Bibliometric Analysis of the 100 Most Cited Articles on Intervertebral Disk Research
From 1900 to 2017 Year

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Study Design: A bibliometric review of the literature.

Object: To analyze and quantify the most frequently cited papers in intervertebral disk research.

Summary of Background Data: The number of citations that a paper has received reflects its impact in related research area. In the field of disk research, however, it remains unknown which papers are most cited. By searching related literature databases, we identified the most cited 100 articles that advanced the understanding of the intervertebral disk to provide a historic view of scientific research of the disk.

Materials and Methods: Intervertebral disk original research-related publications from January 1, 1900 to December 31, 2017 were retrieved from the Web of Science database. Each retrieved article was analyzed using the Cited Reference Search tool to identify the most cited articles. The number of citations, year of publication, publishing journal, authorship, country of publication, and the knowledge maps of keywords were gathered and generated.

Results: The number of citations of the 100 selected articles ranges from 209 to 1269, and they were published from 1953 to 2009. Basic research is the most common type of study (n = 60), followed by epidemiological study (n = 40). *Spine* published 57 of the most cited 100 papers. The greatest contribution came from the United States of America (n = 41), followed by the United Kingdom (n = 18) and Japan (n = 9). Frequently appearing keywords classified into 3 clusters: "biological study," "clinical study," and "imageological study." The keyword "degeneration" was mentioned the most, 51 items, and the word "development" was the latest hot spot in the most cited articles.

Conclusions: In the field of disk research, some papers were heavily cited more than 100 times, suggesting these studies have substantially contributed to the body of knowledge of the intervertebral disk and findings were widely accepted by related clinicians and scientists.

Key Words: bibliometric analysis, spine, disk degeneration

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Back pain is a global public health problem. Researches showed that the prevalence rates ranged from 12% to 35%, with about two thirds of adults suffering from back pain occasionally.[1] Currently, with the aging population increasing worldwide, the concern with back pain has been growing. Not only individuals and families are under tremendous pressure, but the society is also responsible for the problems.[2] Previous studies demonstrated that back pain was strongly associated with disk degeneration.[3] A great number of specialists and researchers have focused their efforts on intervertebral disk research, especially in the field of disk degeneration, trying to figure out the mechanism of disk degeneration as well as its risk factors. Therefore, a large number of articles have been published annually, which have given new insights into the biological or biomechanical characteristics of disk and disk degeneration. However, the quality of scientific papers remains unclear in this area.

It is commonly believed that publication represents the central part of a research process, while the times of an academic report cited by another author can serve as an academic reference for this article.[4,5] The article referenced by another peer-reviewed article receives a "citation." A citation can be described as an abbreviated alphanumeric expression contained in the body of an intellectual work that represents an entry in the references section of this work for the purpose of recognizing the contributions of the works of others to the topic of discussion in which the citation appears.[6] The purpose of the

citation is to acknowledge other authors for their important valuable work that they have previously published.[7] The reputation of an author can be proportional to the number of citations his or her published work receives.[8] Thus, the citation has always been regarded as a direct evaluation for how well an article is recognized in its research field. Citation analysis of a particular journal and specific subject area has become a popular method of assessing the impact of a journal, article, or author.

The bibliometric method is based on the citation analysis for studying growth, development and spread of any area of research, as well as providing various quantitative and qualitative indicators of scientific achievement and authors' influence. In addition, this method has been frequently used by the heads of department, research planners, policymakers, and individual scientists.[9] However, there have been few studies addressing the citation analysis of intervertebral disk research, as most of these studies were limited to certain geographical regions and none of them was specifically focused on intervertebral disk.

Since 1945, the information of article citations has been collected by the Institute for Scientific Information, and it has been provided electronically since 1970. Institute for Scientific Information names their latest journal citation system with "Science Citation Index (SCI) Expanded" as a database under the banner of Web of Science. Besides that, this platform provides more than 10,000 high impact journals that are cited by peer-reviewed articles from many different fields of research, including sciences, arts, and humanities. Furthermore, many researchers have used these databases to identify the most widely cited articles in their research field, including orthopedic surgery,[10] spine surgery,[11] and even back pain study.[12]

In order to identify the characteristics of the high-quality articles on intervertebral disk research, we carried out the bibliometric analysis using the Web of Science (Clarivate Analytics) database. Through the characterization of these 100 top cited studies, we tried to help investigators tailor their research interests and design future research on intervertebral disk.

MATERIALS AND METHODS

Study Design and Data Search

The authors searched on Web of Science and identified the 100 top-cited articles related to intervertebral disk, published in professional journals from the January 1, 1900 to the December 31, 2017. As reviews were brief summarization of previous papers, which may weaken the contribution of original research articles, we only included the original research articles in the study, and of which the title contained the terms "intervertebral disc" or "degenerated disc" or "degenerative disc disease" or "disc degeneration." The search was performed on February 1, 2018, and yielded a complete list of articles on intervertebral disk. Ethical approval was not required in this study because no patients or animals have been enrolled.

Inclusion and Exclusion Criteria

The inclusion criteria were as follows: (1) papers should focus on the field of intervertebral disk; (2) papers should be research articles and written in English; (3) the publication date should be between the January 1, 1900 and the December 31, 2017. The exclusion criteria included: (1) papers focused on broad areas with no emphasis on intervertebral disk; (2) abstract, reviews, letters, editorial materials, corrections, book chapters, and patents.

Data Extraction

To ensure consistency of data extraction, we referred the method developed by Huang et al.[12] Four independent investigators (G.Y., Z.L., W.Y., and S.H.) in the field of spinal surgery (with 6, 6, 10, and 20 y of experience, respectively) searched and collected the papers that met the requirements. Afterwards, the searched results were assessed by all the authors to compile 1 comprehensive list of the 100 most cited articles. We reviewed each article which was among the 100 most cited, and extracted the basic information including: authors, year of publications, source journal of the article, geographic origin of the publications, and study field. Any disagreement was discussed among all of the authors for consensus.

Statistical Methods

The manually extracted information of the publications was recorded in Microsoft Excel 2016 (Microsoft, Redmond, WA). All data were presented as counts and analyzed or visualized by Microsoft Excel 2016. VOSviewer (Leiden University, Leiden, the Netherlands), a commonly used software for cocitation network analysis and visualization,[13] was used to analyze the most cited papers, and to visualize the relationships between the most frequently occurring concepts and keywords. In addition, the knowledge maps of the most commonly occurring concepts and the time distribution of keywords were generated in VOSviewer.

RESULTS

The flowchart of the study selection was presented in Figure 1. On the basis of our search strategy, 9843 articles were identified on intervertebral disk in the Web of Science core database. Among those, 343 articles were cited 100 times or more. The 100 most cited articles were published from 1953 to 2009 and their first author and corresponding number of citations were shown in Table 1 (the corresponding title of the paper and journal please see in Supplementary Table 1, Supplemental Digital Content 1, http://links.lww.com/CLINSPINE/A108). The number of citations for the top article ranged from 209 to 1269 with an average of 295.4. Three articles were cited more than 1000 times and 11 articles were cited more than 500 times. Thirty-five articles were published before 1990 and no article was produced after 2010 (Fig. 2).

The 100 most cited articles on intervertebral disk covered a wide range of journals. Comprehensive medical journals such as *The New England Journal of Medicine*
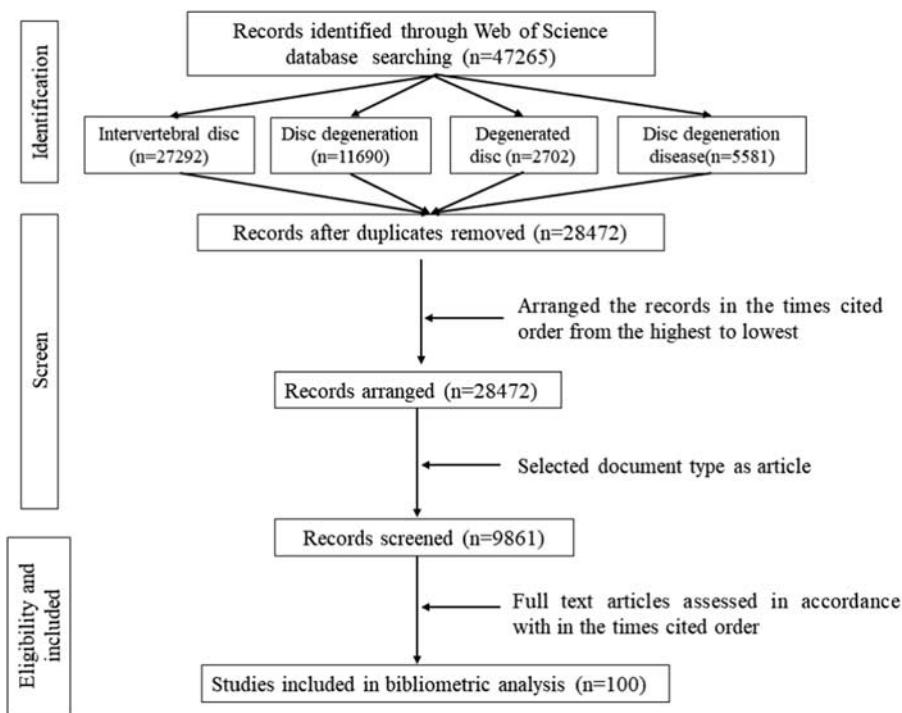
FIGURE 1. Flow diagram of literature selection for bibliometric analysis.

(*NEJM*), *Lancet*, and *Science* published a total of 3 articles; journals that are specialized in spine published 57 articles, whereas journals specialized in orthopedic research or surgery published 12 articles. The journal *Spine* topped the list with 57 articles, followed by *Journal of Bone and Joint Surgery-American* (*JBJS-Am*) with 6 articles. All the journals with <1 article were summarized in Table 2.

Concerning the study topic, there were 60 articles focused on the intervertebral disk basic research, and 40 articles that explored the epidemiology including imageology, treatment, etiology, and risk factors (Table 3). With regard to the production of the authors, M.A. Adams, M.T. Modic, A.L. Nachemson, D. Sakai, and J.N. Weinstein were the most productive with 3 articles individually (Table 4).

The top 100 articles originated from 14 different countries. The United States was the most productive country with 41 articles, followed by United Kingdom with 18 articles and Japan with 9 articles. When sorted by continent, 49 articles were produced in North America, 19 articles were produced in Europe, and 10 articles were produced in Asia. None of the enrolled articles was produced in South America and Africa (Table 5).

The keyword analysis is one of the most important indicators of bibliometrics. As shown in Figure 3A, the 28 terms (defined as being used more than 10 times within titles and abstracts in all of the articles) were classified into 3 clusters: "biological study" with green, "clinical study" with red, and "imageological study" with blue. Among the "biological research" cluster, keywords used in the top

articles were listed as follows: degeneration (51 items), disc (41 items), change (38 items), and intervertebral disc (27 items). For the cluster of "clinical research," the primary keywords were as follows: data (45 items), patient (37 items), age (33 items), year (27 items), and pain (25 items). There were 2 keywords in the "imaging research" cluster: disc degeneration (35 items) and magnetic resonance imaging (12 items). The results demonstrated that the dominant fields of intervertebral disk research were "biological," "clinical," and "imaging studies" (Supplementary Table 2, Supplemental Digital Content 2, http://links.lww.com/CLINSPINE/A109).

In Figure 3B, VOSViewer assigned colors to keywords based on the average years that they appeared in the literature. In brief, the keywords with blue color appeared earlier than the one with yellow. In the early stage of intervertebral disk research, both the biological and clinical fields were the main hotspots. Recent trends showed that the words "evidence," "treatment," "week," and "development" appeared in 2002 and 2003 as keywords in 19, 18, 11, and 12 articles, respectively. The first 3 words belonged to the "clinical research" cluster while only the word "development" was in the cluster of "biological research." There was no new word in the "imageological study" cluster in the last 5 years (Supplementary Table 2, Supplemental Digital Content 2, http://links.lww.com/CLINSPINE/A109).

DISCUSSION

In this study, we determined and characterized the 100 most cited articles on intervertebral disk using the

TABLE 1. The 100 Most Frequently Cited Articles

First Author	Year	Citations No.	Rank	First Author	Year	Citations No.	Rank
Boden	1990	1269	1	Osti	1990	310	40
Pfirrmann	2001	1220	2	Maroudas	1975	309	41
Jensen	1994	1216	3	Kang	1997	305	42
Modic	1988	786	4	Sakai	2003	298	43
Buckwalter	1995	688	5	Thompson	1991	297	44
Weber	1983	684	6	Holm	1981	293	45
Wilke	1999	656	7	Sato	1999	287	46
Thompson	1990	559	8	Urban	1988	282	47
Macnab	1971	554	9	Lotz	1998	279	48
Boos	2002	533	10	Masuda	2005	277	49
Antoniou	1996	507	11	Cheung	2009	276	50
Luoma	2000	494	12	Yorimitsu	2001	276	51
Weinstein	2006	491	13	Farfan	1970	273	52
Modic	1988	465	14	Coppes	1997	272	53
Freemont	1997	448	15	Fujiwara	2000	270	54
Kang	1996	435	16	Horner	2001	266	55
Wiesel	1984	426	17	Marchand	1990	265	56
Burke	2002	417	18	Bogduk	1983	264	57
Olmarker	1993	413	19	Sakai	2006	261	58
Kellgren	1958	406	20	Haro	2000	259	59
Saal	1990	374	21	Weishaupt	1998	259	60
Adams	1996	364	22	Boos	1995	259	61
Nachemson	1981	360	23	Maitre	2004	256	62
Weinstein	2006	355	24	Sambrook	1999	253	63
Mccarron	1987	354	25	Modic	1984	252	64
Takahashi	1996	350	26	Sakai	2005	249	65
Odom	1958	349	27	Risbud	2004	247	66
Adams	2000	348	28	Nishida	1999	246	67
Schwarzer	1995	346	29	Goffin	2003	244	68
Nachemson	1964	340	30	Kelsey	1984	242	69
Cloward	1953	340	31	Gruber	1997	241	70
Roughley	2004	337	32	Nerlich	1997	239	71
Aprill	1992	336	33	Adams	1982	239	72
Miller	1988	332	34	Bogduk	1981	236	73
Brox	2003	326	35	Igarashi	2000	234	74
Maitre	2005	322	36	Teresi	1987	233	75
Battie	1995	322	37	Saal	1990	232	76
Roberts	2000	315	38	Weinhoffer	1995	229	77
Gruber	1998	311	39	Nachemson	1970	229	78
Nachemson	1970	229	79	Lawrence	1969	218	90
Weinstein	2008	228	80	Bartelink	1957	218	91
Weiler	2005	228	81	Butler	1990	217	92
Annunen	1999	226	82	Matsunaga	1999	217	93
Richardson	2006	225	83	Aguiar	1999	216	94
Dunlop	1984	225	84	Pearce	1987	212	95
Mcnally	1992	223	85	Lotz	2000	211	96
Battie	1991	220	86	Mimura	1994	211	97
Crevensten	2004	219	87	Sobajima	2005	211	98
Matsumoto	1998	219	88	Walsh	1990	211	99
Komori	1996	218	89	Spangfort	1972	209	100

Web of Science database. After identifying these classic research articles, we obtained an insight into the historic developmental trends in disk research that reflected the great significance and academic concern of study on disks.

It is well acknowledged that the publishing date can affect citation numbers. The longer the period after publication is, possibly the more easily it is to be cited. Other similar citation analysis report on orthopedic surgery revealed that the majority of top 100 cited papers were published before 1990.[10] In the bibliometric analysis of the most cited articles on lumbar spine surgery,[11] more than half of these articles were published after 1980. However, in our bibliometric analysis, the most productive period was from 1990 to 2000. To account for this result, the improvement of research quality and efficiency in recent years have promoted the number of research papers and citations. In contrast, the emergence of new technologies, such as magnetic resonance imaging has been applied to spinal disorders since the early 1990s, which plays an essential role in the development of disk research.[14] Meanwhile, it should be noted that there was no top article published after 2015 in the current analysis, and we speculated that recently released articles needed time to be cited widely, as the highest citation number of an article per year often occurred 3–10 years after publication.
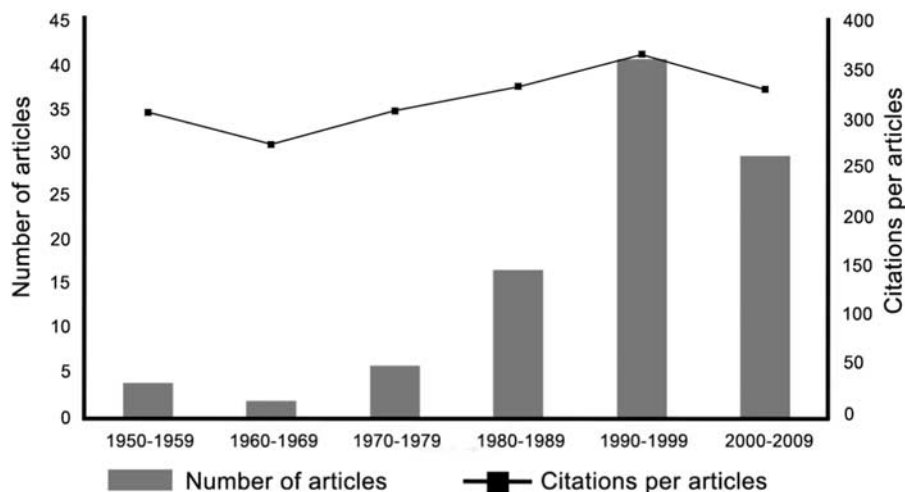
FIGURE 2. Graph demonstrating the number of the 100 most cited articles on intervertebral disk research and the number of mean citations per 10 years.

In this study, we identified that 14 countries contributed to the 100 most cited articles. Similar to the analysis of the top 100 articles in other fields, the United States occupied the largest proportion.[15–17] In contrast, South America and African countries had no contribution to the top 100 articles, which indicated that the disparity of scientific publications between the developing and the developed countries remained significant. Although remarkable progress has been made in scientific research in Asia, high-impact research is still lacking. Countries in these less developed areas still have to endeavor to integrate into the world scientific processes.

It has been reported that the major journals can attract good papers in its field that may have a potential high-citation index, maintaining these journals' impact factor.[18] In this study, we found that *Spine* was the most productive journal, while *JBJS-Am* was the second most productive one with the highest mean citation number per article. These results were in accordance with Bradford's Law, which stated that investigators tend to cite papers from a few core journals in their specialty.[19] In contrast to *Spine*, the other 2 classic spine journals, namely *European Spine Journal* and *The Spine Journal*, had no articles in the current study. Nevertheless, several factors should be considered when assessing journals, such as: the *European Spine Journal* started its publications from 1992; along with *The Spine Journal*, which started publishing from 2001. The relatively recent inception year might partially account for the no articles in the 2 journals.[12]

We studied the main subjects of the most cited papers through keyword analysis by VOSviewer. The most cited papers extracted from Web of Science database were classified into 3 clusters: biological, clinical, and imageological studies. In the biological study cluster, "disc" and "degeneration" were the biological factors that emerged on the map as the most frequently appearing keywords. This finding demonstrated that disk degeneration was a major biological study area related to disk research. In the clinical study cluster, the most frequently occurring keywords included "data," "patient," "age," and "year,"

TABLE 2. Top Journals of Publication

Rank	Journal	No. Articles
1	*Spine*	57
2	*Journal of Bone and Joint Surgery-American*	6
3	*Journal of Bone and Joint Surgery-British*	5
3	*Radiology*	5
5	*JAMA Journal of the American Medical Association*	3
6	*Annals of the Rheumatic Diseases*	2
6	*Biomaterials*	2
6	*Experimental Cell Research*	2
6	*Journal of Anatomy*	2
6	*Journal of Clinical Investigation*	2
6	*Journal of Orthopaedic Research*	2
12	*Acta Orthopaedica Scandinavica*	1
12	*Annals of Biomedical Engineering*	1
12	*Arthritis and Rheumatism*	1
12	*Arthritis Research & Therapy*	1
12	*British Journal of Radiology*	1
12	*Connective Tissue Research*	1
12	*Journal of Neurosurgery*	1
12	*Journal of Pathology*	1
12	*Lancet*	1
12	*New England Journal of Medicine*	1
12	*Science*	1
12	*Stem Cells*	1

TABLE 3. Major Study Topic of the 100 Most Cited Articles on Disk Degeneration

Type of Study	Study Topic	No. Articles	No. Total Citations	No. Mean Citations
Basic research	Biology	37	10,832	292.8
	Biomechanics	14	4323	308.8
	Anatomy	6	1577	262.8
	Animal model	3	798	266
Epidemiology	Imageology	24	11,706	487.8
	Treatment	10	2918	291.8
	Etiology	4	1562	390.5
	Risk factors	2	462	231

TABLE 4. Top Authors and Topics of Publication

First Authors	No. Articles	Topic
M.A. Adams	3	Intervertebral disk physiology, biomechanics
M.T. Modic	3	Intervertebral disk magnetic resonance imaging
A.L. Nachemson	3	Intervertebral disk pressure, nutrition
D. Sakai	3	Intervertebral disk cytology, stem cells
J.N. Weinstein	3	Intervertebral disk surgery

meaning that clinical study was mainly focused on the time course of disease progression related to intervertebral disk. In addition, the distribution of keywords according to the time when they first showed up in the most cited papers illustrated that the research interest was mainly in the field of biological and clinical studies, meaning that molecular mechanisms, clinical etiologies, and treatment were hot topics in the research of intervertebral disk.

There were still several limitations in the current analysis. Although widely used, the citation numbers did not fully reflect the quality of an article. Some factors such as publishing dates, research fields, or specialties may affect the results of citation number. In addition, we have only used the Web of Science electronic database for our analysis. Besides Web of Science, Google Scholar, or SCOPUS databases could also provide citation data. It has been reported that these databases might display varying citation results, which may provide different analysis results.[20] Furthermore, the enrolled articles were confined to the English language. Accordingly, the results of the search will not include those high-impact articles in non-English languages, which could generate a bias against this result. For example, China has a number of strong researchers and their low counts may partially be caused by their willingness to publish in their native language. Finally, although the searching method in the present study attempted to include all the subject words related to intervertebral disk, those words such as "nucleus pulposus," "annulus fibrosus" were not included and potentially have caused the loss of some of the high

TABLE 5. Countries of the 100 Most Cited Articles on Disk Degeneration

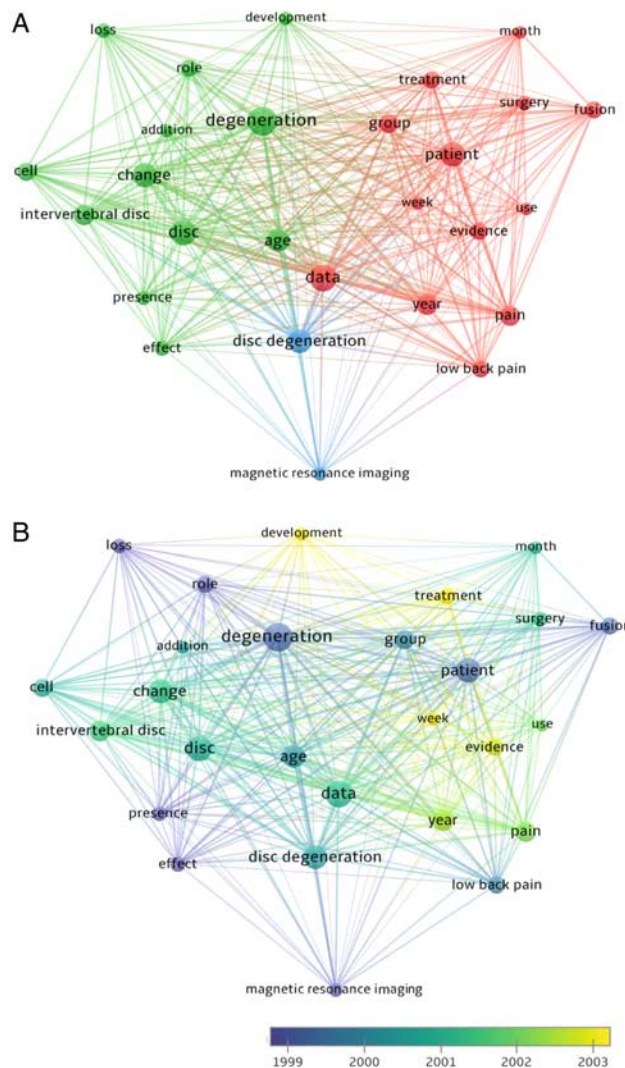| Country of Origin	No. Articles	No. Total Citations	No. Mean Citations
United States	41	14,654	357.4
United Kingdom	18	5310	295.0
Japan	9	2375	263.9
Canada	8	2734	341.8
Australia	5	1409	281.8
Switzerland	4	2566	641.5
Germany	3	1123	374.3
Sweden	4	1275	318.8
Finland	2	720	360
Norway	2	1010	505
Belgium	1	244	244
China	1	276	276
Ireland	1	210	210
The Netherlands	1	272	272

FIGURE 3. The analysis of keywords. A, Mapping on keywords of intervertebral disk. The words were classified into 3 clusters according to different colors. The lager the circle, the words were used more frequently. B, Distribution of keywords according to when they appeared for the average time. Keywords with blue color presented earlier than that with yellow. Two terms are said to co-occur if they both occur on the same line in the corpus file. In general, the smaller the distance between 2 terms, the larger the number of co-occurrences of the terms. full color online

influence articles, leading to a significant limitation in this study.

In conclusion, despite these limitations, the current citation analysis demonstrated the essential advances in the historic intervertebral disk research, which showed an improvement in the research quality and an increase in the number of research papers. This analysis also identified the influential authors, countries, and journals that had outstanding contributions to the study on intervertebral disk. Above all, these insights into priorities and trends on intervertebral disk could help scientists master the research hotspot and benefit the future academic pursuits.

ACKNOWLEDGMENT

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