.0%	8.6%	1.80%
2018	232	10.5%	18	0.0%	7.8%	−0.80%
2019	251	8.2%	23	27.8%	9.2%	1.40%
2020	325	29.5%	25	8.7%	7.7%	−1.50%
2021	350	7.7%	33	32.0%	9.4%	1.70%
2022	170	–	13	–	–	–

Table 2
The top 10 countries/regions with the largest number of papers or cooperation intensity worldwide.

Rank	Countries/regions	Number of publications	Rank	Co-authorship country/region	Total link strength
1	USA	1110	1	USA	448
2	UK	499	2	UK	376
3	Canada	321	3	Canada	220
4	Germany	273	4	Germany	217
5	Peoples R China	204	5	Italy	190
6	Netherlands	186	6	Netherlands	157
7	France	152	7	Belgium	129
8	Italy	151	7	France	129
9	Denmark	143	8	Switzerland	102
10	Australia	115	9	Peoples R China	94
10	Japan	115			

Table 3
The top 10 institutions with the largest number of papers or the largest cooperation intensity worldwide.

Rank	Institutions	Number of publications	Country	Rank	Co-authorship institutions	Total link strength
1	Imperial College London	181	UK	1	University of Toronto	162
2	University of London	139	UK	2	Rigshospitalet	94
3	University of Toronto	130	Canada	2	University of Washington	94
4	University of Copenhagen	106	Denmark	3	Mcgill University	90
5	Harvard University	103	USA	3	University of Copenhagen	90
6	Rigshospitalet	88	Denmark	4	King S College London	84
7	University of California System	84	USA	5	Catharina Hospital	83
8	UDICE French Research Universities	80	France	6	Imperial College of Science, Technology and Medicine, University of London	78
9	Mcgill University	69	Canada	7	Delft University of Technology	74
10	King S College London	65	UK	8	Rensselaer Polytechnic Institute	72

are among them.

As for scholars who have contributed to this field, Professor Aggarwal, from the Imperial College, St. Mary's hospital in the UK, published the most, with a total of 79 papers. Professor Darzi, also from the Imperial College, St. Mary's hospital in the UK, and Professor Konge, from the Rigshospitalet in Denmark, were the second and third scholars, with 71 and 63 relevant papers respectively. Of the top ten prolific authors, four are from British institutions, three are from Danish institutions, two are from American institutions and one is from a Dutch institution (Table 4).

Journals can partly reflect the direction of the research. In addition to educational research journals such as *Journal of Surgical*, the top 10 journals also included some surgical specialties, such as endoscopy (*Surgical Endoscopy and Other Intervention Techniques*), endourology (*Journal of Endourology*), neurosurgery (*World Neurosurgery*), and computer assisted surgery (*International Journal of Computer Assisted Radiology and Surgery* and *International Journal of Medical Robotics and Computer Assisted Surgery*) (Table 5).

3.3. Cooperative relationship analysis of world data

The collaborative network map between countries/regions was shown in Fig. 2A and detailed information of the top 10 co-authorship countries/regions was shown in Table 2. As shown in Fig. 2A, ten clusters were formed with the total link strength of 1595. The USA had the highest total link strength of 448, indicating its extensive cooperation with other countries/regions in this research field. Not only that, the other top five productive countries/regions, besides China, also had the relatively strong partnerships with others.

In contrast, cooperative relationship between institutions was more decentralized. There were seventeen clusters formed with the total link strength of 2954 around the world (Fig. 2B). As shown in Table 3, the University of Toronto in Canada had the highest total links worldwide, with the strength of 162, followed by Rigshospitalet in Denmark (94) and University of Washington in the USA (94).

Moreover, it is found that the authors' cooperative relationship formed more obvious groups than those between countries or institutions. A total of 16 collaborative groups were formed with the total link strength of 1865. As presented in Table 4, professor Konge, from Rigshospitalet in Denmark was the scholar who collaborated the most with others worldwide, with the total link strength of 130, followed by professor Ahmed, from King's College London in the UK (129), and professor Aggarwal, from St. Mary's Hospital in the UK (117).

3.4. Analysis of cited and citing references

Cited references refer to the references in the analyzed literature. When two references are cited by a literature at the same time, they constitute a co-citation relationship, and the higher the number of co-citations, the more similar the research directions of the two cited literature are. Cited references with similar research content constitutes a cluster, thus reflecting a research direction. Literature that cites references from these clusters are referred to as citing references, indicating the existence of similarity in research directions, and the higher the number of citations, the higher the similarity in research content.

A total of 1438 co-cited references were obtained from the top 50 co-cited references per time slice for 2000–2022 worldwide. According to data S1, a total of fifteen clusters were formed, indicating that fifteen main topics were or are still research directions in the field of application of virtual technology in surgical training, each cluster contained multiple contents, and we presented the directions related to the topic of this paper in each cluster as cluster labels in Table 6, while Fig. 4 showed the labels automatically generated by the software. The silhouettes of fifteen clusters ranged from 0.8 to 1, reflecting they had relatively higher homogeneity (Table 6). Based on the average year of appearance of the literature within the clusters, cluster #1 (augmented reality, 2020), #5 (orthopedic surgery resident, 2017), #6 (cataract surgery training, 2016), #14 (study protocol, 2017), and #15 (intraoperative use, 2022) are the research directions that have attracted much attention in recent years and are the ones that we will specifically discuss in the discussion section. The top 5 cited references and citing references in each of these five clusters were listed in Table 7 and Table 8.

Table 4
The top 10 productive authors and the top 10 authors with the largest cooperation intensity worldwide.

Rank	Author	Number of publications	Institution	Rank	Co-authorship author	Total link strength	Institution
1	Aggarwal R	79	Imperial College, UK	1	Konge L	130	Rigshospitalet, Denmark
2	Darzi A	71	Imperial College, UK	2	Ahmed K	129	King's College London, UK
3	Konge L	63	Rigshospitalet, Denmark	3	Aggarwal R	117	Imperial College, St. Mary's Hospital, UK
4	Ahmed K	49	King's College London, UK	4	Dasgupta P	104	King's College London, UK
5	Gallagher AG	44	Department of Surgery Emory University Hospital, USA	4	De S	104	Rensselaer Polytechnic Institute, USA
6	Grantcharov TP	40	Copenhagen University, Glostrup Hospital, Denmark	5	Darzi A	94	Imperial College, St. Mary's Hospital, UK
7	Dasgupta P	37	King's College London, UK	6	Winkler-schwartz A	84	McGill University, Canada
7	Andersen SAW	37	Rigshospitalet, Denmark	7	Jones DB	81	Harvard School of Medicine, USA
8	De S	35	Rensselaer Polytechnic Institute, USA	7	Sankaranarayanan G	81	Rensselaer Polytechnic Institute, USA
9	Schijven MP	33	University of Amsterdam, Netherlands	8	Sørensen MS	76	Rigshospitalet, Denmark

Table 5
The top 10 journals that published the largest number of papers worldwide.

Rank	Journal	Number of publications	2021IF
1	Surgical Endoscopy and Other Intervention Techniques	277	3.453
2	Journal of Surgical Education	130	3.524
3	American Journal of Surgery	61	3.125
4	International Journal of Computer Assisted Radiology and Surgery	59	3.421
5	Journal of Endourology	54	2.619
6	International Journal of Medical Robotics and Computer Assisted Surgery	42	2.483
6	World Neurosurgery	42	2.210
7	Annals of Surgery	40	13.787
7	Surgical Innovation	40	1.785
8	Minimally Invasive Therapy Allied Technologies	38	–

3.5. Burst detection of references and keywords

By using CiteSpace, we performed the burst detection of references and keywords to locate the hot topics in the field of the application of XR in surgical training. Among the top 25 references with the strongest citation bursts worldwide, one literature had outbreak status in recent 5 years: the work of Moglia that assessed the level of evidence in published papers on the efficacy of VR simulators training in robotic surgery [14] (Fig. 5).

We conducted burst detection of keywords in papers from around the world. As shown in Fig. 6, there were 16 keywords that still in the burst state, of which involved 4 surgical-related contents (navigation, anatomy, surgical navigation, spine surgery), 4 key points of simulation research (simulation training, safety, tool, improve), and 8 XR-related contents (3d printing, accuracy, feasibility, augmented reality, artificial intelligence, machine learning, mixed reality, technology) (Fig. 6). Only one keyword ("Augmented reality") extracted from papers published by Chinese scholars had the strongest citation bursts, we therefore did not map it.

3.6. Top 10 most prolific Chinese institutions and scholars and the top 10 journals that publish their papers

A total of 339 institutions were actively involved in this area, with Shanghai Jiao Tong University making a particularly prominent contribution (21 papers), followed by Beihang University (14 papers), University of Hong Kong (14 papers), Peking University (13 papers) and Chinese University of Hong Kong (12 papers) (Table 9).

The difference in the contribution of Chinese scholars in this field was not outstanding for the time being, Professor Chen from Shanghai Jiao Tong University and Professor Tai from Yunnan Normal University ranked first in terms of the number of papers published, but there was little difference between Chinese scholars from other institutions, and there is a possibility of reshuffling the ranking of Chinese scholars' publications in the future (Table 9).

Three of the top ten journals publishing articles by Chinese scholars were the same as the world analysis, namely *International Journal of Medical Robotics and Computer Assisted Surgery*, *International Journal of Computer Assisted Radiology and Surgery, Surgical Endoscopy and Other Intervention Techniques* and *World Neurosurgery*. Seven journals had impact factors higher than 3, implying relatively high quality of the journals (Table 11).

3.7. Cooperative relationship analysis of Chinese data

The intensity of cooperation between Chinese institutions and other institutions in this field was shown in Fig. 3A, with a total of 20 clusters formed and a total link strength of 564 (Fig. 3A). Beihang University and Shanghai Jiao Tong University had the closest cooperation with other institutions, with the total link strength of 31, followed by University of Hong Kong, Taipei Medical University, and China Medical University, with the total link strength of 30, 22 and 21 respectively (Table 9).

Consistent with the international situation, the intensity of cooperation among Chinese scholars was relatively obvious. A total of 8 clusters with the total link strength of 361 were formed, with Professor Tai from Yunnan Normal University had the strongest cooperation with others, with the total link strength of 48 (Fig. 3B and Table 10).

4. Discussion

Effective surgical training is the key to reducing clinical error rates and is the focus of post-graduation education in all surgical departments. XR presents new opportunities for modern surgical training models, and in an era of constant technological change, there is a need to apply technology accurately to a demanding field, which is one of the key reasons why we conducted this study.

Present work is the first bibliometric analysis attempt to describe the prospect of extended reality (XR) being integrated with surgical training, the data of our bibliometric analysis contributes better understand of the field, especially provide valuable insights of the development trajectory and research directions since the 21st century. Our data demonstrated that there is strong enthusiasm and cooperation in the international research on the XR-based surgical training. The research on several surgical specialties has shown initial results been summarized at the very first time, AR will gradually to be considered more involved into the research. Chinese scholars are making steady progress and have great potential in this area. There has not been noted an explosive research phase yet in

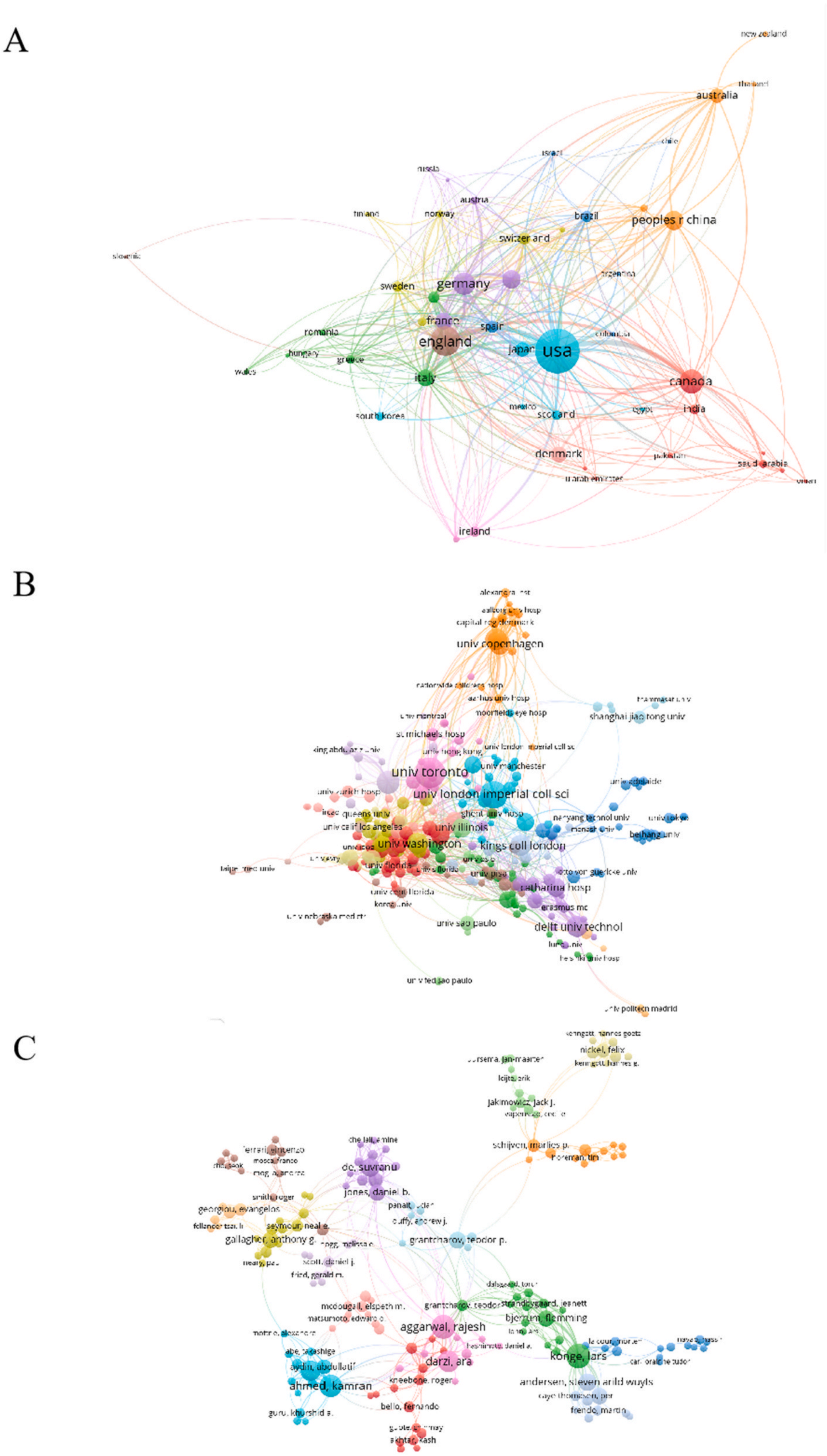

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Fig. 2. The collaboration analysis of countries/regions, institutions, and scholars around the world in this field. **A.** The collaboration network of countries/regions. Ten cooperation clusters with different colors were formed with the total link strength of 1595. **B.** The collaboration network of institutions. Seventeen cooperation clusters with different colors were formed with the total link strength of 2954. **C.** The collaboration network of scholars. Sixteen cooperation clusters with different colors were formed with the total link strength of 1865.

Table 6
The detailed information of clusters of co-cited references from 2000 to September 28, 2022 worldwide.

Cluster ID	Size	Silhouette	Mean (Year)	Label (LLR)
0	256	0.8	2009	invasive surgery
1	204	0.879	2020	augmented reality
2	198	0.921	2002	systematic review
3	143	0.83	2006	endovascular skill
4	96	0.921	2014	robotic surgery
5	94	0.975	2017	orthopedic surgery resident
6	66	0.922	2016	cataract surgery training
7	62	0.925	2014	laparoscopic colectomy
8	57	0.942	2014	temporal bone dissection
9	47	0.989	2015	neurosurgical training
10	34	0.967	2010	transurethral procedure
11	30	0.997	2001	soft tissue deformation
14	6	1	2017	study protocol
15	6	1	2022	intraoperative use
17	5	1	2007	neurosurgical education

Table 7
The top 5 papers in cluster #1, #5, # 6, #14, and #15.

Cluster	Citation	Author	Year	DOI
1	39	Alaker M	2016	10.1016/j.ijsu.2016.03.034
1	36	Bernardo A	2017	10.1016/j.wneu.2017.06.140
1	32	Barsom EZ	2016	10.1007/s00464-016-4800-6
1	30	Moro C	2017	10.1002/ase.1696
1	27	Khor WS	2016	10.21037/atm.2016.12.23
5	39	Cannon WD	2014	10.2106/JBJS.N.00058
5	33	Waterman BR	2016	10.3928/01477447-20160427-02
5	32	Bartlett JD	2018	10.1302/0301-620X.100B5.BJJ-2017-1439
5	29	Aim F	2016	10.1016/j.arthro.2015.07.023
5	22	Rebolledo BJ	2015	10.1177/0363546515574064
6	28	Thomsen ASS	2017	10.1016/j.ophtha.2016.11.015
6	22	Strandbygaard J	2013	10.1097/SLA.0b013e31827eee6e
6	21	Dawe SR	2014	10.1002/bjs.9482
6	19	Stefanidis D	2015	10.1097/SLA.0000000000000826
6	19	Borgersen NJ	2018	10.1097/SLA.0000000000002652
14	15	Yiannakopoulou E	2015	10.1016/j.ijsu.2014.11.014
14	10	Nickel F	2015	10.1097/MD.0000000000000764
14	5	Nickel F	2014	10.1186/1745-6215-15-137
14	4	Nickel F	2016	10.1159/000444449
14	4	Nickel F	2013	10.1007/s00268-013-1963-3
14	4	Nickel F	2016	10.1007/s00423-016-1421-4
15	6	Montemurro N	2021	10.3390/ijerph18199955
15	5	Condino S	2021	10.1007/s10439-021-02834-8
15	4	Montemurro N	2020	10.25259/SNI_697_2020
15	4	Montemurro N	2021	10.1016/j.clineuro.2021.106735
15	3	Canseco JA	2021	10.1007/s00586-020-06535-z

the Chinese pace.

From the data of present work, there have been three research outbreaks around the world during previous 22 years with different outbreaks occurring in different contexts. For example, the short burst from 2003 to 2006 may be related to the beginning of the gradual systematization of simulation medicine education (marked by the successive establishment of simulation medicine-related associations such as the Society for Simulation in Healthcare) and the initial entry of virtual technologies into medical training since the early 2000s, and from 2020 to 2021 mainly to the COVID-19 pandemic, as we could see the emergence of some virtual training studies in the context of the pandemic. It took nine years to double the number of publications per year globally from about 100 in 2008 to about 200 in 2017.

The development trajectory of China in this area, however, is not quite the same as the global trajectory. Compared with the overall global data, China started late and kept low outputs in the following decade since the zero breakthrough in this field of research in

Table 8
The top 5 papers that cite the members in cluster #1, #5, # 6, #14, and #15.

Cluster	Citation	Author	Year	DOI
1	26	Jiang H	2022	10.2196/34860
1	21	Mcknight R	2020	10.1007/s12178-020-09667-3
1	18	Liu T	2020	10.1002/rcs.2160
1	16	Barteit S	2021	10.2196/29080
1	15	Negrillo-Cardenas J	2020	10.1016/j.cmpb.2020.105407
5	22	Frank R	2018	10.1016/j.arthro.2017.10.048
5	21	Rashed S	2018	10.2106/JBJS.RVW.17.00201
5	19	James H	2020	10.2106/JBJS.RVW.19.00167
5	17	Bartlett J	2018	10.1302/0301-620X.100B5.BJJ-2017-1439
5	14	Goh G	2021	10.1007/s00402-021-04037-1
5	14	Yari S	2018	10.1177/2325967118810176
6	11	Thomsen A	2017	10.1111/aos.13505
6	10	Cox T	2015	10.1016/j.suc.2015.03.005
6	7	Jensen K	2017	10.1007/s00464-016-5254-6
6	7	Thomsen A	2017	10.1111/aos.13434
6	7	Selvander M	2013	10.2147/OPTH.S48374
14	5	Kowalewski K	2017	10.1007/s00464-016-5213-2
14	4	De La Garza JR	2017	10.1186/s13063-017-1886-7
14	4	Kowalewski K	2017	10.1007/s00464-017-5452-x
14	3	Schmidt M	2017	10.1016/j.isjp.2017.01.001
14	3	Friedrich M	2017	10.1016/j.isjp.2017.07.002
15	6	Dipalma G	2022	10.3390/jcm11010223
15	6	Montemurro N	2022	–

Table 9
The top 10 institutions with the largest number of papers or cooperation intensity in China.

Rank	Institutions	Number of publications	Rank	Co-authorship country/region	Total link strength
1	Shanghai Jiao Tong University	21	1	Beihang University	31
2	Beihang University	14	1	Shanghai Jiao Tong University	31
2	University of Hong Kong	14	2	University of Hong Kong	30
3	Peking University	13	3	Taipei Medical University	22
4	Chinese University of Hong Kong	12	4	China Medical University	21
5	Taipei Medical University	9	5	Peking University	17
6	Chinese Academy of Medical Sciences Peking Union Medical College	8	6	Chinese University of Hong Kong	16
7	Chinese Academy of Sciences	7	6	University of California	16
7	Naval Medical University	7	7	Chinese Academy of Sciences	14
7	Taipei Medical University Hospital	7	7	National Central University	14
7	Yunnan Normal University	7	7	Tehran University of Medical Sciences	14

2001. Although there was a small leap for a few brief years (i.e., 2003), probably due to enthusiasm and initial attempts for the nascent field, and the quickly cool down was noted in 2008, the possible explanation are many attempts were followed suit and lacking of sustained policy support as well as the limitation of research manpower in this field at the beginning of this century. Although we did not observe an explosive period of development in this field in China, we have noted three milestones, of which 2017 was an important point in time, a year in which not only did the number of publications double from 2014, but the share of total global publications has since increased and stabilized to around 8%. This phenomenon may be closely related to China's policies to promote the development of the VR industry, increase the homogeneity of residency and specialized training, and improve the assessment system for residency and specialized training since around 2016. These policies include but are not limited to *the outline of the* 13th *Five-year Plan for National Economic and Social Development of the People's Republic of China* (2016–2020) in 2016, *Virtual Reality Industry Development White Paper 5.0* in 2016, *Guidance on Promoting Co-construction and Sharing of Public Training Bases* in 2020, *Residency standardized training assessment implementation methods (for trial implementation)* in 2015 and *Guidance on the pilot of the standardized training system for specialist physicians* in 2016. With the dual policy support of vigorously pursuing standardized medical training and developing the technology industry, it is reasonable to predict that there is still room for further upside in the development of XR applications in surgical training in China.

In order to get a comprehensive picture of developments in a field is to identify which institutions and authors have made outstanding contributions to the field. We have found five clusters were prominent: pink, light blue, yellow, orange, and purple clusters. The XR-related studies in these five clusters all involved laparoscopic surgery [15–17] and orthopedic surgery [18,19], yet all had their own unique research directions. For example, the pink cluster, with the University of Toronto, the institution with the highest intensity of international collaboration, at its core, has conducted XR-based training in endoscopy [20], ophthalmology [21],

Table 10
The top 10 productive authors and authors with the largest cooperation intensity in China.

Rank	Author	Number of publications	Institution	Rank	Co-authorship author	Total link strength	Institution
1	Chen XJ	8	Shanghai Jiao Tong University	1	Tai YH	48	Yunnan Normal University
1	Tai YH	8	Yunnan Normal University	2	Shi JS	43	Yunnan Normal University
2	Li Q	7	Yunnan Normal University	3	Li Q	42	Yunnan Normal University
2	Shi JS	7	Yunnan Normal University	4	Chen Y	33	Chinese Academy of Medical Sciences Peking Union Medical College
3	Lin YP	6	Shanghai Jiao Tong University	5	Fu X	33	Chinese Academy of Medical Sciences Peking Union Medical College
3	Pan JJ	6	Beihang University	6	Liu JF	33	Chinese Academy of Medical Sciences Peking Union Medical College
4	Li ZY	5	Shanghai University	7	Niu F	33	Chinese Academy of Medical Sciences Peking Union Medical College
4	Heng PA	5	Chinese University of Hong Kong	8	Qiao J	33	Chinese Academy of Medical Sciences Peking Union Medical College
4	Guo SX	5	Beijing Institute of Technology	9	Xu SX	33	Chinese Academy of Medical Sciences Peking Union Medical College
4	Hao AM	5	Beihang University	10	Hao AM	26	Beihang University
4	Tsai MD	5	Chung Yuan Christian University	10	Wei L	26	Deakin University

Table 11
The top 10 journals that published the largest number of papers in China.

Rank	Journal	Number of publications	2021IF
1	International Journal of Medical Robotics and Computer Assisted Surgery	9	2.483
2	Surgical Endoscopy and Other Intervention Techniques	7	3.453
3	International Journal of Computer Assisted Radiology and Surgery	5	3.421
4	Journal of Medical Systems	5	4.920
5	World Neurosurgery	5	2.210
6	Computer Methods and Programs in Biomedicine	4	7.027
7	Computers in Biology and Medicine	4	6.698
8	European of Dental Education	4	2.528
9	Journal of Healthcare Engineering	4	3.822
10	Plos One	4	3.752

neurosurgery [22] and urology [23]; the light blue cluster, with Imperial College of Science, Technology and Medicine, University of London, the institution with the sixth highest intensity of international collaboration, as the central institution, also focuses on XR-based colonoscopy training [24] and endovascular procedures [25]; the yellow cluster, with University of Washington, the institution with the second highest intensity of international collaboration, as the core, also conducts XR-based dermatologic surgery training [26], endoscopy training [27], and urology training [28]; the orange Cluster, with the Rigshospitalet, the institution with the second highest intensity of international collaboration at its core, also studies XR-based endovascular surgery [29], virtual ultrasound training [30], hysteroscopy training [31], thoracoscopic surgery [32], otolaryngology surgery [33] and ophthalmology surgery training [34]; and the purple cluster, with Catharina hospital, the fifth highest intensity of international collaboration, at its core, has also conducted studies related to XR-based colonoscopy training [35] and endourological skills training [36]. Current data demonstrated that the collaboration among Chinese institutions and international institutions has great upside space.

Study of author collaboration networks, collaborative groups and research concerns, are able to provide guidance for the readers in future research. According to our data, there are sixteen research clusters with slightly different research directions from an international perspective. For example, the researches of Aggarwal R et al.'s collaborative team (pink cluster in Fig. 2C) mainly involved the course construction of XR trainer-based ophthalmology training [37], colonoscopy training [24], laparoscopic cholecystectomy [38], endovascular techniques [39]; the work of Konge et al.'s (ranked 1st in total cooperation intensity) collaborative team (green cluster in Fig. 2C) was focused on the XR-based thoracoscopic surgery [40]; Ahmed et al.'s (ranked 2nd in total cooperation intensity) collaborative team (light blue cluster in Fig. 2C) focuses on XR-based training for robotic surgery [41], endovascular surgery [42], and endoscopic surgery [43]; the collaborative team of De et al. (ranked fifth in total collaboration intensity) (purple cluster in Fig. 2C) focuses on the construction and validation of an XR-based laparoscopic simulator [44], electrosurgery skill simulator [45], endoscopic surgical trainer [46] and suturing simulator [47]. In the case of China, there are now eight clusters of closely related scholars. However, after reviewing the studies of these scholars, it is found that despite the various directions involved, including XR-based training in laparoscopic rectum surgery [48], XR in neurosurgical navigation [49], and XR-based ultrasound-guided renal biopsy training [50],

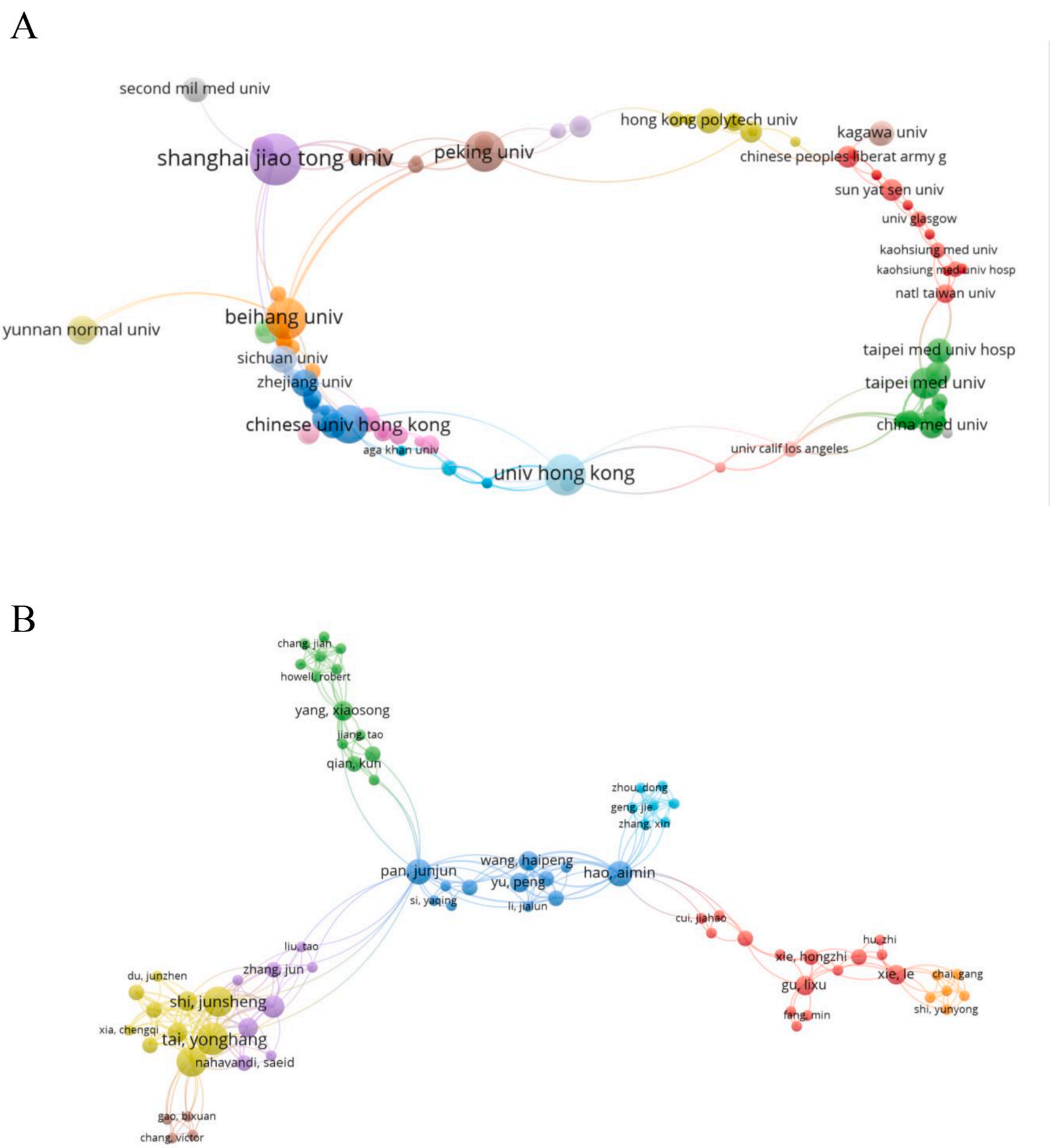

Fig. 3. The collaboration analysis of Chinese institutions and scholars in this field. **A.** The collaboration network of institutions. Twenty cooperation clusters with different colors were formed with the total link strength of 564. **B.** The collaboration network of scholars. Eight cooperation clusters with different colors were formed with the total link strength of 361.

there is still a lack of research on the full curriculum system of surgical skills training based on XR, which may be the content that domestic scholars are investing in or need to pay attention to.

Co-citation analysis and burst detection can provide the intellectual base and research frontier of a certain area. According to the results of co-citation analysis of references, five research contents have received much attention in recent years: augmented reality (Cluster #1, 2020), orthopedic surgery resident (Cluster #5, 2017), cataract surgery training (Cluster #6, 2016), study protocol (Cluster #14, 2017), and intraoperative use (Cluster #15, 2022).

4.1. Development of AR in surgical training

The application of AR in surgical skills training is in its infancy, but its development is very rapid, because it has advantages such as provide real immersive experience and help trainees understand spatial information [51]. A few years ago, AR was used in a very

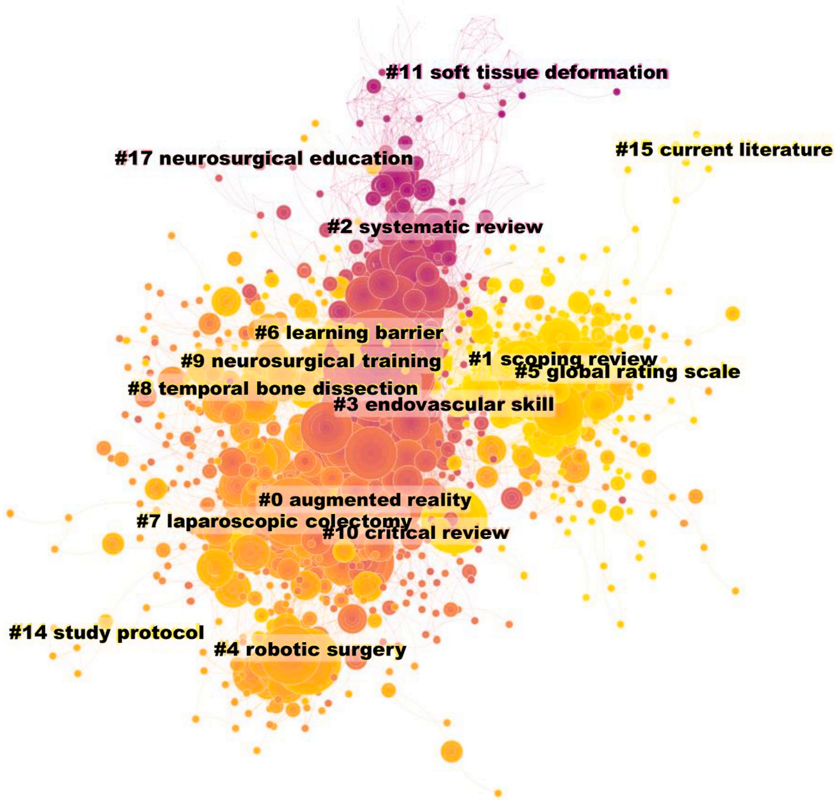

Fig. 4. The analysis of co-citation references of the publications around the world in this field. Fifteen clusters with different research topics were formed, reflecting in different colors in map. The line between the nodes reflected the co-citation relationship between the two studies, and the size of the node meant the number of the co-cited times.

limited number of surgical areas, mainly laparoscopic surgical training and neurosurgical procedures, and fewer AR devices were used (the ProMIS Augmented Reality Simulator™, a laparoscopic simulator, the Perk Station, the Immersive Touch®, a Mixed Reality Ventriculostomy Simulator) [51]. In recent years, the application areas of AR have expanded rapidly, especially in orthopedic surgery [52,53]. However, AR has not yet demonstrated significant advantages in skill or knowledge retention compared to traditional training or VR for the time being. Therefore, the effectiveness of AR needs to be further confirmed before it can be fully applied to surgical training, and the high price is also a factor to be considered [52].

4.1.1. *Current situation and prospect of orthopedic surgery*

Despite numerous international associations (American College of Surgeons, American Academy of Orthopedic Surgeons, and Accreditation Council for Graduate Medical Education, etc) highly recommending the use of virtual simulators for training outside the operating room, orthopedics was still a late adopter in integrating XR into the training system compared to other surgical departments such as general surgery [54]. Our data demonstrated that virtual simulator-based orthopedic surgical training is one of the hot research directions in recent years, following the research path of first proving the validity of the simulator before its wide application to the clinic. The study by Cannon et al. found that the transfer validity of simulators in the orthopedic field has been less studied compared to construct validity, which would significantly hinder their clinical application [55]. They then conducted a randomized controlled trial to remedy this deficiency, and in addition to demonstrating that trainees trained in the virtual simulator (ArthroSim virtual-reality arthroscopic knee simulator) have higher surgical skills in the operating room than traditionally trained trainees, they pointed out that validation metrics needed to be further determined and finalized, such as time, proprietary global rating scale or a visualization rating scale [55]. Confirmation of transfer validity remains a step that needs further refinement in all virtual simulator-related studies.

In the recent decade, several virtual orthopedic simulators have emerged, such as insight ARTHRO VR Shoulder Simulator, Procedicus Virtual Reality Knee Trainer, Sawbones Knee Simulator, Touch Surgery VR Platform App, and ArthroSim VR Knee Simulator [56]. Notably, these simulators are predominantly arthroscopic simulators, with relatively fewer simulators for other orthopedic aspects such as fracture fixation and orthopedic drilling simulation [56]. In addition, evidence on the concurrent validity of these simulators is still lacking compared to construct validity and learning curve progression evidence, which requires further attention to confirm the superiority of these simulators over other training models [56].

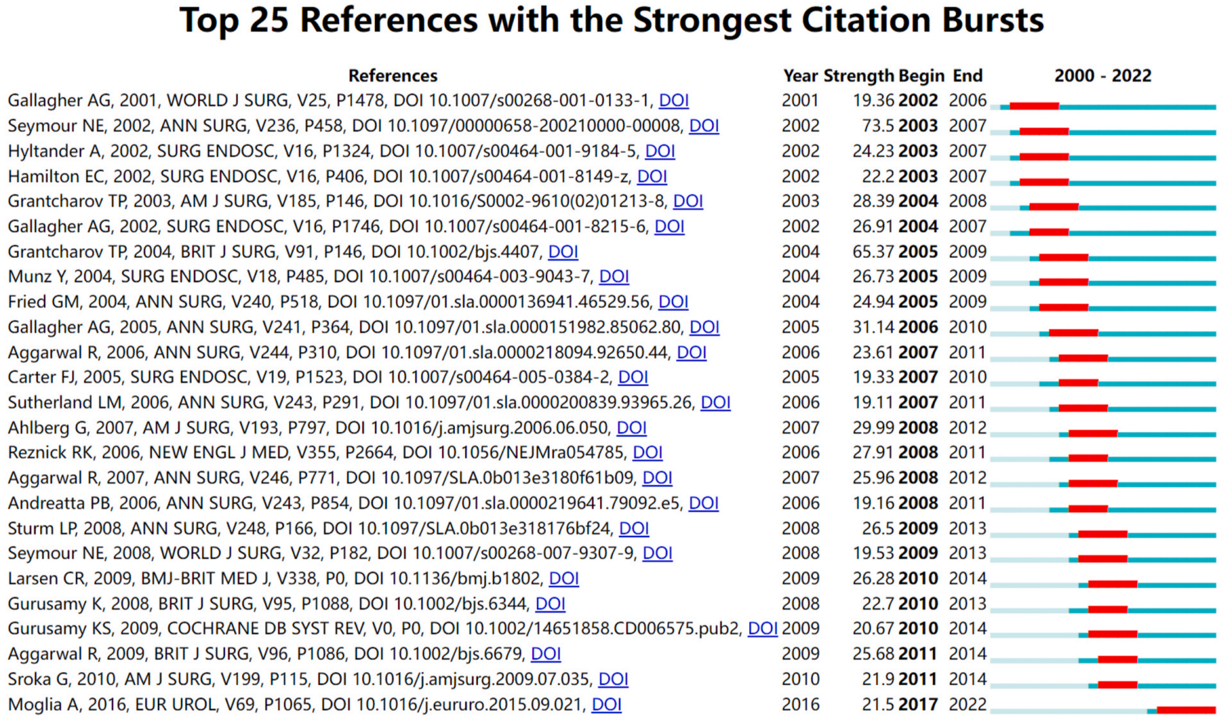

Fig. 5. The top 25 references with the strongest citation bursts from the publications around the world. "Begin" referred to the year the reference began to have citation burst, "end" referred to the year the reference ended the citation burst, red line was the duration of citation burst, and "strength" referred to the intensity of its citation burst.

4.1.2. *Current situation and prospect of cataract surgery*

Cataract is the leading cause of blindness and vision impairment in the world, and the only effective treatment is surgical removal. As the world's elderly population increases, the volume of cataract surgery continues to grow and ophthalmologists urgently need to be trained, making cataract surgery the ophthalmic procedure with the most applications of virtual technology training [34]. Thomsen et al.'s study, the most cited study in Cluster #6, found that surgeons at different levels, particularly novice and intermediate surgeons (less than 75 procedures on patients), could benefit from proficiency-based training with the VR simulator (EyeSi) [34]. They further suggested that building a virtual technology-based cataract training curriculum may benefit ophthalmologists and patients after clarifying the level of trainees, expanding the sample size, reducing assessment bias, and standardizing training cases [34]. The study that cited the most papers in cluster 6 was also Thomsen et al.'s study, in which they systematically analyzed the virtual technology-based cataract surgery training situation, noting that performance on the EyeSi simulator was highly correlated with real-life surgery performance, and that virtual-based cataract skills training was transferable to the clinic but not significantly to other procedures [57].

In particular, it is important to note that the value of virtual technology-based training in cataract surgery remains inconclusive due to the heterogeneity among studies, a common challenge for virtual technology-based training [34]. Nevertheless, cataract surgery remains a priority area for virtual technology in ophthalmic surgery, and identifying the optimal trainee level for virtual training, confirming the strength of the link between training and clinical outcomes, and refining training content are the next research priorities [57].

4.1.3. *Study protocol*

After analyzing the top 5 cited and citing references, we found that the main focus of cluster #14 (study protocol) was on laparoscopic surgery training. In recent years, with the increasing proportion of laparoscopic surgery in surgical area, corresponding training programs have been gradually established to ensure that surgeons are fully equipped with laparoscopic skills before performing surgery on patients [58]. Virtual technology has received much attention as an important type of training method, but so far no standardized study protocol has been established and lots of details still need to be explored. Yiannakopoulou et al. noted that VR simulation training provides an alternative means of improving performance in laparoscopic surgery and that future research efforts should focus on the impact of VR simulation on advanced surgical performance, standardization of training, the potential for synergistic effects in combination with mental training, and individualized training to construct more comprehensive study protocols [59]. Nickel et al. also explored through several studies the factors that may need to be considered in constructing efficient study protocols for virtual laparoscopic surgery training, including but not limited to the use of single-person practice or two-person practice together, the need to utilize video for assessment in training, and whether there is additional value in adding VR to multimodal training

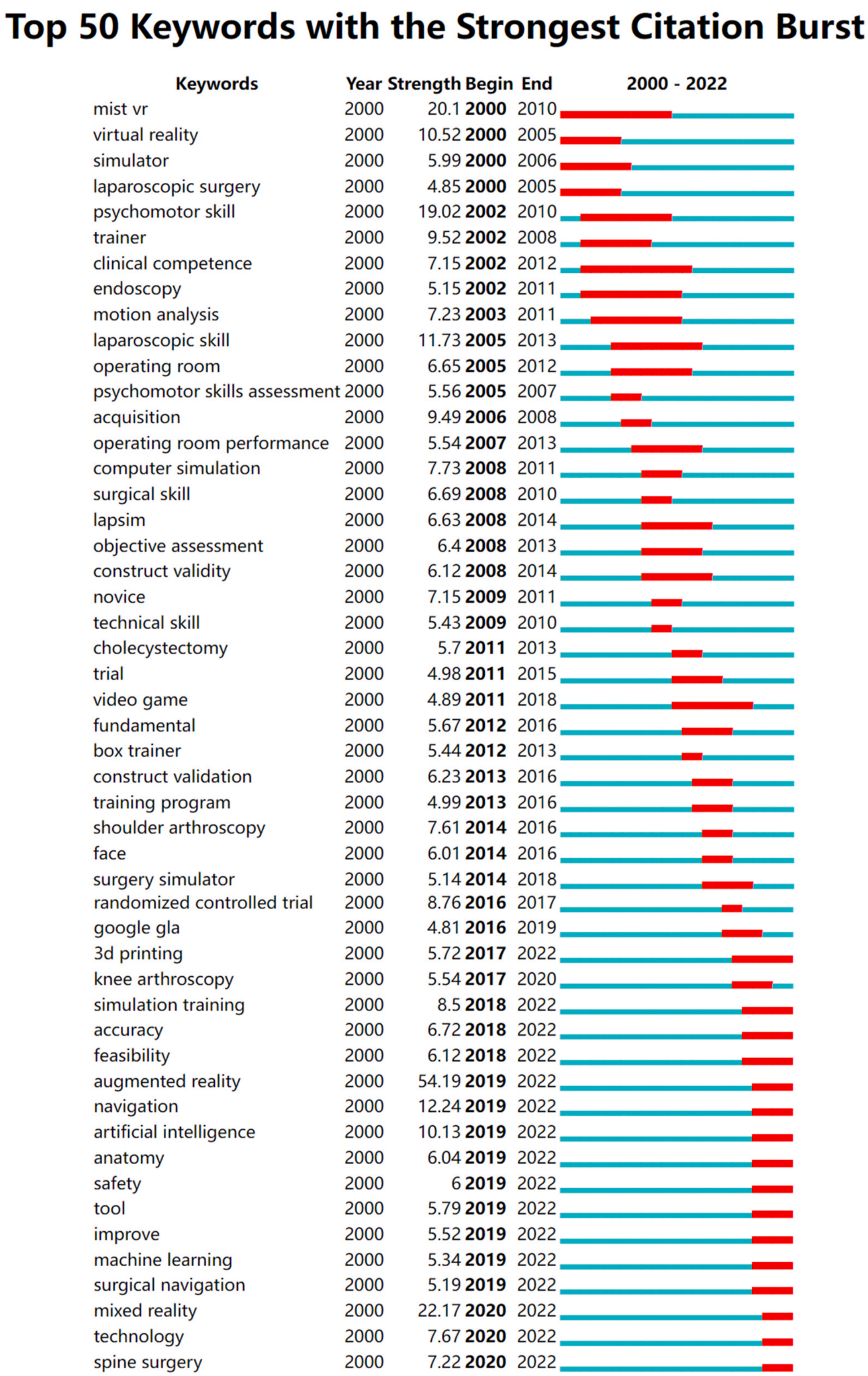

Fig. 6. The top 50 keywords with the strongest citation bursts from the publications around the world. "Begin" referred to the year the keyword began to have citation burst, "end" referred to the year the keyword ended the citation burst, red line was the duration of citation burst, and "strength" referred to the intensity of its citation burst.

[58,60,61]. Other researchers are also active in establishing and developing study protocols, such as the sensor and expert model-based laparoscopic training system "iSurgeon" developed and initially validated by Kowalewski et al. [62], and the study conducted by De La Garza on whether the learning curve during VR training was more satisfactory for students who rated the videos with a checklist during E-learning [63].

4.1.4. Intraoperative use

Cluster #15 (intraoperative use) is a recently formed cluster that focuses on the value of virtual technologies, particularly AR, in intraoperative use. Surgical procedures, especially neurosurgery, require the operator to have a clear understanding of the spatial relationship between the target anatomy, the structures at risk and the surgical instruments in order to avoid unnecessary mishaps or inadvertent injuries to vascular or neural structures [64]. Neurosurgery was the first surgical department to apply computer technology to intraoperative navigation and still holds the largest share of the surgical navigator market. However, traditional navigators require surgeons to constantly switch between surgical scenes and monitors, affecting surgical efficiency and judgment [64]. AR technology can reduce the cognitive load by blending virtual and real surgical scenes, and may become the next generation of surgical navigation, but existing AR devices (i.e., Optical See-Through AR headset) often have problems such as inaccurate surgical navigation and low contrast, which need to be further optimized. Based on our findings, several studies have been exploring more clinically applicable AR devices, such as wearable AR (VOSTARS), and the application area remains predominantly neurosurgery. This novel type of AR can further reduce visualization errors in anatomical structures and positioning compared to traditional virtual devices (e.g., Microsoft HoloLens®), thus allowing effective tracking of surgical trajectories and accurate assessment of surgical precision, making it a powerful assistant for tumor resection, craniotomy, and skull base surgery [65].

4.1.5. Burst detection

Among the top 50 keywords that have or had the strongest citation bursts, four surgical-related contents are still in the burst state, which was complementary to the above-mentioned direction of the study of co-cited and -citing references, especially for orthopedics and intraoperative use. At the same time, there is an urgent need for further research on the related aspects of simulation teaching or virtual technology, including patient safety, feasibility and accuracy of simulators, which to a large extent requires the cooperation and joint efforts of multi-disciplinary scholars. The keyword of surgical specialties with the strongest citation bursts had not been extracted from the keywords in the Chinese publications.

It is also noted that although XR has obvious technical and application advantages over traditional training methods, its technical disadvantages and application limitations cannot be ignored, which mainly include: the high financial burden, the lack of training standards and sufficient evidence that training results of XR translate into clinical practice. However, it is precisely because the future is promising and the current development is incomplete that more and more scholars are devoting themselves to this field. It is worth noting that because of the various technical means and characteristics of XR and the different applications in different surgical method training fields, the current research is scattered and not systematic, which is not conducive for novices to enter this field, which is also one of the significances of our article.

4.1.6. Limitations

Present work is the first bibliometric analysis attempt to describe the prospect of extended reality (XR) being integrated with surgical training, the data of our bibliometric analysis contributes better understand of the field, especially provide valuable insights of the development trajectory and research directions since the 21st century. Despite the findings, this study has some limitations [1]: We retrieved the literatures only from WoSCC, and other database such as PubMed and Scopus were not included; we chose WoSCC because it is considered to be a rigorous and reliable representation of literature and citations that facilitate the analysis of articles and related information [2,12] the collaboration and productivity of countries, institutions, and authors does not necessarily correspond to the quality of the research [3]; while bibliometrics can provide insights into the direction of the field, such predictions are dynamic and only short-term [4]; we only selected the articles and reviews for full text information, and some genres such as conference articles were not included, which may contain unpublished research results.

5. Conclusion

Present work is the first bibliometric analysis attempt to describe the prospect of extended reality (XR) being integrated with surgical training, the data contributes better understand of the field, especially provide valuable insights of the development trajectory and research directions since the 21st century. There is strong enthusiasm and cooperation in the international research on the XR-based surgical training. China had a late start, Chinese scholars are making steady progress and have great potential in this area. Although the research publication growth has accelerated since around 2016 due to the reform of the medical postgraduate education system and the rapid development of Chinese information technology in China, there has not been noted an explosive research phase yet in the Chinese pace. There is great upside space for Chinese institutions and scholars to strengthening international and domestic cooperation. The research on several surgical specialties has been summarized at the very first time and AR will gradually to be more involved and take important role of the research.

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CRediT authorship contribution statement

Wei Li: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Siyuan Ma:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Lei Zhou:** Writing – review & editing, Formal analysis, Data curation. **Lars Konge:** Supervision. **Junjun Pan:** Writing – review & editing. **Jialiang Hui:** Software, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e27340.

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