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Bibliometric analysis of transforaminal lumbar interbody fusion: research status, trends, and future directions

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- *Purpose:* Transforaminal lumbar interbody fusion (TLIF) is a classic surgical procedure for posterior lumbar fusion. This study aims to analyze the TLIF field by bibliometric method and comprehensively summarize the research status and trends.
- *Methods:* All TLIF-related articles were retrieved from the Web of Science. The data were analyzed using R software and SPSS to calculate corresponding indicators. Visualizations were drawn using VOSviewer and Scimago Graphica, including country, institution, journal, author, and keywords.
- *Results:* A total of 919 articles were included. The annual publication volume of TLIF-related articles presented an exponential growth. North America, Europe, and Asia were the main sources of articles, with the USA and China being the main contributors and the USA being the global research center for TLIF. The level of the national economy was an important factor affecting TLIF-related research. The highest number of contributions in this field was made by Kern Singh among authors and by Rush University among institutions. The *European Spine Journal* was the most influential journal. The research focus has gradually shifted from perfecting the TLIF technique toward emphasizing the patient level. The improvement of minimally invasive techniques and how to improve clinical outcomes as well as accelerate postoperative rehabilitation of patients may be the hot spot of future research.
- *Conclusions:* With the advancement of medical technology and the popularization of minimally invasive concepts in recent years, TLIF and its derivative technologies have attracted increasing attention. Patient-centered minimally invasive surgery is a hot research topic in the field of TLIF currently and will continue to be so into the future

Keywords

- transforaminal lumbar interbody fusion
- TLIF
- bibliometric analysis
- Web of Science
- knowledge structure

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Introduction

Lumbar interbody fusion (LIF) is an effective procedure for treating lumbar disorders, including degenerative disease, trauma, infection, and tumors (1). Based on the different surgical approaches, LIF can be roughly classified into five main branches: posterior approaches of posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF), anterior approaches of anterior lumbar interbody fusion (ALIF), extreme/direct lateral interbody fusion (XLIF/DLIF), and oblique lateral interbody fusion (OLIF). Both anterior and posterior LIF procedures involve removing the intervertebral disc, inserting interbody cage and graft materials, as well as internal fixation between the vertebral bodies. Previous studies have shown that both approaches can achieve satisfactory fusion rates with similar clinical outcomes (2). However, the advantages and disadvantages of different approaches to LIF are not equal. For example, the classic anterior approach of ALIF and the lateral approach of OLIF have the advantages of direct access to the intervertebral disc, without disturbing the spinal canal. Surgeons can handle the disc under direct vision and place larger interbody cages, resulting in better restoration of disc height and lumbar

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lordosis. However, those approaches require familiarity with abdominal anatomy. The risks of complications associated with the approaches, such as injury to major vessels, incisional hernias, and retrograde ejaculation, are significantly higher than posterior approaches, and the learning curves are steeper. Furthermore, both anterior and lateral interbody fusion are indirect decompression, which may result in a risk of incomplete decompression for radiculopathy caused by disc herniation and severe spinal stenosis, limiting the indications for surgery. In contrast, surgeons are more familiar with the posterior anatomy, resulting in the learning curve being relatively flat, which provides advantages in reducing operation time and hospital stay. Moreover, posterior surgery provides direct decompression and has a wider range of indications. However, due to its requiring entry into the spinal canal, the risk of dural injury is relatively higher, and the ability to correct sagittal imbalance and restore lumbar lordosis is inferior to anterior or lateral surgery (3, 4).

Since Harms *et al.* first reported in 1982, TLIF has gradually become one of the classic surgical procedures for posterior lumbar fusion with its reliable safety and effectiveness, and has achieved significant clinical outcomes. Compared to PLIF, TLIF can preserve the contralateral posterior column structure and reduce soft tissue injury, resulting in a smaller impact on the spinal biomechanical stability and thus favoring patients' postoperative rehabilitation. In recent years, the number of TLIF procedures has significantly increased globally, which may be attributed to the development of TLIF driven by advances in surgical techniques and medical devices, as well as the increasing incidence of degenerative lumbar diseases caused by aging population (5). Currently, numerous scholars have conducted in-depth research on the safety, effectiveness, and clinical outcomes of TLIF and its derivative procedures, and have published lots of high-quality articles. However, in view of the steep learning curve of the TLIF, particularly the minimally invasive TLIFs that have emerged in recent years, beginners often require significant learning investment during the initial learning phase. Meanwhile, in recent years, due to the rapid development of nonfusion minimally invasive spine surgeries represented by transforaminal endoscopy, and other technologies such as ALIF and OLIF, it remains to be seen whether the development direction and research hot spots of TLIF have changed.

Bibliometric analysis is a quantitative method for analyzing published literature, which is an effective tool for evaluating the current state and prospects of research in a specific field. In the field of TLIF, bibliometric analysis can provide an in-depth understanding of the basic knowledge structure, including the authors, countries, institutions, journals, hot topics and trends of research.

This study is the first to employ the bibliometric method to analyze the TLIF field, providing a comprehensive overview of the current research status in this area. It highlights the main research hot spots and clarifies the future research directions, aiming to provide assistance to researchers and surgeons, especially beginners, in quickly getting started in this field.

Materials and methods

Search strategy

All the data for this study was retrieved from the Web of Science Core Collection (WoSCC) database. The search keywords were identified as 'Transforaminal Lumbar Interbody Fusion OR TLIF' with the article type limited to 'Article' or 'Review' and the language restricted to English, with no restrictions on the publication date.

Tools

The data was processed and analyzed using R software, VOSviewer, Scimago Graphica, IBM SPSS Statistics 26, and Microsoft Excel 2016. The bibliometrix package in R software was used for statistical analysis and calculation of relevant impact indicators such as citation frequency, *H*-index, and *G*-index. VOSviewer is a data analysis and visualization tool based on the Java platform, commonly used for bibliometric data analysis and graphical visualization. Similarly, Scimago Graphica can also be used for graphical visualization and complements VOSviewer. We used the above software to conduct bibliometric analysis and visualizations of year, country, institution, journal, author, and keyword.

Data extraction

The search was conducted on February 16, 2023. Two authors independently verified the search results, removed any irrelevant ones, and discussed any discrepancies until a consensus was reached. A total number of 919 articles were included, and the publication year, country, institution, journal, author, keywords, as well as citation frequency were extracted and recorded for further analysis (Fig. 1).

Results

Publication trend

A total of 919 TLIF-related articles were identified from the WoSCC database, consisting of 847 Original Articles and 72 Reviews (Fig. 1). All articles were published between 2008 and 2023, and the annual publication volume showed an exponential growth (R^2 = 0.9713), with an average of 61 articles per year from 2008 to 2022.

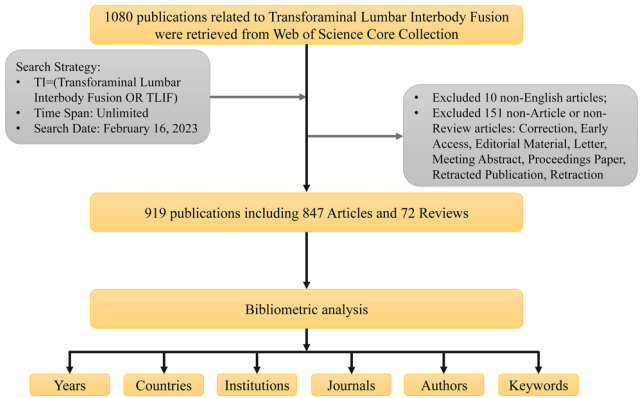

Figure 1
Flowchart of the screening process for TLIF-related publications.

The year 2013 saw the fastest year-on-year increase in publication volume (43%), while 2018 to 2022 were the top 5 years with the most publications, indicating that TLIF-related research has been attracting increasing attention in recent years (Fig. 2).

Country distribution

All articles were published from 46 different countries. China (339 articles; 3846 citations) and the USA (310 articles; 7282 citations) were the two countries that contributed the most to the TLIF field, accounting for 70.2% of the total number of articles and 69.3% of the total citations (Table 1). Coauthorship between countries was analyzed using VOSviewer and Scimago Graphica software. Lines indicated the existence of co-authorship between countries, and the thickness of the lines reflected the strength of cooperation. It was obvious that North America, Europe, and Asia were the main sources of

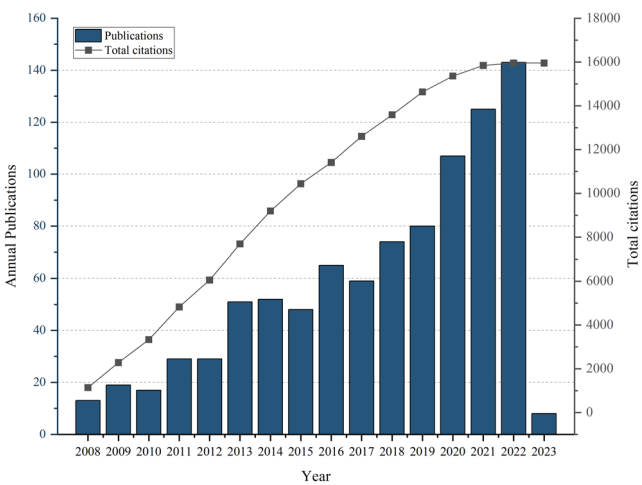

Figure 2
Trends in TLIF-related publications from 2008 to 2023.

TLIF-related articles from Fig. 3 and 4, and the USA was the global research center for TLIF which had close cooperation with China (Fig. 3 and 4). In addition, this study found a significant linear correlation between a country's publication output and GDP level ($R^2 = 0.953$, $P<0.01$).

Further analysis of annual publication output of each country revealed that the USA had been dominant in the field until 2021. In contrast, China experienced a relatively rapid growth period since 2015 (average annual growth rate from 2015 to 2022: China 26.0% vs the USA 17.2%) and surpassed the USA for the first time in 2021, becoming the country with the highest number of publications in the field (Fig. 5).

Institution distribution

In total, 907 institutions participated in the publication of TLIF-related articles. Figure 6 showed the top ten institutions in terms of publication volume. Among them, five institutions were in China (Army Medical University, Shanghai Jiao Tong University, Tongji University, Fudan University, and Shandong University), three in the USA (Rush University, University of Michigan, and Northwestern University), and the remaining two were in Singapore (Singapore General Hospital) and Japan (Yonsei University), respectively. In terms of publication volume, total citation frequency, and *H*-index, Rush University had an absolute advantage over other institutions and had become the most contributing institution in the field. In addition, the institution with the highest average citation frequency was Vanderbilt University (89.00 times; USA), followed by University of California San Francisco (46.50 times; USA) and Wooridul Spine Hospital (41.20 times; South Korea).

We used VOSviewer to construct a network visualization graph to analyze the co-authorship relationship between institutions (Fig. 7A). The same color represents the same cluster, and the thickness of the lines between institutions represents the strength of collaboration. University of California San Francisco, Norton Leatherman Spine Center, Duke University, etc., formed the main clusters and collaborated extensively with other institutions. The co-authorship strength between Singapore General Hospital and Mount Elizabeth Medical Centre was the strongest, indicating that the two institutions may have highly similar research directions. Overlay visualizations were constructed to analyze the changes of the major research institutions over time (Fig. 7B). Twin Cities Spine Center and Wooridul Spine Hospital were the main institutions conducting TLIF research in the early stages (around 2011), while Qingdao University, Chulalongkorn University, and Weill Cornell Medical College had become the primary force in recent years (around 2021). In addition, about 63% of

Table 1 Top ten countries in terms of publication volume.

Rank	Country	Publications	Total citations	Mean citations	*H*-index
1	China	339	3846	11.38	30
2	USA	310	7282	23.57	46
3	South Korea	60	1209	20.15	19
4	Japan	39	701	17.97	14
5	Singapore	22	559	25.41	9
6	Germany	21	266	12.67	10
7	India	14	165	11.79	7
8	Turkey	13	99	7.62	5
9	France	11	225	20.45	6
10	Australia	9	401	44.56	7

the major research institutions in recent years (marked in yellow or close to yellow) were affiliated with China, accounting for the rapid growth of China's publication volume in recent years. It was worth noting that among the institutions with more than five publications, most of institutions were located in Asia (43 institutions) or North America (26 institutions), except for Universidade do Porto in Europe.

Journal distribution

All articles related to TLIF were published in 127 academic journals. The top ten journals accounted for 50.6% of the total number of articles and 68.3% of the total citations (Table 2). The journal with the highest publication volume was *World Neurosurgery* ($n=109$), followed by *European Spine Journal* ($n=62$), *Spine* ($n=57$), *Journal of Neurosurgery: Spine* ($n=51$), and *Clinical Spine Surgery* ($n=51$). Although *World Neurosurgery* had a significantly higher publication volume than other journals, the journals with the highest total citations and *H*-index were *European Spine Journal* (1940 citations; *H*-index = 25), *Journal of Neurosurgery: Spine* (1811 citations; *H*-index = 22), and *Spine* (1741 citations; *H*-index = 23). Among the top ten journals mentioned above, *Neurosurgical Focus* (IF = 4.332) and *Spine Journal* (IF = 4.297) had the highest impact factor (IF) and were both located in JCR Q1.

The journals with more than ten articles were further analyzed by VOSviewer, and 24 journals were included. It was evident from the figure that *Frontiers In Surgery*, *Neurospine*, *Global Spine Journal*, and *Journal of Orthopaedic Surgery and Research* were the most prolific journals. Scholars who seek to stay abreast of the latest research developments in this field were encouraged to focus on these journals in particular (Fig. 8).

Author distribution

In total, 3730 authors participated in the publication of TLIF-related articles. Kern Singh, from Rush University in the USA, made the most outstanding contributions to this field and had published a cumulative total of 56 articles as corresponding author, followed by Zhou Yue, from Army Medical University in China, and Park Paul, from University of Michigan in the USA (Table 3). It was noteworthy that the authors with the highest *H*- and *G*-indexes were still Kern Singh, Zhou Yue, and Park Paul, indicating that they had significant influence in the TLIF field. Among the top ten authors in terms of publication volume, seven were from the USA, two

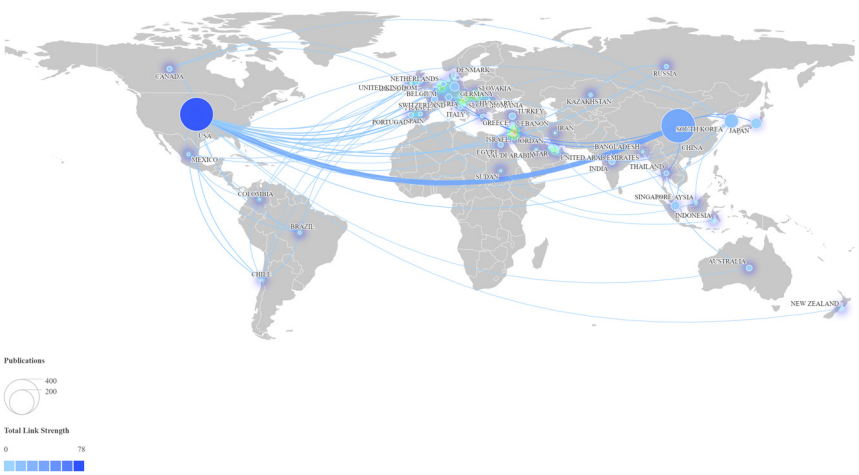

Figure 3
Contribution and co-authorship network of countries. The size of the nodes reflected the number of publications from each country.

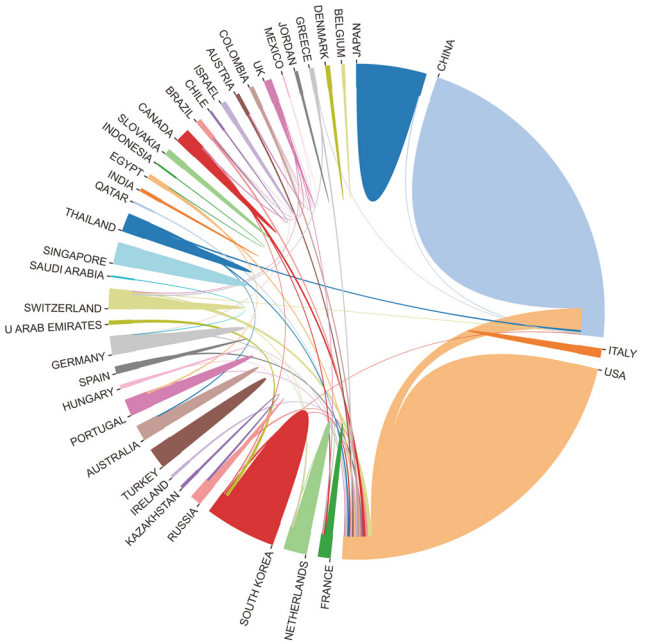

Figure 4
Network diagram of co-authorship between countries. The shape area represented the number of publications from each country.

from China, and one from South Korea. The density visualization constructed by VOSviewer showed that Kern Singh had the highest total link strength, indicating his extensive collaboration with other authors and absolute authority in this field (Fig. 9).

Highly cited literature

Table 4 provided detailed information on the top ten most cited articles in the TLIF field (Table 4). All articles

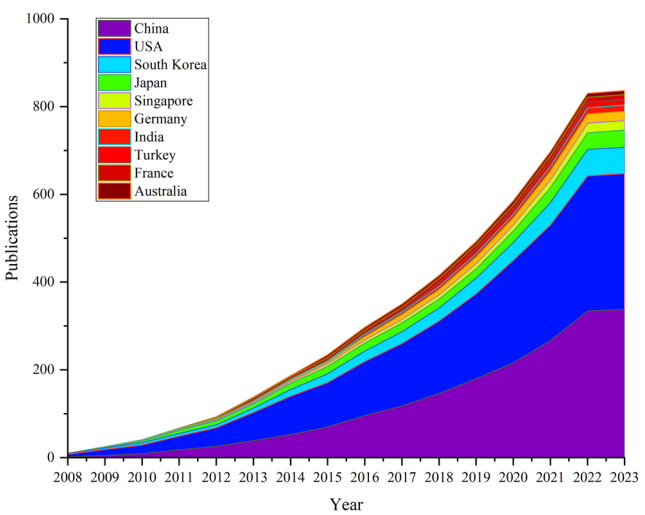

Figure 5
Annual number of publications in the top ten countries.

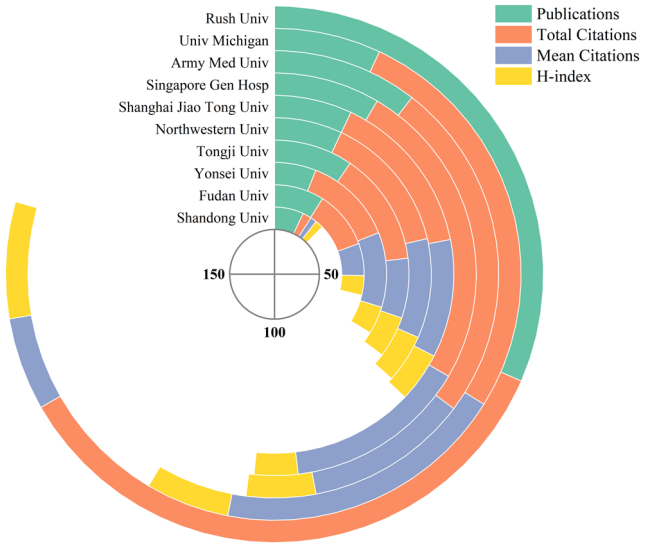

Figure 6
Contribution of the top ten institutions in terms of publication volume. The 'Total Citations' in the figure was calculated by dividing the actual value by 10.

were published around 2010, with citation frequencies ranging from 148 to 251. An analysis of the article themes revealed that minimally invasive TLIF was the primary direction of most research, with a comparison between minimally invasive TLIF and open TLIF being the most common research topic.

Keywords analysis and research interest

Keywords can reflect the research theme, while the evolution of high-frequency keywords can reveal the research hot spots and trends. By using VOSviewer to conduct a visual analysis of the keywords, with a minimum word frequency set to 10, a total of 149 high-frequency keywords were included for further analysis. All keywords were divided into six clusters, with the core keywords of each cluster being #1: 'outcomes', #2: 'tlif',' #3: 'anterior', #4: 'spondylolisthesis', #5: 'complications', and #6: 'pedicle screw' (Fig. 10A). According to the main research topics of clusters, they can be summarized into four categories – #1 and #4: Clinical Outcomes, #2 and #6: Surgical Technique, #3: Surgical Efficacy, and #5: Surgical Safety. It was evident from the figure that the TLIF technique itself and the efficacy of TLIF in treating lumbar disorders were hot research topics. In addition, we created overlay visualization to analyze the trend of research hot spots over time (Fig. 10B). 'Bone morphogenetic protein-2', 'reduction', and 'fixation' were high-frequency keywords in early studies (around 2014), indicating that the early focus of TLIF research was on the technique itself, including bone graft materials, internal fixation methods, surgical efficacy, and the

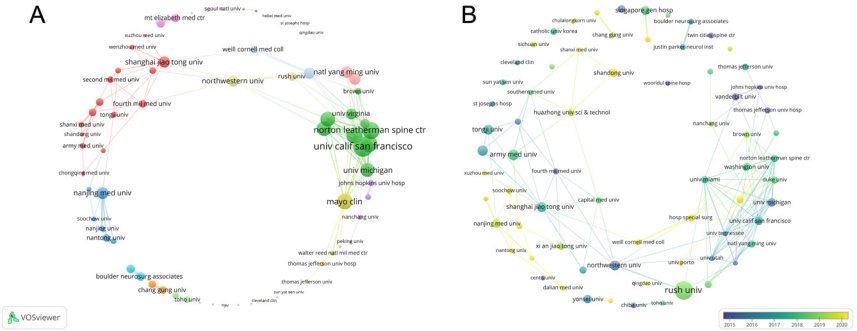

Figure 7
(A) Network visualization of institutional co-authorship. The size of the nodes indicated the total link strength of co-authorship with other institutions (B) Overlay visualization of institutions. The color of each node indicated the average publication year.

like. Of these, bone morphogenetic protein (BMP) was a popular direction in early studies. 'Patient-reported outcomes', 'endoscopy', and 'olif', on the other hand, have been the research hot spots in recent years (around 2020), which indicated that the focus of TLIF research may have gradually shifted from perfecting and developing TLIF technique to emphasizing outcomes at the patient level. Minimally invasive surgery and how to improve the clinical outcome of patients may be the focus of future research.

Discussion

TLIF was developed by Harms and Rolinger on the basis of PLIF to address the potential risks such as nerve root injury, dural tear, and epidural fibrosis associated with PLIF. It has been widely used in the treatment of lumbar degenerative diseases and has become one of the classic lumbar fusion surgeries (6). TLIF involves removing the unilateral superior together with inferior articular processes and utilizing the intervertebral foramen space to achieve nerve root decompression and interbody cage implantation. This technique achieves reconstruction of the three-column structure while reducing the damage to the posterior column and adjacent vertebral biomechanical stability (7). There is no significant difference in fusion rate compared to PLIF, while TLIF has the advantages of shorter operative time and lower incidence of complications (8). In recent years, with the popularization of minimally invasive concepts and the development of medical technology and devices, TLIF derivative techniques such as minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF), percutaneous endoscopic transforaminal lumbar interbody fusion (PETLIF), and robot-assisted minimally invasive TLIF have emerged. These techniques have achieved good clinical efficacy in reducing iatrogenic injury, shortening hospital stays as well as improving clinical satisfaction, and have shortened the postoperative rehabilitation process, which matches the concept of enhanced recovery after surgery (ERAS) in recent years.

In this study, TLIF-related articles included in the WoSCC from 2008 to 2023 were analyzed by bibliometric approach. We statistically analyzed the publications from various countries, institutions, journals, and authors, calculated the corresponding influence indicators, and constructed a visual graphic analysis of the research status and trends. The learning curve for TLIF and its derivative technologies is relatively steep, posing significant challenges for beginners and requiring a substantial investment of time. Therefore, this study aims to provide an intuitive and systematic understanding of the basic knowledge structure and major research hot spots in the TLIF field, guiding subsequent theoretical learning and clinical practice to enable faster proficiency in TLIF techniques. Additionally, the analysis of research hot spots can offer references for researchers when formulating research proposals.

Table 2 The top ten most productive journals.

Rank	Journal	Publications	Total citations	Mean citations	*H*-index	Impact factor	JCR partition	Country
1	*World Neurosurgery*	109	1291	11.84	20	2.21	Q3	USA
2	*European Spine Journal*	62	1940	31.29	25	2.721	Q2	USA
3	*Spine*	57	1741	30.54	23	3.241	Q2	USA
4	*Journal of Neurosurgery: Spine*	51	1811	35.51	22	3.467	Q2	USA
5	*Clinical Spine Surgery*	51	425	8.33	12	1.723	Q3	USA
6	*Spine Journal*	42	1462	34.81	20	4.297	Q1	USA
7	*Journal of Spinal Disorders & Techniques*	24	1005	41.88	18	N/A	N/A	USA
8	*Neurosurgical Focus*	24	771	32.13	16	4.332	Q1	USA
9	*BMC Musculoskeletal Disorders*	23	306	13.30	8	2.562	Q3	UK
10	*Global Spine Journal*	22	142	6.45	8	2.23	Q3	Germany

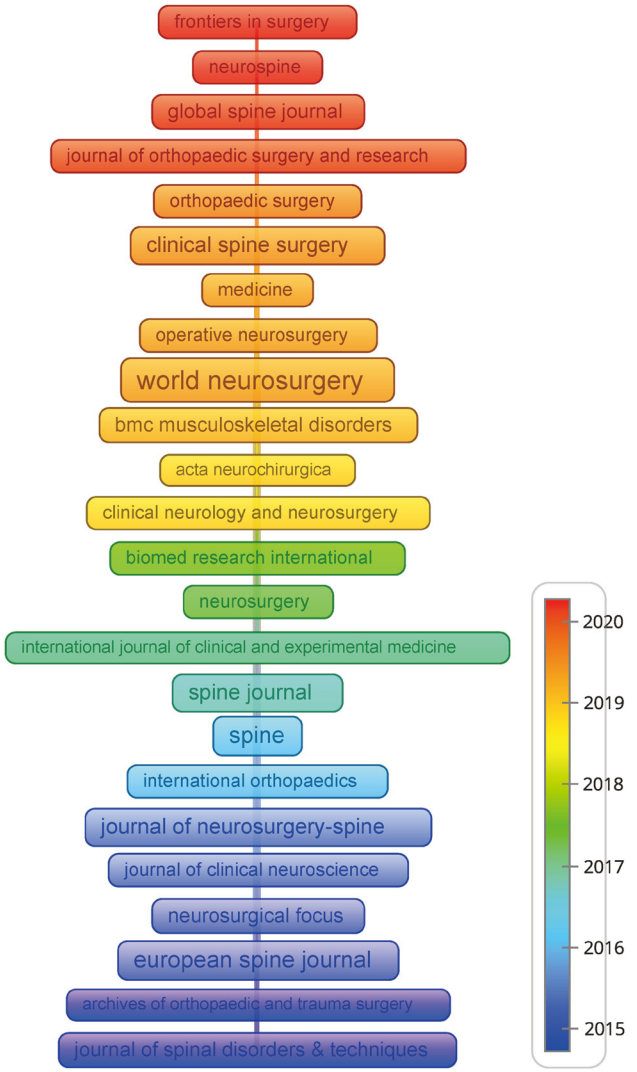

Figure 8
The evolution of major journals in the TLIF field over time. The color indicates the average publication year.

This study found an exponential increase in the number of TLIF-related publications since 2008 (Fig. 2), indicating that TLIF-related research has gained widespread attention among scholars in recent years. This may be related to the popularization of the minimally invasive concept and the development of medical devices and surgical techniques. As one of the classic procedures for lumbar interbody fusion, TLIF has been widely recognized by the medical profession for its good therapeutic effect and high safety (9). With the rapid popularization of the minimally invasive concept in recent years, more and more scholars focus on the combination of the minimally invasive concept with TLIF, aiming to minimize iatrogenic injuries as much as possible while ensuring clinical efficacy to accelerate the process of postoperative rehabilitation (10, 11). On this basis, TLIF-related publications continue to increase.

From the perspective of national contribution, both China and the USA far surpass other countries in terms of publication volume, total citations, and *H*-index, indicating that the two countries occupy a dominant position in the TLIF field (Table 1). Furthermore, China and the USA have engaged in close international cooperation, promoting their solid discourse power in the field (Fig. 3 and 4). This study found a significant positive correlation between national publication volume and GDP, with most articles published by high-GDP countries in North America, Europe, and Asia, indicating that TLIF research may be influenced by national economic levels. Actually, TLIF has been developed for more than 40 years since it was first proposed in 1982. However, limited by the development of medical materials and devices, MIS-TLIF was not formally proposed until 2002 (12). In recent years, popular lumbar interbody fusion techniques, such as PETLIF, OLIF, and robot-assisted MIS-TLIF, have relied on the innovation of medical equipment driven by scientific and technological progress. However, countries with low GDP invest far less in the medical field compared to high GDP countries, resulting in slower progress in medical research and insufficient training of senior researchers, which may also explain why most articles are published by high GDP countries (13). Additionally, Ravindra *et al.* conducted a meta-analysis on the global incidence of degenerative lumbar diseases (lumbar spondylolisthesis, disc degeneration, and lumbar

Table 3 The top ten most productive authors.

Author	Publications	Total citations	Mean citations	*H*-index	*G*-index	Institution	Country
Kern Singh	56	628	11.2	13	23	Rush University	USA
Yue Zhou	20	499	25	10	20	Army Medical University	China
Paul Park	17	586	34.5	12	17	University of Michigan	USA
Brittany E Haws	15	129	8.6	7	10	Rush University	USA
Benjamin Khechen	13	126	9.69	7	10	Rush University	USA
Jie Zhao	12	180	15	7	12	Shanghai Jiao Tong University	China
Nisheka N Vanjani	12	13	1.08	2	3	Rush University	USA
Michael Y Wang	11	562	51.1	8	11	Univ Miami	USA
Jin-Sung Kim	11	232	21.1	8	11	Catholic Univ Korea	South Korea
Richard G Fessler	11	170	15.5	7	11	Rush University	USA

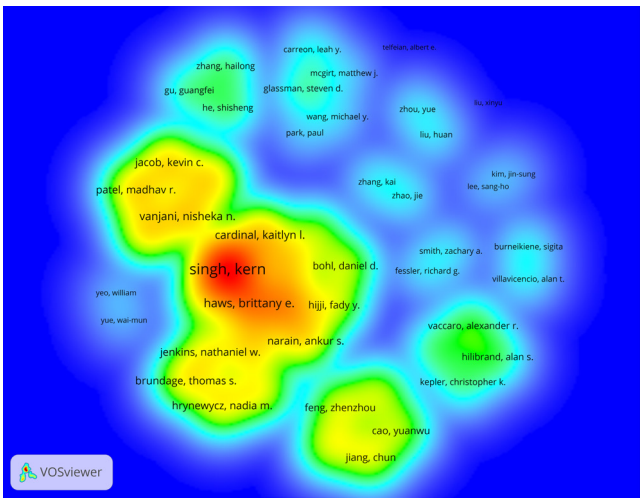

Figure 9
Density visualization of authors. Higher density means higher total link strength.

stenosis) and found that Europe together with North America had the highest incidence rates, while Western Pacific region (including China and Japan) had the highest case volume, which may have also contributed to the development of TLIF-related research in these regions (14).

It was evident from Fig. 6 that Rush University was the most influential institution in the TLIF field. Notably, the average publication years of the top ten most influential institutions listed in Fig. 6 were around 2017. For scholars interested in recent developments in TLIF research, it may be beneficial to focus on the primary research directions and publications of the institutions marked in yellow in Fig. 8. On the other hand, scholars seeking to learn classic articles or research findings may benefit from focusing on the institutions marked in purple. Furthermore, the majority of institutions contributing to the TLIF field were from Asia or North America, and institutions from other continents could enhance their cross-national cooperation to promote their development in the field.

The analysis of journals can evaluate the impact of the journal in the TLIF field, which can serve as one of the indicators for assessing the quality of articles as well as helping researchers to select suitable journals for their research findings. Among the top ten journals in terms of publication volume, *Neurosurgical Focus* and *Spine Journal* had the highest impact, indicating their high reputation and authority in the TLIF field. It was worth noting that the journals with the highest *H*-index were *European Spine Journal*, *Spine*, and *Journal of Neurosurgery: Spine*, which indicated that these three journals also had a significant influence in this field. Additionally, although East Asia was one of the main contributors to the TLIF field, there were few influential journals, and most of the high-impact journals were affiliated with the USA. Therefore, this study suggested that Asian countries can strengthen the development of international journals to further enhance their academic influence. Based on the overlay visualization of major journals (Fig. 8), it is apparently that *World Neurosurgery*, *Clinical Spine Surgery*, and *Global Spine Journal* were highly influential journals with a high publication volume in recent years, thus researchers can refer to this when selecting an appropriate journal for their TLIF-related research.

The analysis of authors can identify influential researchers and teams, which is helpful in promoting communication and cooperation among the authors. In addition, the viewpoints of high-impact authors may promote the research trend and provide powerful references for other researchers in developing research direction and plans. Kern Singh (Rush University, USA) had made the greatest contribution to the TLIF field, ranking first in terms of publication volume, *H*-index, and *G*-index, and had extensive and close cooperation with other authors (Table 3 and Fig. 9), indicating his

Table 4 The top ten most cited articles.

Authors	Year	Article Title	Total citations
Dhall *et al.* (51)	2008	Clinical and radiographic comparison of mini-open transforaminal lumbar interbody fusion with open transforaminal lumbar interbody fusion in 42 patients with long-term follow-up	251
Wong *et al.* (52)	2008	Neurologic impairment from ectopic bone in the lumbar canal: a potential complication of off-label PLIF/TLIF use of bone morphogenetic protein-2 (BMP-2)	242
Parker *et al.* (53)	2011	Utility of minimum clinically important difference in assessing pain, disability, and health state after transforaminal lumbar interbody fusion for degenerative lumbar spondylolisthesis	214
Rihn *et al.* (54)	2009	Complications associated with single-level transforaminal lumbar interbody fusion	192
Lee *et al.* (55)	2012	Clinical and radiological outcomes of open versus minimally invasive transforaminal lumbar interbody fusion	185
Shunwu *et al.* (56)	2010	Minimally Invasive Transforaminal Lumbar Interbody Fusion for the Treatment of Degenerative Lumbar Diseases	182
Schizas *et al.* (57)	2009	Minimally invasive versus open transforaminal lumbar interbody fusion: evaluating initial experience	177
Wang *et al.* (58)	2010	Comparison of one-level minimally invasive and open transforaminal lumbar interbody fusion in degenerative and isthmic spondylolisthesis grades 1 and 2	173
Seng *et al.* (59)	2013	Five-Year Outcomes of Minimally Invasive Versus Open Transforaminal Lumbar Interbody Fusion A Matched-Pair Comparison Study	165
Parker *et al.* (60)	2014	Minimally Invasive versus Open Transforaminal Lumbar Interbody Fusion for Degenerative Spondylolisthesis: Comparative Effectiveness and Cost-Utility Analysis	148

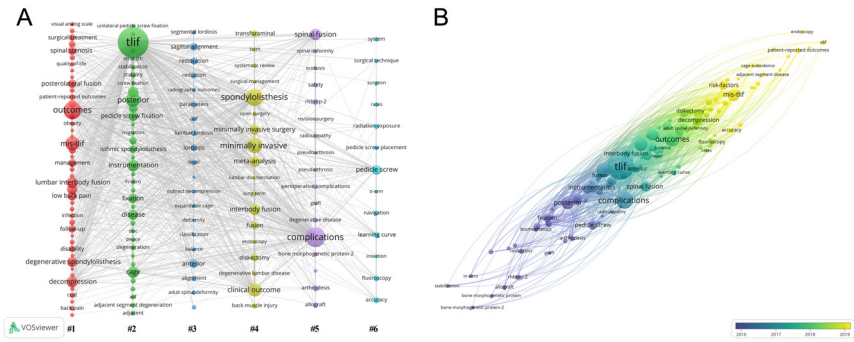

Figure 10

(A) Network visualization of keywords. Each cluster represented a sub-subject of the research, with node size indicating the frequency of the keyword occurrence. (B) Overlay visualization of keywords. The node color indicates the average publication year.

tremendous academic influence in TLIF field. Analysis of the latest research findings of Kern Singh and his team revealed that the influencing factors of clinical outcomes after TLIF together with the efficacy comparison between MIS-TLIF and ALIF were the main research directions of his team in recent years. This is consistent with the previous speculation that the research focus has shifted toward improving patient clinical outcomes. Kern Singh and his team found that hospitalized patients, patients with milder preoperative lower extremity pain and patients with shorter preoperative symptom duration may achieve better clinical outcomes (15, 16, 17). On the other hand, patients with severe preoperative disability, significant low back pain, low mental functioning, and higher degrees of obesity (BMI $\geq$ 30) tend to have worse clinical outcomes (18, 19, 20, 21). ASA (American Society of Anesthesiologists) classification, severity of comorbidities, time to surgery (TTS), and duration of symptoms (DOS) had no significant impact on patient clinical outcomes (22, 23, 24). Notably, contrary to previous research that considered advanced age as an independent risk factor for TLIF, Kern Singh *et al.* suggested that age may not be a significant risk factor affecting the success of MIS-TLIF, as long as appropriate surgical inclusion criteria were followed (25, 26). In addition, Kern Singh and his team compared the clinical outcomes of patients undergoing MIS-TLIF or ALIF for isthmic spondylolisthesis and revision, and found that ALIF only significantly increased operative time and intraoperative blood loss, whereas there was no significant difference in long-term clinical outcomes between the two procedures (27, 28). As representative procedures for anterior and posterior lumbar fusion, ALIF and TLIF have been widely used for the treatment of lumbar disorders. However, there were few prospective randomized controlled studies that compare the clinical efficacy of the two procedures (29). Previous studies had shown that there was no significant difference between ALIF and TLIF in terms of fusion rate, but ALIF had a significantly higher incidence of vascular injury and a lower incidence of dural injury than TLIF (2). In addition, ALIF had been considered to significantly restore disc height and achieve sufficient foramen indirect decompression (30). Different from previous studies that focused on clinical indicators such as fusion rate and complication rate, recent studies by Kern Singh *et al.* have focused on clinical outcomes, minimum clinically important difference (MCID), and other patient indicators, indicating a shift in their research focus from clinical to patient perspective, which may also be in line with the trend of TLIF research. As can be seen from Fig. 10, the collaboration between the author teams was mainly concentrated in the teams of Kern Singh, Nisheka Vanjani, Nathaniel Jenkins *et al.* It is recommended that other teams can strengthen cooperation to collectively promote the development of the TLIF field.

Keyword clusters can reflect the research topics and hot spots in the field. Since its initial proposal, TLIF has been continuously developed toward the direction of minimally invasive surgery under in-depth research and refinement by numerous scholars. Traditional open TLIF has a satisfactory fusion rate. However, like other posterior open surgeries, open TLIF requires extensive dissection and retraction of the paravertebral soft tissue, which can increase intraoperative blood loss and the risk of fusion disease (31). MIS-TLIF is a combination of traditional TLIF and minimally invasive techniques aiming to reduce iatrogenic injury, accelerate postoperative rehabilitation and improve clinical outcome (32). MIS-TLIF has been proved to achieve a similar fusion rate comparable to traditional TLIF, while preserving the physiological function of paravertebral soft tissues, reducing the incidence of postoperative low back pain, shortening hospital stay, and improving patient quality of life (33). In addition, MIS-TLIF has also been proved to be suitable for obese patients and can achieve the same clinical efficacy as patients with normal BMI (34). However, due to the limitations of small incisions, the placement of percutaneous pedicle screws often relies on repeated intraoperative fluoroscopy adjustments, significantly increasing the risk of radiation exposure to surgeons and patients (35). As one of the hot spots of TLIF research, there is still no consensus on the selection

of posterior internal fixation. Currently, there are four common methods of internal fixation: bilateral pedicle screw fixation (BPS), unilateral pedicle screw fixation (UPS), unilateral pedicle screw combined with contralateral translaminar facet joint screw fixation (UPS+TFS), and cortical bone trajectory (CBT) screw fixation. Among these, BPS is the most widely used single-segment fixation method in clinical practice, which can obtain rigid internal fixation on the three-column. However, the disadvantages of BPS include significant soft tissue injury during the screw placement, longer operation time, and increased risk of adjacent segment degeneration (ASD) due to the high stiffness of rigid internal fixation (36). UPS can simplify surgical procedures and reduce damage to the posterior column as well as adjacent vertebral bodies, but it is not sufficient to provide enough stability for the lumbar spine. After surgery, it can produce segmental off-axis movement and has a higher risk of cage migration and subsidence (37). To solve the shortcomings of these two internal fixation methods, researchers have innovated the UPS technique, aiming to increase its structural stability while retaining the advantages of UPS, thus UPS+TFS came into being. Compared with traditional BPS, UPS+TFS has more advantages in shortening operation time, reducing intraoperative blood loss and soft tissue injury, while its clinical efficacy and biomechanical stability are the same as BPS (38, 39). However, the long-term reliability of UPS+TFS is still lacking long-term follow-up verification, and the technique is cumbersome and requires higher surgical skills. Therefore, BPS is still the preferred method for posterior internal fixation. In recent years, with the rapid development of various TLIF auxiliary technologies such as O-arm fluoroscopy, navigation-assisted pedicle screw placement, and percutaneous pedicle screw fixation, the accuracy of pedicle screw insertion has significantly improved, which effectively saves operation time, reduces intraoperative radiation exposure, and is more conducive to the postoperative recovery (40, 41).

Since the first proposal of lumbar interbody fusion, autologous iliac crest bone graft (ICBG) has been regarded as the gold standard for interbody fusion. However, the iliac crest mainly consists of cancellous bone, which has inadequate resistance to pressure load and is prone to complications such as graft displacement and fusion failure, especially in patients with osteoporosis. Additionally, harvesting bone from the iliac crest requires a separate surgical incision, increasing the patient's burden and the risk of pain and infection at the donor site (42). Bone morphogenetic protein 2 (BMP-2), as a substitute for autologous iliac crest bone, has been widely used in clinical practice. Compared with ICBG, BMP-2 has advantages in improving fusion rate, reducing intraoperative blood loss, and shortening hospital stay, with no significant difference in the incidence of adverse events (43). However, high-dose BMP-2 significantly increases the risk of complications such as radiculitis and seroma (44). Furthermore, it is worth noting that previous studies have shown that BMP-2 may increase the risk of cancer, leading to catastrophic effects on patient prognosis (45). Further research is needed to explore the relationship between BMP and cancer. With the development of endoscopic techniques in recent years, PETLIF is gradually maturing and being applied in clinical practice. The advantages of PETLIF lie in the use of percutaneous endoscopic techniques via the Kambin triangle to achieve interbody fusion. Compared to MIS-TLIF, it has the benefits of less trauma, less blood loss, and shorter hospital stay, with no significant difference in fusion rate and clinical outcomes (46). Moreover, due to its minimally invasive nature, PETLIF has the potential to be performed under local anesthesia, allowing patients to remain conscious during surgery, thus enabling surgeons to obtain real-time feedback from patients and reducing the risk of nerve root injury (47). It can be said that the proposal of PETLIF is another big step in the minimally invasive road of TLIF. Like other minimally invasive techniques, PETLIF has a steep learning curve and requires higher surgical skills from the surgeon, making it challenging for beginners to master. Moreover, due to the limited space of Kambin triangle, PETLIF has higher requirements for the size and placement of the cage, requiring further development of surgical instruments. Meanwhile, with the improvement of endoscopic-assisted instruments, uniportal full endoscopic posterolateral transforaminal lumbar interbody fusion (endo-TLIF) and unilateral biportal endoscopic transforaminal lumbar interbody fusion (UBE-TLIF) have also been actively carried out. Although they have not yet become mainstream procedures, it remains to be seen whether they will replace MIS-TLIF or become a powerful supplement to MIS-TLIF in the future. Due to its respective advantages and disadvantages, anterior and posterior lumbar fusion has always been a hot spot in LIF research. As one of the representative minimally invasive procedures for anterior lumbar fusion, OLIF has been widely used in clinical practice since its first proposal in 2012 and has achieved satisfactory therapeutic effects (48). OLIF establishes a working channel between the retroperitoneal vascular sheath and the anterior border of the psoas muscle, reducing damage to the surrounding structures and obtaining a larger operating space, which results in a better indirect decompression effect than posterior lumbar fusion. A recent meta-analysis showed that OLIF could achieve similar clinical outcomes to MIS-TLIF, including disc height restoration,

hospital stay duration, visual analog scale (VAS) score, and Oswestry Disability Index (ODI) score, while having advantages in restoring lumbar lordosis and reducing intraoperative blood loss (49). However, OLIF has limitations of narrow indications and the inability to direct decompression. It should be noted that although there is no significant difference in complication rate between the two procedures, the main complications are not exactly the same, which may be attributed to different approaches.

Limitations

The main limitation of this study is that all data were obtained from the WoSCC database. As one of the most comprehensive and authoritative databases worldwide, WoSCC has been widely used in bibliometrics and is considered the optimal choice (50). However, we have found that some highly cited articles are not included in this database. Nonetheless, this does not affect our analysis of the TLIF field, as the work of individual authors may advance the research progress, but it does not have a qualitative impact on research trends. In addition, only English-language publications were included in this study, and influential non-English publications may have been omitted.

Conclusion

This study conducted a comprehensive bibliometric analysis of previous publications related to TLIF. The study has shown an exponential increase in TLIF-related publications, indicating that the relevant research was garnering increasing attention from experts and scholars. The USA and China had been the main contributors to this field, with the USA serving as the global research center for TLIF. The level of the national economy was an important factor affecting TLIF-related research. Professor Kern Singh and Rush University were the most prominent authors and institutions in this field, respectively. The *European Spine Journal* was the most influential journal in this field. The main focus of early research was to refine and develop the TLIF technique. With the growing popularity of minimally invasive concepts, the research focus had shifted toward patient-centered outcomes, and improving minimally invasive techniques, enhancing patient clinical outcomes, as well as accelerating postoperative rehabilitation may be the hot spots in future research.

Our study aims to help clinicians and researchers, especially beginners, understand the basic knowledge structure together with main research hot spots and trends in the TLIF field, providing a reference for their future mastery of TLIF techniques as well as development of related research proposals.

ICMJE Conflict of Interest Statement
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the study reported.

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