Classification and citation analysis of the 100 top-cited articles on adult spinal deformity since 2011: A bibliometric analysis

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Abstract

Background: Studies of the 100 most-cited articles are reported for many subjects. However, none has analyzed the article characteristics associated with high citation frequency. This study aims to (1) graphically depict characteristics of the 100 top-cited articles addressing adult spinal deformity (ASD), (2) diagram the association between articles according to subject and major topic medical subject headings (MeSHs), and (3) investigate whether major topic MeSH correlates with article citation frequency.

Methods: The 100 top-cited ASD publications since 2011 were retrieved using a PubMed Central search on May 6, 2020. Using titles and abstracts, eight subject categories were identified: surgery, conservative treatment, normal values in spinopelvic alignment, review, cervical alignment, classification, compensatory mechanism, and spine-hip relationship. Sankey diagrams were used to organize the information. Network analysis was performed according to article subject and major topic MeSHs. Pearson's r was used to determine whether the weighted number of citations correlates with major topic MeSHs and the number of citations.

Results: The average number of citations per article was 34.8 (range, 19–156). The most represented country was USA (n = 51). The most productive and highly cited journal was *Spine (Phila Pa 1976)* (n = 34; average, 38.2 citations per article). The most frequent subject categories and major topic MeSHs were "surgery" (n = 53) and "scoliosis" (weighted count, 9.8), while articles with the subject "compensatory" had the highest average number of citations (64.7). The most highly cited article, by Dr. F. Schwab in 2012, had 156 citations. Network analysis revealed the relationships between these articles according to major topic MeSHs. The weighted number of citations according to major topic MeSHs correlated significantly with article citation frequency (Pearson's r, 0.57; *p* < 0.001).

Conclusion: Multiple characteristics of the 100 top-cited ASD articles are presented in diagrams to guide evidence-based clinical decision-making in ASD.

Keywords: Bibliometrics; Journal article; Social network analysis; Spinal curvatures; Spondylosis

1. INTRODUCTION

Spinal deformity includes any abnormality in the formation, alignment, or shape of the vertebral column.[1,2] Such conditions have been recognized for many millennia,[3] with documentation of scoliosis correction dating back at least 5000 years.[4] With the marked evolution of new instrumentation, surgical correction of adult spinal deformity (ASD) has become more popular in recent years. Accordingly, spine surgeons need to have a thorough understanding of ASD with respect to preoperative evaluation and planning, surgical techniques, outcomes, and complications. Much information on ASD is available in published articles.

The ranking of articles according to the number of citations received is a means of determining the most influential articles in a field of interest.[5]

A search of titles containing the phrase "100 top-cited" in PubMed Central retrieved 198 publications. Most of these articles included 3 categories of information: descriptive statistics, research achievements in countries/institutes, and major topics or article types with research domains. A number of the articles examined the most influential papers using citation analysis in orthopedic surgery[6] and subspecialties in orthopedics including arthroscopy,[7] foot and ankle,[8] arthroplasty,[9] pediatric orthopedics,[10] and spinal deformity.[5,11,12]

Although these bibliometric studies identified the main concepts of great distinction within the field and provided clinical guidelines for orthopedists and researchers in a discipline, 2 perspectives were frequently neglected: (1) visual representation of all relevant characteristics of the articles[13–15] and (2) a model for predicting the number of article citations.[16–19]

The objective of this study is to analyze the 100 top-cited articles on ASD using a systematic search strategy to provide (1) visual representation of the most dominant article subjects and research domains, (2) diagrams illustrating the association between articles based on their subjects and major topic medical subject headings (MeSHs), (3) a prediction model of article

citation frequency based on major topic MeSHs, (4) a list of authors who contributed to the field of ASD, and (5) the clinical significance of the most cited articles.

2. METHODS

2.1. Data sources

We exhaustively searched PubMed Central using the keywords "adult spinal deformity" or "sagittal alignment" or "spinopelvic alignment" or "kyphoscoliosis" or "sagittal plane deformity" or "sagittal imbalance" or "degenerative scoliosis" regardless of the country of origin and language. The 100 top-cited articles on ASD from 2011 to 2020 were retrieved on May 6, 2020. Only articles with major topic MeSHs[20] were included in the analyses. Ethics approval was not necessary for this study because all data were obtained from the publicly available PubMed database.

2.2. Data extraction and organization

We extracted the following data from each article: title, abstract, authors, publication year, country of origin, citation count, journal, PMID, and major topic MeSHs. If the corresponding author had more than one affiliation from different countries, the first affiliation was used as the country of origin. Duplicate major topic MeSHs for each article were removed, and subheadings were discarded. Based on the titles and abstracts, the 100 top-cited articles in the field of ASD were categorized by an experienced spine surgeon (P.-H.C.) into the following eight subject categories: surgery, conservative treatment (conservative), normal values in spinopelvic alignment (normal), review, cervical alignment (cervical), classification, compensatory mechanism (compensatory), and spine-hip relationship (spine-hip). If the article subject was difficult to categorize, we consulted another senior spine surgeon (S.-T.W.) for confirmation.

2.3. Visual representation and diagrams

Sankey diagrams were used to provide the overall information of the articles including publication year, country of origin, article subject, and journal using the "networkD3" package (https://christophergandrud.github.io/networkD3/). Two Sankey diagrams were drawn for each of two connection types: article counts and number of citations shared by the characteristics. Only connections with more than one article or 40 article citations were displayed to create a clean layout. Network analysis[21–23] was performed to investigate the associations between the articles based on article subjects and major topic MeSHs using the "igraph" package.[24] We included only highly influential articles with more than 40 citations in the analysis. Articles belonging to the same subject category were labeled the same color. To make a clean and informative layout, only articles sharing more than one identical major topic MeSHs were linked together in the force-directed diagram using the Fruchterman-Reingold algorithm.[25] All plot drawings were performed in the R environment (www.R-project.org/).[26]

2.4. Weighted number of citations according to major MeSHs

The weighted number of citations for article j according to major topic MeSHs ($Citation_{MeSH,j}$) was determined using Eq. 1 to 5 below:

$$MeSH_{E,ij} = \begin{cases} 1, & \text{if } MeSH_i \text{ in article } j \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

The weighted count of a specific major topic MeSH was then calculated using Eq. 2, where A_j denotes the number of major topic MeSHs in article j and n = 100 in this study.

$$MeSH_{N,i} = \sum_{j=1}^{n} \left(\frac{1}{A_j} \times MeSH_{E,ij} \right) \quad (2)$$

Similarly, the weighted citation number of a specific major topic MeSH was calculated using Eq. 3, where C_j denotes the number of citations in article j.

$$MeSH_{Ci,i} = \sum_{j=1}^{n} \left(C_j \times \frac{1}{A_j} \times MeSH_{E,ij} \right) \quad (3)$$

The mean number of citations for a specific major topic MeSH was computed using Eq. 4, as used to determine the impact factor (IF) of a journal.

$$MeSH_{IF,i} = \frac{MeSH_{Ci,i}}{MeSH_{N,i}} \quad (4)$$

As such, the weighted number of citations for article j according to major topic MeSHs can be yielded by Eq. 5, where L_j denotes the number of major topic MeSHs in article j.

$$Citation_{MeSH,j} = \frac{\sum_{i=1}^{L_j} MeSH_{IF,i}}{A_j} \quad (5)$$

2.5. Statistics

The total number and mean number of citations per article were calculated for each subject category and each major topic MeSH. Pearson's r was used to determine the association between the weighted number of citations according to major topic MeSHs, $Citation_{MeSH,j}$, and the number of citations. The t statistic for Pearson's r was calculated using the following formula: t = CC × sqrt ([n – 2] / [1 – CC × CC]). The significance level was set at $p < 0.05$.

3. RESULTS

3.1. Descriptive statistics

The 100 top-cited articles in the field of ADS are listed in Supplementary Table 1 http://links.lww.com/JCMA/A119. Readers are invited to examine all 100 articles included in the study. The number of citations per article ranged from 19 to 156 (average, 34.8) in PubMed Central on May 6, 2020. The most productive countries were USA (n = 51; 36.4 citations per article), followed by France (n = 10; 45.8 citations per article) and Italy (n = 9; 31.9 citations per article; Table 1). Most of the articles were published in 2013 (n = 26) and 2012 (n = 22). None of the top-cited articles were published after 2016. The two dominant journals with the most publications were *Spine (Phila Pa 1976)* (n = 34) and *Eur Spine J* (n = 28; Table 2). The most highly cited journal was *Spine (Phila Pa 1976)*, with an average of 38.2 citations per article, followed by *Eur Spine J* (36.9 citations per article) and *Neurosurgery* (36.6 citations per article).

3.2. Most-cited articles according to subject and major topic MeSH

The two subject categories with the most articles were "surgery" (n = 53), "conservative" (n = 11), and "normal" (Fig. 1A). After

Table 1

Distribution of 100 top-cited articles over the last 10 years according to country

Country	2011	2012	2013	2014	2015	2016	n	Ci	IF[a]
USA	4	12	16	8	7	4	51	1854	36.4
France	5	1	2		1	1	10	458	45.8
Italy	1	1	2	3	2		9	287	31.9
Japan	1	2	1	1	1	1	7	222	31.7
South Korea	1	1	2	1			5	132	26.4
China		2		1	1		4	108	27.0
Germany			1		1	1	3	72	24.0
Belgium		1		1			2	48	24.0
Canada	1						1	48	48.0
Spain					1		1	47	47.0
Turkey			1				1	45	45.0
Slovenia		1					1	38	38.0
Hungary		1					1	30	30.0
Switzerland				1			1	30	30.0
Egypt			1				1	23	23.0
Brazil				1			1	21	21.0
Australia					1		1	19	19.0
Total	13	22	26	16	16	7	100	3482	34.8

Ci = citation; IF = impact factor.

[a]IF = Ci / n.

normalization by the number of articles, articles belonging to the subject category "compensatory" had the greatest average number of citations (64.7), followed by "classification" (60.7) and "cervical" (52.3).

A total of 78 unique major topic MeSHs were identified among the articles. The number of major topic MeSHs per article ranged from 1 to 8 (average, 3.9). The major topic MeSH, "scoliosis" had the highest weighted count (9.8), followed by "spinal fusion" (9.7) and "spine" (7.5; Fig. 1B). Ten major topic articles had more than four weighted counts, and "cervical vertebrae" (43.7), "spinal curvatures" (40.9), and "scoliosis" (38.7) had the highest mean number of citations.

Articles in the subject category of "surgery" could be further classified into eight subcategories (Supplementary Table 2

http://links.lww.com/JCMA/A120). Of 53 articles, 19 reported surgical outcomes (three reported surgical outcomes in pedicle subtraction osteotomy), 12 complications, 11 lateral lumbar interbody fusion for ASD correction, eight proximal junctional kyphosis, two comparisons between the surgical and conservative treatment of ASD, and one oblique lumbar interbody fusion in ASD correction. Articles investigating the subject of "normal" were published by authors from France, Japan, South Korea, Belgium, and China, which reported normal spinopelvic and cervical alignments in their national population (Table 1).

3.3. Visual representation of article information

Associations between the investigated characteristics are depicted in the Sankey diagrams (Fig. 2). The link width is proportional to the article counts shared by the characteristics shown in Fig. 2A and article citations shown in Fig. 2B. According to both article count and number of citations, the "surgery" articles from USA played an important role in ASD research as did those published in *Spine (Phila Pa 1976)*. The top-cited articles from Italy focused on "surgery," while those from France investigated "conservative," "classification," and "compensatory." More than half of the top-cited articles published in *Spine (Phila Pa 1976)* focused on "surgery," while the diversity of article subjects was greater in *Eur Spine J*.

3.4. Network analysis based on article subject and major topic MeSH

The force-directed diagram in Fig. 3 includes 24 articles that have over 40 citations. Most of these articles had at least one major topic MeSH in common. Therefore, only articles sharing more than one identical term were linked together to illustrate the underlying network structure. The most-cited article (PMID 22045006) was authored by Dr. Frank Schwab from the NYU Hospital for Joint Diseases in 2012,[27] with 156 citations, followed by articles with 117 (PMID 23722572)[28] and 100 citations (PMID 23768023).[29] Most articles with the subject "surgery" shared similar major topic MeSHs and were, therefore, linked together. PMID 22836363[30] and PMID 23873244,[31] which both investigated extreme lateral interbody fusion, shared three identical major topic MeSHs. The other two articles sharing

Table 2

Distribution of cited articles across the eight article subject categories of adult spinal deformity according to journal

Journal	Surgery	Conservative	Normal	Review	Cervical	Classification	Compensatory	Spine-hip	N	Ci	IF[a]
Spine (Phila Pa 1976)	22		6	1	3	2			34	1299	38.2
Eur Spine J	10	6	3	2		3	3	1	28	1033	36.9
J Neurosurg Spine	6				3	1			10	359	35.9
Neurosurgery	6	1			1				8	293	36.6
Spine J	1	2		2					5	146	29.2
Clin Orthop Relat Res	2								2	45	22.5
J Bone Joint Surg Am	1							1	2	49	24.5
J Clin Neurosci	2								2	45	22.5
Scientific World Journal	2								2	49	24.5
Clin Neurol Neurosurg				1					1	20	20.0
Int Orthop				1					1	33	33.0
J Back Musculoskelet Rehabil		1							1	23	23.0
J Spinal Disord Tech	1								1	25	25.0
Neurosurg Clin N Am		1							1	20	20.0
Orthop Traumatol Surg Res				1					1	24	24.0
Spine Deform				1					1	19	19.0
Total	53	11	10	8	7	6	3	2	100	3482	34.8

Ci = citation; IF = impact factor.

[a]IF = Ci / n.

A

Article Category	N	Ci	IF
Surgery	53	1621	30.6
Conservative	11	335	30.5
Normal	10	292	29.2
Review	8	266	33.3
Cervical	7	366	52.3
Classification	6	364	60.7
Compensatory	3	194	64.7
Spine-hip	2	44	22.0
Total	100	3482	

B

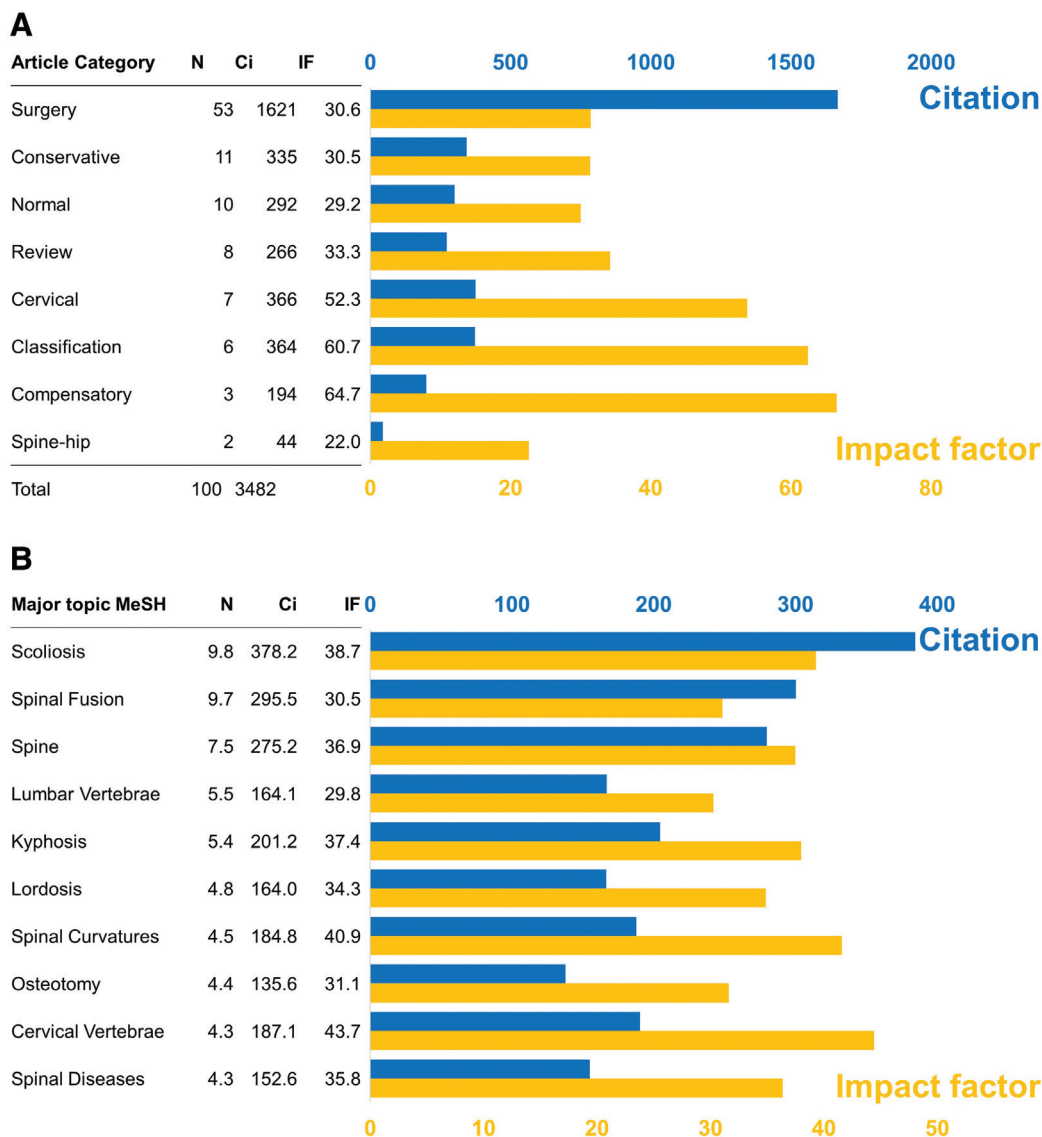| Major topic MeSH	N	Ci	IF
Scoliosis	9.8	378.2	38.7
Spinal Fusion	9.7	295.5	30.5
Spine	7.5	275.2	36.9
Lumbar Vertebrae	5.5	164.1	29.8
Kyphosis	5.4	201.2	37.4
Lordosis	4.8	164.0	34.3
Spinal Curvatures	4.5	184.8	40.9
Osteotomy	4.4	135.6	31.1
Cervical Vertebrae	4.3	187.1	43.7
Spinal Diseases	4.3	152.6	35.8

Fig. 1 A, The total number of article citations by subject category and mean citation number after normalization to article counts. The most-cited subject category was "compensatory," followed by "classification" and "cervical." B, The weighted number of article citations by major topic MeSH and mean citation number after normalization to the weighted count of major topic MeSH. Only 10 major topic MeSHs with more than four weighted counts are shown; the most-cited MeSH was "cervical vertebrae," followed by "spinal curvatures" and "scoliosis." Ci = citation; IF = impact factor.

three identical major topic MeSHs were PMID 22504517 and PMID 22366971. PMID 22504517 is a multicenter study on the complications of primary adult scoliosis surgery,[32] while PMID 22366971 investigates the complications in three-column osteotomy.[33] The articles linked together had similar study subjects, and researchers are encouraged to use this network diagram to review these related top-cited articles in a systematic manner. A network diagram incorporating articles with more than 30 citations is also provided (Supplementary Fig. 1 http://links.lww.com/JCMA/A113).

3.5. Association between major topic MeSHs and article citation frequency

The weighted number of citations for all 100 top-cited articles according to major topic MeSHs ($Citation_{MeSH,j}$) was calculated using equations Eq. 1 to 5 and significantly correlated with the number of article citations (Pearson's r = 0.57; $p < 0.001$; Fig. 4). However, the ($Citation_{MeSH,j}$) tended to be higher than the actual number of article citations. The regression equation is defined as follows: article citation = $0.12 \times (Citation_{MeSH,j}) + 30.52$.

4. DISCUSSION

We determined the characteristics of the 100 top-cited articles in ASD from PubMed Central and organized them into eight subject categories. Sankey diagrams and network analysis were used to determine the characteristics and underlying relationships between these articles. Using these concise diagrams, spine surgeons may be able to find relevant articles more efficiently, facilitating evidence-based decision-making for patients with symptomatic ASD.

The article subject categories associated with frequent citation were identified using social network analysis. The subject category "compensatory" earned the highest mean number of citations. One possible reason for this result is that spine surgeons must understand both the spinopelvic alignment at the
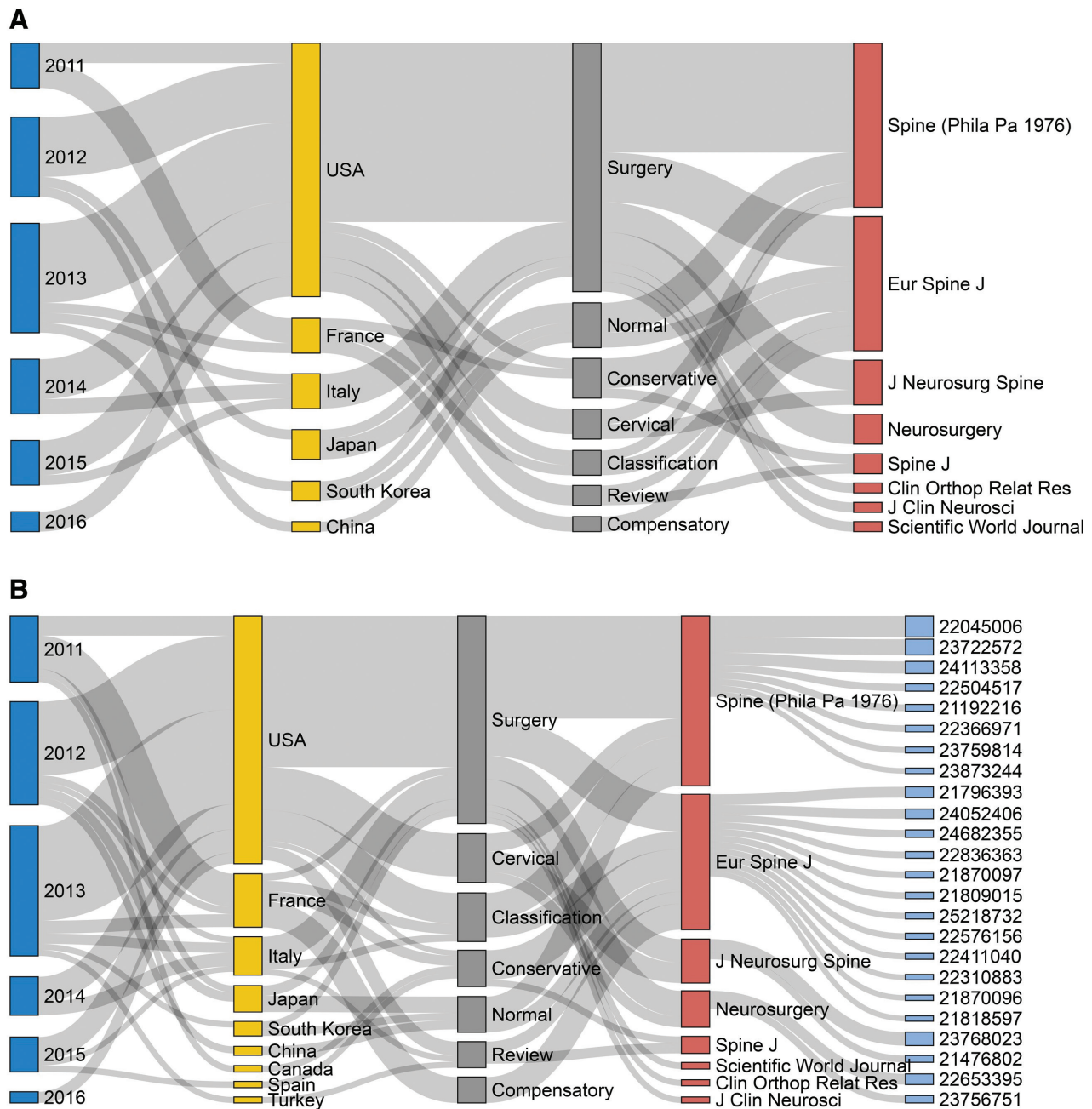
Fig. 2 Sankey diagrams depicting the association between article characteristics including publication year, country of origin, article subject, and journal. More to less frequent characteristics are organized from top to bottom. A, The links between characteristics represent the number of shared articles; only those with more than one article are shown. B, The links between characteristics represent the total number of article citations shared; only those with more than 40 article citations are displayed.

pathologic levels and compensatory mechanisms in the other spinal regions. Of the common major topic MeSHs listed in these top-cited articles, "cervical vertebra" was associated with the highest mean number of citations. This may be partly attributed to the important role of deteriorated cervical vertebrae in symptomatic ASD.

The most-cited article on ASD was written by Schwab et al in 2012, published in *Spine (Phila Pa 1976)*[27] and categorized as "classification" in this study. This article describes a new ASD classification for coronal curve types and sagittal modifiers. The three main modifiers in spinopelvic parameters are the pelvic index (PI) minus lumbar lordosis (LL), sagittal vertical axis

(SVA), and pelvic tilting (PT). With these proposed new classifications for ASD, spine surgeons may use the classification as an international communication tool to discuss any topic regarding ASD. From our point of view, the SRS-Schwab ASD classification has been fundamentally and clinically widely accepted in all scientific studies related to ASD.

The second most highly cited article was written by Schwab et al and published in 2013 in *Spine (Phila Pa 1976)*,[28] classified as "surgery" in our study. This original article describes a study conducted by the International Spine Study Group (ISSG) and discusses the correlations between spinopelvic parameters and health-related quality of life scores in patients with ASD
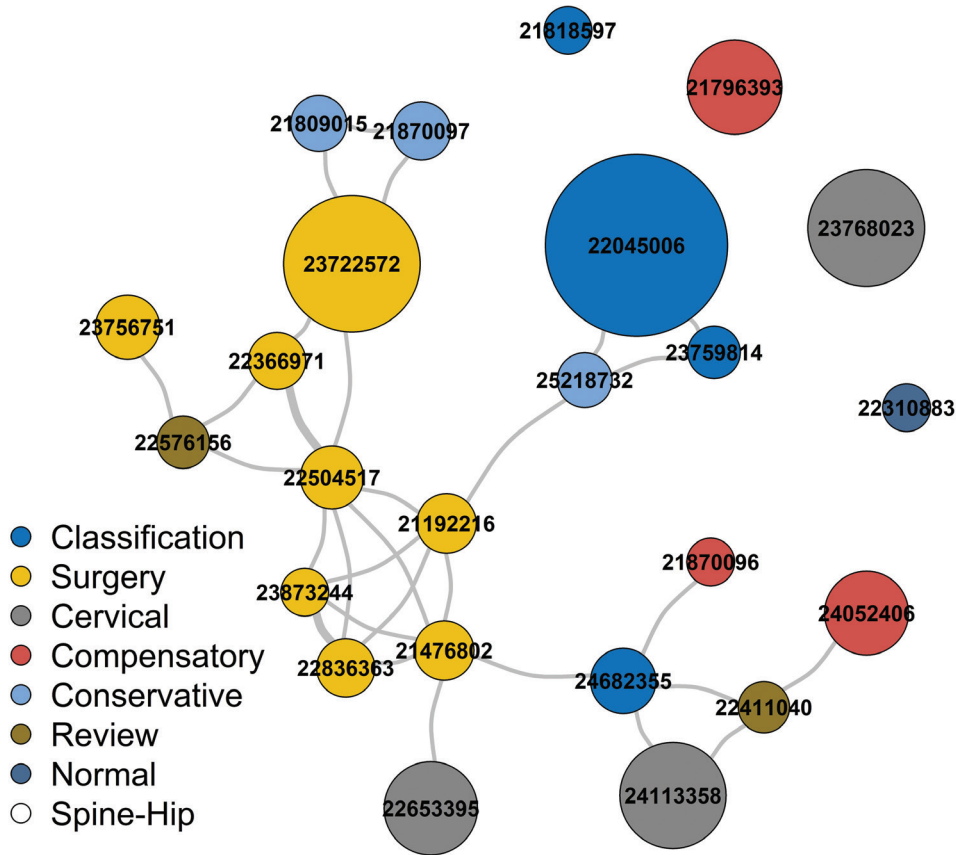
Fig. 3 Force-directed network diagram depicts the associations between the articles according to article subject and major topic MeSH. A total of 24 articles with more than 40 citations are displayed; only articles sharing more than one identical major topic MeSH are linked together. The node size and link width are proportional to the number of article citations and shared major topic MeSHs, respectively.

following posterior correction surgery. The spinopelvic parameters PT $\geq$ 22°, SVA $\geq$ 47 mm, and PI – LL $\geq$ 11° play important roles in severe disability (Oswestry disability index, >40).
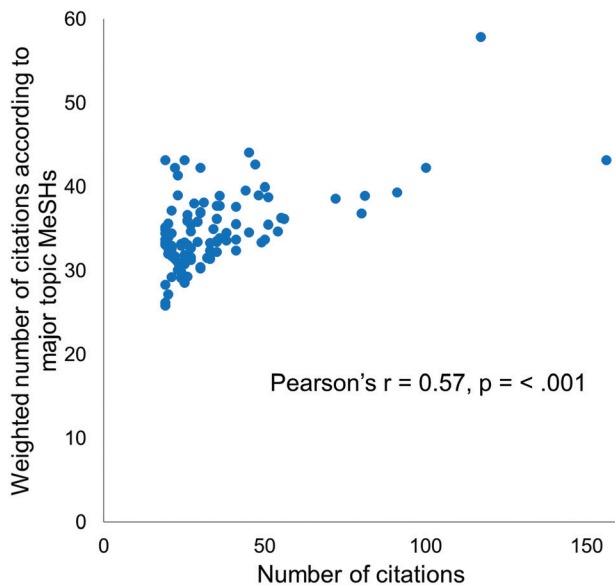

Fig. 4 Weighted number of citations according to major topic medical subject heading (MeSH) correlated significantly with the number of article citations (Pearson's r = 0.57; *p* < 0.001).

The article provides precise thresholds for clinical use and preoperative decision-making by spine surgeons. Dr. Schwab from the NYU Hospital for Joint Diseases is the first author of both of these articles reporting fundamental milestones in ASD research.

The third most-cited article is by Scheer et al, published in *J Neurosurg Spine* in 2013[29] and classified as "cervical" in our study. This review article addresses multiple normal values in cervical alignments in C2–C7 lordosis, chin-bow vertical angle, T-1 slope, thoracic inlet angle, and SVA with different age distributions. The authors describe the cervical parameters in detail and discuss the association between these parameters and cervical pathologies such as deformity, myelopathy, and adjacent segment disease. In addition, the normal values for LL, PI, sacrum slope, and PT according to age are also elucidated. The availability of normative values for these parameters in cervical and spinopelvic alignment allows surgeons to evaluate their patients clinically and to make better preoperative assessments for decision-making. The second and third most-cited articles were published cooperatively by members of ISSG, who also published five other highly cited articles in the field of ASD: one paper was categorized as "surgery,"[34] two as "classification,"[35,36] and two as "cervical."[37,38]

The third, fourth, and fifth most-cited articles in our results were narrative review articles covering cervical alignment and overall compensatory mechanisms in ASD. Excluding review articles, the third most-cited original article was published by Tang et al in 2012 in *Neurosurgery* in conjunction with ISSG.[38] This study reports that regional cervical sagittal alignment of the C2–C7 SVA has a large effect on the neck disability index,

with a threshold of approximately 40 mm. The study findings indicate that the severity of disability increases with positive sagittal malalignment following posterior cervical fusion surgery—a result similar to that observed in the thoracolumbar spine.[28] Accordingly, spine surgeons should give greater consideration to the global spinopelvic alignment of the regional cervical and thoracolumbar spine and treat the spine as a whole.

A study by Zhang Y et al also reviewed the 100 top-cited articles on spinal deformity using bibliometric analysis.[11] However, the authors investigated congenital scoliosis, early-onset scoliosis, adolescent idiopathic scoliosis, and ASD together in one study. By contrast, the present study focused solely on the subspecialty field of ASD, which makes the study more specific and relevant. The key features of this study include (1) a diagram highlighting the most prominent article subject categories and major topic MeSHs, (2) visual representation of the connections between article characteristics, (3) network analysis of the underlying relationships between articles according to major topic MeSHs, (4) evidence suggesting that major topic MeSHs are associated with the article citation frequency, and (5) a discussion of the features of the most-cited ADS articles that contributed to their frequent citation in the past 10 years.

This study has several limitations. First, the study data were retrieved only from PubMed Central, thereby differing from other studies that used the Web of Science (Science Citation Index [SCI]) and Google Scholar.[5–10] Several journals in PubMed were not indexed in the SCI database, and certain SCI-indexed journals were not included in PubMed. These differences between databases may introduce bias into the results of our study and others. Second, certain biases may be introduced regarding citation extraction because the number of citations increases with time. The number of citations of a given article might differ between studies if the periods and the citation sources differ. Third, only articles with MeSHs were included. Those without MeSHs could still have a large number of citations. Fourth, although the visual representation of our network analysis results is unique and useful, condensing a large number of relevant variables into one clear diagram was challenging. Thus, only articles with more than 40 citations are displayed in the network. Fifth, we discussed only three highly cited original articles and the overall trends underlying citation frequency. Other articles with unique features were not discussed in detail. Furthermore, only articles in the field of ASD were included. Other subspecialties, particularly adolescent idiopathic scoliosis, early-onset scoliosis, and congenital scoliosis remain to be investigated using the same method in future studies.

Finally, multiple factors affect the frequency of article citation. One study reports that IFs are higher for journals that publish reviews and original articles than those publishing case reports.[39] Rigorous systematic reviews are reported to receive more than twice the mean number of citations than other systematic or narrative reviews.[40] The value of case reports for high IF is low since they are rarely cited in articles.[41] Thus, our finding that major topic MeSHs were associated with the number of citations should be viewed in light of the multiple influences determining the citation frequency for a given article.

In conclusion, this study identified the 100 most-cited articles in the field of ASD and provides insight and summaries for use by spine surgeons working in this challenging field. This helpful information may aid in evidence-based clinical decision-making. The provided Sankey diagrams and network analysis add novel elements for visualizing the results of this bibliometric analysis of 100 top-cited articles. This approach may be applicable to other academic disciplines.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data related to this article can be found at http://links.lww.com/JCMA/A119; http://links.lww.com/JCMA/A120; http://links.lww.com/JCMA/A113.

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