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High impact works on stem cell transplantation in intervertebral disc degeneration

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Abstract

Background Low back pain is a major disorder that causes disability and is strongly associated with intervertebral disc degeneration (IDD). Because of the limitations of contemporary interventions, stem cell transplantation (SCT) has been increasingly used to regenerate degenerative discs. Nevertheless, analyses of high-impact papers in this field are rare. This study aimed to determine and analyze the 100 highest-cited documents on SCT in IDD.

Methods The 100 highest-cited documents were retrieved from the Web of Science (WoS) database. Descriptive statistics were calculated and correlation analysis was conducted to determine the relationship between WoS citations, the Altmetric Attention Score (AAS), and Dimensions citations.

Results The citation counts of the top 100 most cited papers ranged from 13 to 372. These studies were conducted in 17 countries and were published in 48 journals between 2003 and 2021. The top three contributing countries were the China (31), United States (22), and Japan (14). Bone marrow-derived stem cells were the most common type of stem cells (70.00%), followed by adipose-derived stem cells (13.75%), and nucleus pulposus-derived stem cells (7.50). Rabbit was the most studied species (41.25%), followed by rat (21.25%), human (13.75%), sheep (8.75%), dog (8.75%), and pig (6.25%). Tokai University School of Medicine (11) had the largest number of documents, followed by The University of Hong Kong (8), and Southeast University (4). Sakai D (10) was the most fruitful author, followed by Cheung KMC (6), Melrose J (3), Pettine K (3), Lotz JC (3), and Murphy MB (3). We observed a very high correlation between the WoS and Dimensions citations ($p < 0.001$, $r = 0.994$).

Conclusions This study highlights the highest impact works on SCT in IDD, thereby providing a deeper understanding of the historical works related to SCT in IDD, as well as benefits for future studies in this field.

Keywords Stem cell, Progenitor cell, Stromal cell, Cell transplantation, Intervertebral disc degeneration

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Background

Low back pain (LBP) affects up to 84% of adults in their lifetime and is thought to be the most common vital musculoskeletal disorder to cause hospital visits [1–3]. LBP is also the predominant reason for sick leave and subsequent disability worldwide, representing an immense socioeconomic burden [4, 5]. The total cost of LBP in the United States is estimated to exceed $100 billion per year [6]. Intervertebral disc degeneration (IDD) is the predominant cause of LBP; however, for many patients, contemporary treatments for IDD aimed at alleviating symptoms or minimizing disability do not offer satisfactory outcomes [5–7]. Neither surgical nor non-surgical interventions are capable of hindering the progress of IDD or reversing it to regain the functional discs [3, 7, 8]. Hence, new treatment strategies focused on curing IDD are required.

Increasing attention has been paid to stem cell (SC) therapy in IDD because of the limitations of the current invention options [7–12]. With the rapid development of stem cell transplantation (SCT), numerous studies have been published on IDD [9–12]. Several important studies may have great potential to promote the growth of SCT in IDD [8–11]. The tendency of a certain field is commonly reflected in high-impact works [13–17]; thus, the evaluation of such works can help researchers and clinicians to rapidly identify the most influential papers in a specific field to deepen their research or identify novel directions in light of classic studies [16–19]. Analyses of the highest-cited papers have been conducted in various fields but have not yet been applied to SCT in IDD [13–30]. Therefore, the purpose of the present study was to determine and analyze the 100 highest-cited documents on SCT in IDD, allowing for a better understanding of the historical works as well as serving as a resource for future studies in this field.

Materials and methods

Retrieval strategy

The requirement for Institutional Review Board approval was waived because the study did not involve humans or animals. The Web of Science (WoS) database was used as the literature source, and the works were retrieved on January 10, 2023. A topic search was conducted using the following search strategy: ("stem cell" OR "progenitor cell" OR "stromal cell") AND ("intervertebral disc" OR "intervertebral disk" OR "annulus fibrosus" OR "nucleus pulposus" OR "endplate"). The search was not limited by the publication time, article type, or language. The identified papers were listed in descending order based on WoS citations. We included all experimental in vivo studies that evaluated intervertebral disc regeneration after SCT in animal and human models, as well as review papers discussing in vivo SCT for intervertebral disc regeneration. The included studies exploring multiple cell types should have at least one group investigating SC. The studies only investigated general cell without SC were excluded. Studies only involving in vitro experiment were also excluded. Two authors independently screened the articles. In the case of disagreements regarding study selection between the two authors, a third author made the final decision. The 100 highest-cited papers on SCT in IDD were included in this study.

Data management

After the final list was determined, data extraction and analysis were performed independently by two authors. If no consensus reached, a third author was consulted to make the final decision. The extracted data included the title, year, citation count, journal, article type, country, institution, author, source species, and type of stem cells. WoS citations were collected from the citation count for each paper, which were listed in the WoS database. Citations per year (since publication) was calculated. The main authors, including the first and corresponding authors, were recorded. Each paper was further analyzed using the free Dimensions app database (www.Dimensions.ai) following previous publications [14, 15]. The number of citations in the Dimensions database and the Altmetric Attention Score (AAS) for each paper were listed in the Dimensions free app [14, 15]. Dimensions citations and AAS of the top 100 papers were collected for further analysis. To analyze the relative capability of the research output between countries, the number of papers published in each country was standardized by population size and gross domestic product (GDP). The relationships among the number of papers, population, and GDP were analyzed. For each country, the latest data of population size and GDP for 2022 were obtained from the World Bank (www.worldbank.org).

Statistical analysis

Descriptive statistics, including total counts, average counts, and percentages, were used to depict the extracted data. Correlation analysis was performed to detect the relationship between WoS citations, AAS, average AAS, and Dimensions citations. The correlation coefficient of the Pearson's test (r) < 0.3 was defined as poor, 0.3–0.5 as low, 0.5–0.7 as moderate, 0.7–0.9 as high, and > 0.9 as very high. Statistical significance was set at $p < 0.05$.

Results

Top 100 list

A total of 2293 records were initially identified in the WoS database. All the records were extracted and

arranged in descending order based on the number of citations. After excluding 319 papers with 0 citations, 1974 papers with at least 1 citation were obtained. Based on reviewing of the title, abstract, and citation rank, 100 most cited papers were eligible of inclusion. The full texts of these papers were further reviewed. None of the papers were excluded. The 100 most cited papers on SCT in IDD were finally included (Table 1). The flowchart of study selection is depicted in Fig. 1.

The number of WoS citations per paper ranged from 13 to 372. When sorted by citations per year (since publication), the three papers with the highest total WoS citations were ranked differently: the most cited paper with 372 citations ranked fifth with 17.71 citations per year, the second most cited with 325 citations ranked fourth with 18.06 citations per year, and the third most cited with 324 citations ranked second with 24.92 citations per year (Table 2). Furthermore, according to citations per year (since publication), the top three papers with 33.75, 24.92, and 23.50 citations per year ranked 6th (270 citations), 3rd (324 citations), and 5th (282 citations) in total WoS citations respectively. The number of Dimensions citations ranged from 14 to 343. The highest AAS recorded were 535, followed by 97 and 93. The top three papers according to AAS all originated from America and also ranked as the top three when sorted by citations per year, with scores of 66.88, 13.86, and 13.29 respectively. Additionally, 27% of the studies, totaling 27, did not have an AAS. All studies were published in English.

Year of publication

Figure 2 presents the annual distribution of the top 100 studies, which were published between 2003 and 2021. The highest number of works were published in 2016, with 14 papers, followed by 2014 and 2019, each with 11 papers.

Article type

The article types of the top 100 works are shown in Fig. 3. A total of 80 original studies were included. The average number of citations of these works was 77.51. The remaining 20 papers were reviews, with an average of 65.30 citations.

Source journal

A total of 48 journals contributed to the 100 studies, with 19 journals publishing at least two of these studies (Table 3). The most frequently represented journals were *Spine* and *The Spine Journal*, each with 8 publications, followed by *International Orthopaedics* with 7, and the *Journal of Orthopaedic Research* with 6. *Spine* also had the highest total citations at 916, followed by *Biomaterials* with 776, and *The Spine Journal* with 490. Among the 48 journals, *Nature Reviews Rheumatology* had the highest impact factor (33.7), followed by *Nature Communications* (16.6) and *Advanced Drug Delivery Reviews* (16.1). No significant correlation was found between the average number of WoS citations and the average AAS ($r = -0.036$, $p = 0.882$).

Country distribution

Table 4 presents the country affiliations of the top 100 most-cited studies. Seventeen countries contributed to these influential papers. China led with 31 publications, followed by the United States with 22 and Japan with 14. In terms of total citations, Japan ranked first with 2,264 citations, followed by the United States with 1,539, and China with 1,439. Ten countries published at least two papers each. No significant correlation was observed between the average number of WoS citations and the average AAS ($r = 0.099$, $p = 0.705$). When research output was normalized by population, Australia ranked first (34.97), followed by Switzerland (34.49) and Ireland (19.89). Similarly, when normalized by GDP, Australia again ranked first (58.34), with Switzerland (36.91) and Sweden (31.88) following.

Institution of origin

The affiliated institutions that contributed two or more papers are listed in Table 5, with fifteen institutions included in the list. Tokai University School of Medicine, with 11 papers, had the leading publication record, followed by The University of Hong Kong (8), and Southeast University (4). Tokai University School of Medicine had the highest total citations (1950), followed by the University of Hong Kong (550), and the University of Valladolid and CSIC (446). Regarding the average number of citations, the University of Valladolid and CSIC ranked first (233.00), followed by Tokai University School of Medicine (177.27), and the University of California (140.67).

Main author

Table 6 lists the first and corresponding authors who contributed two or more papers. Sakai D led the list with 10 papers, followed by Cheung KMC with 6, and Melrose J, Pettine K, Lotz JC, and Murphy MB, each with 3 papers. Sakai D also achieved the highest total number of citations (1,911), followed by Cheung KMC (451) and García-Sancho J (446). In terms of average citations per paper, García-Sancho J had the highest average (233.00), followed by Sakai D (191.10) and Lotz JC (140.67). When considering average citations per year (since publication), García-Sancho J again ranked highest (21.18), with Sakai D (12.59) and Vadalà G (12.44) following.

Table 1 The top 100 works on SCT in IDD according to the number of WoS citations

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
1	Sakai D	2003	Transplantation of mesenchymal stem cells embedded in Atelocollagen gel to the intervertebral disc: a potential therapeutic model for disc degeneration	[31]	*Biomaterials*	372	17.71	339	9	0.43
2	Sakai D	2006	Regenerative effects of transplanting mesenchymal stem cells embedded in atelocollagen to the degenerated intervertebral disc	[32]	*Biomaterials*	325	18.06	307	6	0.33
3	Orozco L	2011	Intervertebral disc repair by autologous mesenchymal bone marrow cells: a pilot study	[33]	*Transplantation*	324	24.92	343	32	2.46
4	Sakai D	2005	Differentiation of mesenchymal stem cells transplanted to a rabbit degenerative disc model: potential and limitations for stem cell therapy in disc regeneration	[34]	*Spine*	316	16.63	295	19	1.00
5	Sakai D	2012	Exhaustion of nucleus pulposus progenitor cells with ageing and degeneration of the intervertebral disc	[35]	*Nature Communications*	282	23.50	295	8	0.67
6	Richardson SM	2016	Mesenchymal stem cells in regenerative medicine: Focus on articular cartilage and intervertebral disc regeneration	[36]	*Methods*	270	33.75	315	7	0.88
7	Crevensten G	2004	Intervertebral disc cell therapy for regeneration: Mesenchymal stem cell implantation in rat intervertebral discs	[37]	*Annals of Biomedical Engineering*	267	13.35	268	6	0.30
8	Hiyama A	2008	Transplantation of mesenchymal stem cells in a canine disc degeneration model	[38]	*Journal of Orthopaedic Research*	207	12.94	204	9	0.56
9	Vadalà G	2012	Mesenchymal stem cells injection in degenerated intervertebral disc: cell leakage may induce osteophyte formation	[39]	*Journal of Tissue Engineering and Regenerative Medicine*	201	16.75	214	10	0.83

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
10	Yoshikawa T	2010	Disc regeneration therapy using marrow mesenchymal cell transplantation: a report of two case studies	[40]	*Spine*	184	13.14	190	0	0.00
11	Sobajima S	2008	Feasibility of a stem cell therapy for intervertebral disc degeneration	[41]	*Spine Journal*	172	10.75	166	5	0.31
12	Henriksson HB	2009	Transplantation of human mesenchymal stems cells into intervertebral discs in a xenogeneic porcine model	[42]	*Spine*	161	10.73	164	6	0.40
13	Ganey T	2009	Intervertebral disc repair using adipose tissue-derived stem and regenerative cells experiments in a canine model	[43]	*Spine*	150	10.00	150	5	0.33
14	Leung VY	2006	Regeneration of intervertebral disc by mesenchymal stem cells: potentials, limitations, and future direction	[44]	*European Spine Journal*	148	8.22	148	3	0.17
15	Zhang YG	2005	Bone mesenchymal stem cells transplanted into rabbit intervertebral discs can increase proteoglycans	[45]	*Clinical Orthopaedics and Related Research*	134	7.05	138	3	0.16
16	Sakai D	2008	Future perspectives of cell-based therapy for intervertebral disc disease	[46]	*European Spine Journal*	134	8.38	129	0	0.00
17	Serigano K	2010	Effect of cell number on mesenchymal stem cell transplantation in a canine disc degeneration model	[47]	*Journal of Orthopaedic Research*	133	9.50	132	0	0.00
18	Noriega DC	2017	Intervertebral disc repair by allogeneic mesenchymal bone marrow cells: a randomized controlled trial	[48]	*Transplantation*	122	17.43	127	20	2.86
19	Yang Fan	2009	Mesenchymal stem cells arrest intervertebral disc degeneration through chondrocytic differentiation and stimulation of endogenous cells	[49]	*Molecular Therapy*	118	7.87	120	3	0.20

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
20	Miyamoto T	2010	Intradiscal transplantation of synovial mesenchymal stem cells prevents intervertebral disc degeneration through suppression of matrix metalloproteinase-related genes in nucleus pulposus cells in rabbits	[50]	*Arthritis Research & Therapy*	105	7.50	108	3	0.21
21	Pettine K	2015	Percutaneous injection of autologous bone marrow concentrate cells significantly reduces lumbar discogenic pain through 12 months	[51]	*Stem Cells*	102	11.33	120	6	0.67
22	Acosta FL Jr	2011	Porcine intervertebral disc repair using allogeneic juvenile articular chondrocytes or mesenchymal stem cells	[52]	*Tissue Engineering Part A*	101	7.77	115	4	0.31
23	Kumar H	2017	Safety and tolerability of intradiscal implantation of combined autologous adipose-derived mesenchymal stem cells and hyaluronic acid in patients with chronic discogenic low back pain: 1-year follow-up of a phase I study	[53]	*Stem Cell Research & Therapy*	95	13.57	95	2	0.29
24	Yang H	2010	Transplanted mesenchymal stem cells with pure fibrinous gelatin-transforming growth factor-beta 1 decrease rabbit intervertebral disc degeneration	[54]	*Spine Journal*	85	6.07	78	6	0.43
25	Jeong JH	2010	Regeneration of intervertebral discs in a rat disc degeneration model by implanted adipose-tissue-derived stromal cells	[55]	*Acta Neurochirurgica*	83	5.93	74	0	0.00
26	Hoogendoorn RJ	2008	Adipose stem cells for intervertebral disc regeneration: current status and concepts for the future	[56]	*Journal of Cellular and Molecular Medicine*	74	4.63	75	3	0.19

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
27	Feng G	2011	Transplantation of mesenchymal stem cells and nucleus pulposus cells in a degenerative disc model in rabbits: a comparison of 2 cell types as potential candidates for disc regeneration Laboratory investigation	[57]	*Journal of Neurosurgery: Spine*	74	5.69	76	0	0.00
28	Yim RL	2014	A systematic review of the safety and efficacy of mesenchymal stem cells for disc degeneration: insights and future directions for regenerative therapeutics	[58]	*Stem Cells and Development*	74	7.40	74	6	0.60
29	Sakai D	2017	Cell therapy for intervertebral disc repair: Clinical perspective	[59]	*Journal of Orthopaedic Translation*	72	10.29	80	6	0.86
30	Clouet J	2019	Intervertebral disc regeneration: From cell therapy to the development of novel bioinspired endogenous repair strategies	[60]	*Advanced Drug Delivery Reviews*	71	14.20	93	2	0.40
31	Leung VY	2014	Mesenchymal stem cells reduce intervertebral disc fibrosis and facilitate repair	[61]	*Stem Cells*	71	7.10	76	8	0.80
32	Haufe SM	2006	Intradiscal injection of hematopoietic stem cells in an attempt to rejuvenate the intervertebral discs	[62]	*Stem Cells and Development*	70	3.89	77	3	0.17
33	Ho G	2008	Effect of severity of intervertebral disc injury on mesenchymal stem cell-based regeneration	[63]	*Connective Tissue Research*	69	4.31	64	3	0.19
34	Wei A	2009	The fate of transplanted xenogeneic bone marrow-derived stem cells in rat intervertebral discs	[64]	*Journal of Orthopaedic Research*	66	4.40	65	0	0.00
35	Vadalà G	2016	Stem cells sources for intervertebral disc regeneration	[65]	*World Journal of Stem Cells*	65	8.13	65	2	0.25
36	Zeng Y	2015	Injectable microcryogels reinforced alginate encapsulation of mesenchymal stromal cells for leak-proof delivery and alleviation of canine disc degeneration	[66]	*Biomaterials*	65	7.22	70	0	0.00

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
37	Elabd C	2016	Intra-discal injection of autologous, hypoxic cultured bone marrow-derived mesenchymal stem cells in five patients with chronic lower back pain: a long-term safety and feasibility study	[67]	*Journal of Translational Medicine*	64	8.00	73	535	66.88
38	Pettine K	2017	Autologous bone marrow concentrate intradiscal injection for the treatment of degenerative disc disease with three-year follow-up	[68]	*International Orthopaedics*	62	8.86	66	7	1.00
39	Yang H	2015	TGF-β I suppresses inflammation in cell therapy for intervertebral disc degeneration	[69]	*Scientific Reports*	59	6.56	46	1	0.11
40	Centeno C	2017	Treatment of lumbar degenerative disc disease-associated radicular pain with culture-expanded autologous mesenchymal stem cells: a pilot study on safety and efficacy	[70]	*Journal of Translational Medicine*	58	8.29	66	93	13.29
41	Wang H	2014	Utilization of stem cells in alginate for nucleus pulposus tissue engineering	[71]	*Tissue Engineering Part A*	58	5.80	56	1	0.10
42	Chun HJ	2012	Tansplantation of human adipose-derived stem cells in a rabbit model of traumatic degeneration of lumbar discs	[72]	*World Neurosurgery*	58	4.83	51	1	0.08
43	Liang CZ	2013	Dual release of dexamethasone and TGF-β3 from polymeric microspheres for stem cell matrix accumulation in a rat disc degeneration model	[73]	*Acta Biomaterialia*	56	5.09	56	3	0.27
44	Murrell W	2009	Olfactory stem cells can be induced to express chondrogenic phenotype in a rat intervertebral disc injury model	[74]	*Spine Journal*	56	3.73	53	0	0.00
45	Allon AA	2010	Structured coculture of stem cells and disc cells prevent disc degeneration in a rat model	[75]	*Spine Journal*	54	3.86	61	0	0.00

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
46	Pettine K	2016	Treatment of discogenic back pain with autologous bone marrow concentrate injection with minimum two year follow-up	[76]	*International Orthopaedics*	53	6.63	68	37	4.63
47	Zhou X	2018	Genipin cross-linked type II collagen/chondroitin sulfate composite hydrogel-like cell delivery system induces differentiation of adipose-derived stem cells and regenerates degenerated nucleus pulposus	[77]	*Acta Biomaterialia*	52	8.67	60	1	0.17
48	Comella K	2017	Effects of the intradiscal implantation of stromal vascular fraction plus platelet rich plasma in patients with degenerative disc disease	[78]	*Journal of Translational Medicine*	52	7.43	66	97	13.86
49	Jeong JH	2009	Human mesenchymal stem cells implantation into the degenerated coccygeal disc of the rat	[79]	*Cytotechnology*	49	3.27	45	0	0.00
50	Sakai D	2015	Migration of bone marrow-derived cells for endogenous repair in a new tail-looping disc degeneration model in the mouse: a pilot study	[80]	*Spine Journal*	49	5.44	50	1	0.11
51	Pang X	2014	Human umbilical cord mesenchymal stem cell transplantation for the treatment of chronic discogenic low back pain	[81]	*Pain Physician*	48	4.80	51	0	0.00
52	Binch ALA	2021	Cell-based strategies for IVD repair: clinical progress and translational obstacles	[82]	*Nature Reviews Rheumatology*	46	15.33	55	26	8.67
53	Loibl M	2019	Controversies in regenerative medicine: Should intervertebral disc degeneration be treated with mesenchymal stem cells?	[83]	*JOR Spine*	45	9.00	49	0	0.00
54	Oehme D	2014	Mesenchymal progenitor cells combined with pentosan polysulfate mediating disc regeneration at the time of microdiscectomy: a preliminary study in an ovine model	[84]	*Journal of Neurosurgery: Spine*	45	4.50	54	4	0.40

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
55	Bendtsen M	2011	Autologous stem cell therapy maintains vertebral blood flow and contrast diffusion through the endplate in experimental intervertebral disc degeneration	[85]	*Spine*	44	4.89	46	0	0.00
56	Wang Z	2015	Efficacy of intervertebral disc regeneration with stem cells: a systematic review and meta-analysis of animal controlled trials	[86]	*Gene*	44	3.38	50	23	2.56
57	Marfia G	2014	Potential use of human adipose mesenchymal stromal cells for intervertebral disc regeneration: a preliminary study on biglycan-deficient murine model of chronic disc degeneration	[87]	*Arthritis Research & Therapy*	43	4.30	43	6	0.60
58	Hee HT	2010	Effects of implantation of bone marrow mesenchymal stem cells, disc distraction and combined therapy on reversing degeneration of the intervertebral disc	[88]	*Journal of Bone and Joint Surgery: British Volume*	42	3.00	43	0	0.00
59	Anderson DG	2005	Cell-based therapy for disc repair	[89]	*Spine Journal*	41	2.16	47	0	0.00
60	Schol J	2019	Cell therapy for intervertebral disc herniation and degenerative disc disease: clinical trials	[90]	*International Orthopaedics*	39	7.80	49	3	0.60
61	Omlor GW	2010	Methods to monitor distribution and metabolic activity of mesenchymal stem cells following in vivo injection into nucleotomized porcine intervertebral discs	[91]	*European Spine Journal*	39	2.79	41	0	0.00
62	Zeckser J	2016	Multipotent mesenchymal stem cell treatment for discogenic low back pain and disc degeneration	[92]	*Stem Cells International*	37	4.63	38	5	0.63
63	Cai F	2015	Evaluation of intervertebral disc regeneration with implantation of bone marrow mesenchymal stem cells (BMSCs) using quantitative T2 mapping: a study in rabbits	[93]	*International Orthopaedics*	36	4.00	35	0	0.00

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
64	Sheyn D	2019	Human iPSCs can be differentiated into notochordal cells that reduce intervertebral disc degeneration in a porcine model	[94]	*Theranostics*	34	6.80	42	6	1.20
65	Wang YT	2010	Regeneration potential and mechanism of bone marrow mesenchymal stem cell transplantation for treating intervertebral disc degeneration	[95]	*Journal of Orthopaedic Science*	33	2.36	25	0	0.00
66	Sun W	2014	Sox9 gene transfer enhanced regenerative effect of bone marrow mesenchymal stem cells on the degenerated intervertebral disc in a rabbit model	[96]	*PLoS One*	31	3.10	26	0	0.00
67	Chen X	2016	A comparison between nucleus pulposus-derived stem cell transplantation and nucleus pulposus cell transplantation for the treatment of intervertebral disc degeneration in a rabbit model	[97]	*International Journal of Surgery*	30	3.75	29	0	0.00
68	Gou S	2014	Stem cell therapy for intervertebral disk regeneration	[98]	*American Journal of Physical Medicine & Rehabilitation*	30	3.00	33	3	0.30
69	Tam V	2014	A comparison of intravenous and intradiscal delivery of multipotential stem cells on the healing of injured intervertebral disk	[99]	*Journal of Orthopaedic Research*	30	3.00	34	6	0.60
70	Zhou X	2018	Injectable decellularized nucleus pulposus-based cell delivery system for differentiation of adipose-derived stem cells and nucleus pulposus regeneration	[100]	*Acta Biomaterialia*	30	5.00	37	0	0.00
71	Hussain I	2019	Mesenchymal stem cell-seeded high-density collagen gel for annular repair: 6-week results from in vivo sheep models	[101]	*Neurosurgery*	29	5.80	31	2	0.40
72	Freeman BJC	2016	Allogeneic mesenchymal precursor cells promote healing in postero-lateral annular lesions and improve indices of lumbar intervertebral disc degeneration in an ovine model	[102]	*Spine*	28	3.50	34	3	0.38

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
73	Ahn J	2015	Transplantation of human Wharton's jelly-derived mesenchymal stem cells highly expressing TGFβ receptors in a rabbit model of disc degeneration	[103]	*Stem Cell Research & Therapy*	28	3.11	32	4	0.44
74	Shu CC	2017	A histopathological scheme for the quantitative scoring of intervertebral disc degeneration and the therapeutic utility of adult mesenchymal stem cells for intervertebral disc regeneration	[104]	*International Journal of Molecular Sciences*	27	3.86	31	4	0.57
75	Melrose J	2016	Strategies in regenerative medicine for intervertebral disc repair using mesenchymal stem cells and bioscaffolds	[105]	*Regenerative Medicine*	26	3.25	26	1	0.13
76	Migliorini F	2019	Autogenic mesenchymal stem cells for intervertebral disc regeneration	[106]	*International Orthopaedics*	26	5.20	31	2	0.40
77	Ishiguro H	2019	Intervertebral disc regeneration with an adipose mesenchymal stem cell-derived tissue-engineered construct in a rat nucleotomy model	[107]	*Acta Biomaterialia*	25	5.00	30	0	0.00
78	Li YY	2014	Delivering mesenchymal stem cells in collagen microsphere carriers to rabbit degenerative disc: reduced risk of osteophyte formation	[108]	*Tissue Engineering Part A*	25	2.50	35	1	0.10
79	Wang F	2019	Injectable hydrogel combined with nucleus pulposus-derived mesenchymal stem cells for the treatment of degenerative intervertebral disc in rats	[109]	*Stem Cells International*	25	5.00	32	0	0.00
80	Xu J	2016	BMP7 enhances the effect of BMSCs on extracellular matrix remodeling in a rabbit model of intervertebral disc degeneration	[110]	*FEBS Journal*	22	2.75	24	4	0.50
81	Hiraishi S	2018	Discogenic cell transplantation directly from a cryopreserved state in an induced intervertebral disc degeneration canine model	[111]	*JOR Spine*	21	3.50	21	57	9.50

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
82	Wang W	2018	Transplantation of hypoxic-Preconditioned bone mesenchymal stem cells retards intervertebral disc degeneration via enhancing implanted cell survival and migration in rats	[112]	*Stem Cells International*	21	3.50	30	0	0.00
83	Silverman LI	2020	In vitro and in vivo evaluation of discogenic cells, an investigational cell therapy for disc degeneration	[113]	*Spine Journal*	19	4.75	18	52	13.00
84	Liao JC	2016	Cell therapy using bone marrow-derived stem cell overexpressing BMP-7 for degenerative discs in a rat tail disc model	[114]	*International Journal of Molecular Sciences*	19	2.38	20	1	0.13
85	James G	2016	Mesenchymal stem cell treatment of intervertebral disc lesion prevents fatty infiltration and fibrosis of the multifidus muscle, but not cytokine and muscle fiber	[115]	*Spine*	19	2.38	21	2	0.25
86	Maidhof R	2017	Timing of mesenchymal stem cell delivery impacts the fate and therapeutic potential in intervertebral disc repair	[116]	*Journal of Orthopaedic Research*	19	2.71	21	1	0.14
87	Steffen F	2017	Bone marrow-derived mesenchymal stem cells as autologous therapy in dogs with naturally occurring intervertebral disc disease: feasibility, safety, and preliminary results	[117]	*Tissue Engineering Part C: Methods*	18	2.57	20	70	10.00
88	Wang SZ	2016	Intervertebral disc regeneration using platelet-rich plasma-containing bone marrow-derived mesenchymal stem cells: A preliminary investigation	[118]	*Molecular Medicine Reports*	18	2.25	16	1	0.13
89	Wei JN	2016	Transplantation of CXCR4 overexpressed mesenchymal stem cells augments regeneration in degenerated intervertebral discs	[119]	*DNA and Cell Biology*	18	2.25	22	6	0.75

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
90	Henriksson HB	2019	The traceability of mesenchymal stromal cells after injection into degenerated discs in patients with low back pain	[120]	*Stem Cells and Development*	17	3.40	19	3	0.60
91	Beeravolu N	2018	Human umbilical cord derivatives regenerate intervertebral disc	[121]	*Journal of Tissue Engineering and Regenerative Medicine*	16	2.67	20	13	2.17
92	Chiang ER	2019	Use of allogeneic hypoxic mesenchymal stem cells for treating disc degeneration in rabbits	[122]	*Journal of Orthopaedic Research*	16	3.20	18	2	0.40
93	Croft AS	2021	The application of mesenchymal stromal cells and their homing capabilities to regenerate the intervertebral disc	[123]	*International Journal of Molecular Sciences*	16	5.33	19	2	0.67
94	Sun Y	2019	Clinical trials of intervertebral disc regeneration: current status and future developments	[124]	*International Orthopaedics*	15	3.00	20	1	0.20
95	Hang D	2017	One-stage positron emission tomography and magnetic resonance imaging to assess mesenchymal stem cell survival in a canine model of intervertebral disc degeneration	[125]	*Stem Cells and Development*	15	2.14	18	0	0.00
96	Hou Y	2016	Study design: in vitro and in vivo assessment of bone morphogenic protein 2 combined with platelet-rich plasma on treatment of disc degeneration	[126]	*International Orthopaedics*	15	1.88	14	0	0.00
97	Daly CD	2018	Mesenchymal progenitor cells primed with pentosan polysulfate promote lumbar intervertebral disc regeneration in an ovine model of microdiscectomy	[127]	*Spine Journal*	14	2.33	21	3	0.50
98	Feng G	2020	Nanofibrous spongy microspheres to deliver rabbit mesenchymal stem cells and anti-miR-199a to regenerate nucleus pulposus and prevent calcification	[128]	*Biomaterials*	14	3.50	18	1	0.25

Table 1 (continued)

Rank	First Author	Year	Title	Reference	Journal	WoS Citations	WoS Citations per Year (Since Publication)	Dimensions Citations	AAS	AAS per Year (Since Publication)
99	Zhou Y	2014	Effects of transplantation of hTIMP-1-expressing bone marrow mesenchymal stem cells on the extracellular matrix of degenerative intervertebral discs in an in vivo rabbit model	[129]	*Spine*	14	1.40	20	1	0.10
100	Shu CC	2018	Efficacy of administered mesenchymal stem cells in the initiation and co-ordination of repair processes by resident disc cells in an ovine (Ovis aries) large destabilizing lesion model of experimental disc degeneration	[130]	*JOR Spine*	13	2.17	17	0	0.00

WoS Web of Science, *AAS* Altmetric Attention Score

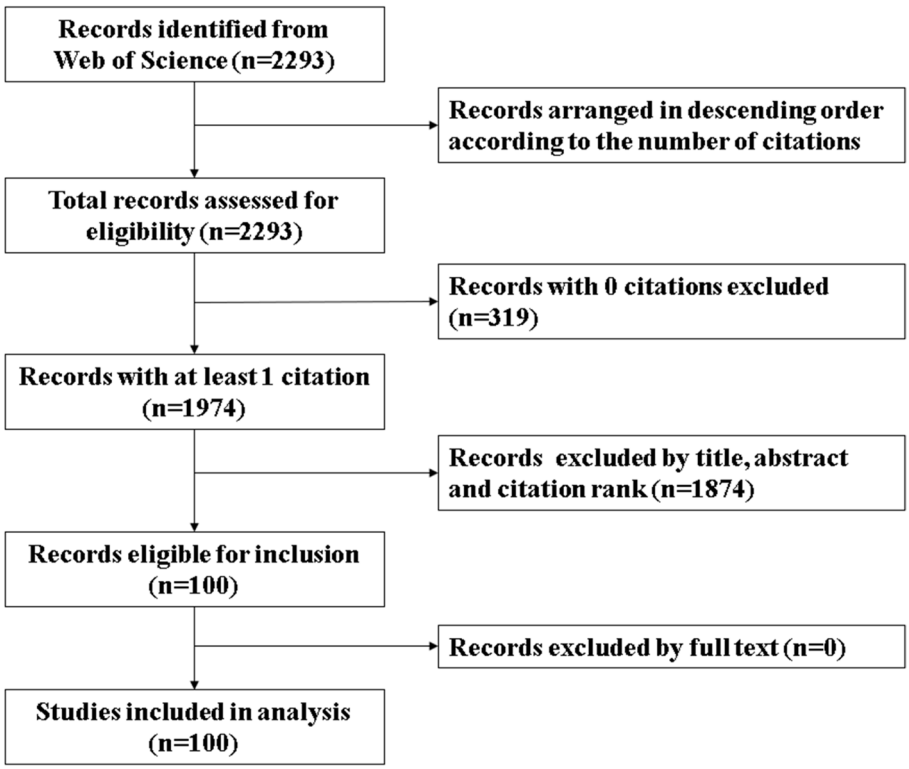

Fig. 1 Flowchart detailing the selection process for the top 100 works on SCT in IDD

Classification of species

Figure 4 presents the classification of the species used in the 80 original studies on SCT. A total of six species were represented across these studies. Rabbits were the most commonly studied species, appearing in 33 papers (41.25%), followed by rats in 17 studies (21.25%), humans in 11 studies (13.75%), and sheep and dogs in 7 studies each (8.75%). Pigs were the least represented, featured in 5 studies (6.25%).

In the 11 clinical trials, sample sizes varied from 2 to 33 participants. These trials explored various spinal conditions, including low back pain, low back pain with radicular symptoms, lumbar discogenic pain, and lumbar spinal stenosis. The follow-up periods ranged from 1 to 6 years. Bone marrow-derived stem cells (BMSCs) were the most frequently employed in 7 trials, while adipose-derived stem cells (ADSCs) were used in 2 trials. Umbilical cord-derived stem cells (UCSCs) and hematopoietic stem cells (HSCs) were each utilized in 1 trial.

Category of stem cells

Figure 5 illustrates the types of stem cells investigated in the 80 original studies. Among these, most studies (79) focused on a single type of stem cell, while one study explored four different types. In total, ten types of stem cells were examined, including BMSCs, ADSCs, nucleus pulposus-derived stem cells (NPSCs), UCSCs, induced pluripotent stem cells (iPSCs), cartilage endplate-derived stem cells (CESCs), annulus fibrosus-derived stem cells (AFSCs), HSCs, olfactory stem cells (OSCs), and synovial stem cells (SSCs). BMSCs were the most frequently discussed, featured in 56 studies (70.00%), followed by ADSCs in 11 studies (13.75%), and NPSCs in 6 studies (7.50%).

Correlation analysis

The citation counts of the top 100 WoS works were very high correlated with their citations in Dimensions ($r=0.994$, $p<0.001$). Figure 6 shows a clear linear correlation between WoS citations and Dimensions citations. In addition, a poor correlation was found between the number of citations of WoS and AAS ($r=0.000$, $p=0.996$) (Fig. 7).

Discussion

LBP has become the leading cause of disability worldwide, severely influencing the quality of life of patients and placing a huge burden on both society and the economy [2, 3, 5, 6]. LBP is associated with IDD [9–11, 98], for which the current strategies are limited and cannot solve the root cause [11, 98]. Therefore, there is a crucial need to develop new treatment options to retard

Table 2 The top 100 works on SCT in IDD according to WoS citations per year (since publication)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
1	Richardson SM	2016	Mesenchymal stem cells in regenerative medicine: Focus on articular cartilage and intervertebral disc regeneration	[36]	*Methods*	270	33.75	315	7
2	Orozco L	2011	Intervertebral Disc Repair by Autologous Mesenchymal Bone Marrow Cells: A Pilot Study	[33]	*Transplantation*	324	24.92	343	32
3	Sakai D	2012	Exhaustion of nucleus pulposus progenitor cells with ageing and degeneration of the intervertebral disc	[35]	*Nature Communications*	282	23.50	295	8
4	Sakai D	2006	Regenerative effects of transplanting mesenchymal stem cells embedded in atelocollagen to the degenerated intervertebral disc	[32]	*Biomaterials*	325	18.06	307	6
5	Sakai D	2003	Transplantation of mesenchymal stem cells embedded in Atelocollagen((R)) gel to the intervertebral disc: a potential therapeutic model for disc degeneration	[31]	*Biomaterials*	372	17.71	339	9
6	Noriega DC	2017	Intervertebral Disc Repair by Allogeneic Mesenchymal Bone Marrow Cells: A Randomized Controlled Trial	[48]	*Transplantation*	122	17.43	127	20
7	Vadalà G	2012	Mesenchymal stem cells injection in degenerated intervertebral disc: cell leakage may induce osteophyte formation	[39]	*Journal of Tissue Engineering and Regenerative Medicine*	201	16.75	214	10
8	Sakai D	2005	Differentiation of mesenchymal stem cells transplanted to a rabbit degenerative disc model - Potential and limitations for stem cell therapy in disc regeneration	[34]	*Spine*	316	16.63	295	19
9	Binch ALA	2021	Cell-based strategies for IVD repair: clinical progress and translational obstacles	[82]	*Nature Reviews Rheumatology*	46	15.33	55	26
10	Clouet J	2019	Intervertebral disc regeneration: From cell therapy to the development of novel bioinspired endogenous repair strategies	[60]	*Advanced Drug Delivery Reviews*	71	14.20	93	2
11	Kumar H	2017	Safety and tolerability of intradiscal implantation of combined autologous adipose-derived mesenchymal stem cells and hyaluronic acid in patients with chronic discogenic low back pain: 1-year follow-up of a phase I study	[53]	*Stem Cell Research & Therapy*	95	13.57	95	2
12	Crevensten G	2004	Intervertebral disc cell therapy for regeneration: Mesenchymal stem cell implantation in rat intervertebral discs	[37]	*Annals of Biomedical Engineering*	267	13.35	268	6

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
13	Yoshikawa T	2010	Disc Regeneration Therapy Using Marrow Mesenchymal Cell transplantation A Report of Two Case Studies	[40]	*Spine*	184	13.14	190	0
14	Hiyama A	2008	Transplantation of mesenchymal stem cells in a canine disc degeneration model	[38]	*Journal of Orthopaedic Research*	207	12.94	204	9
15	Pettine K	2015	Percutaneous injection of Autologous Bone Marrow Concentrate Cells Significantly Reduces Lumbar Discogenic Pain Through 12 Months	[51]	*Stem Cells*	102	11.33	120	6
16	Sobajima S	2008	Feasibility of a stem cell therapy for intervertebral disc degeneration	[41]	*Spine Journal*	172	10.75	166	5
17	Henriksson HB	2009	Transplantation of Human Mesenchymal Stems Cells Into Intervertebral Discs in a Xenogeneic Porcine Model	[42]	*Spine*	161	10.73	164	6
18	Sakai D	2017	Cell therapy for intervertebral disc repair: Clinical perspective	[59]	*Journal of Orthopaedic Translation*	72	10.29	80	6
19	Ganey T	2009	Intervertebral Disc Repair Using Adipose Tissue-Derived Stem and Regenerative Cells Experiments in a Canine Model	[43]	*Spine*	150	10.00	150	5
20	Serigano K	2010	Effect of Cell Number on Mesenchymal Stem Cell transplantation in a Canine Disc Degeneration Model	[47]	*Journal of Orthopaedic Research*	133	9.50	132	0
21	Loibl M	2019	Controversies in regenerative medicine: Should intervertebral disc degeneration be treated with mesenchymal stem cells?	[83]	*JOR Spine*	45	9.00	49	0
22	Pettine K	2017	Autologous bone marrow concentrate intradiscal injection for the treatment of degenerative disc disease with three-year follow-up	[68]	*International Orthopaedics*	62	8.86	66	7
23	Zhou X	2018	Genipin cross-linked type II collagen/chondroitin sulfate composite hydrogel-like cell delivery system induces differentiation of adipose-derived stem cells and regenerates degenerated nucleus pulposus	[77]	*Acta Biomaterialia*	52	8.67	60	1
24	Sakai D	2008	Future perspectives of cell-based therapy for intervertebral disc disease	[46]	*European Spine Journal*	134	8.38	129	0

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
25	Centeno C	2017	Treatment of lumbar degenerative disc disease-associated radicular pain with culture-expanded autologous mesenchymal stem cells: a pilot study on safety and efficacy	[70]	*Journal of Translational Medicine*	58	8.29	66	93
26	Leung VY	2006	Regeneration of intervertebral disc by mesenchymal stem cells: potentials, limitations, and future direction	[44]	*European Spine Journal*	148	8.22	148	3
27	Vadalà G	2016	Stem cells sources for intervertebral disc regeneration	[65]	*World Journal of Stem Cells*	65	8.13	65	2
28	Elabd C	2016	Intra-discal injection of autologous, hypoxic cultured bone marrow-derived mesenchymal stem cells in five patients with chronic lower back pain: a long-term safety and feasibility study	[67]	*Journal of Translational Medicine*	64	8.00	73	535
29	Yang Fan	2009	Mesenchymal Stem Cells Arrest Intervertebral Disc Degeneration Through Chondrocytic Differentiation and Stimulation of Endogenous Cells	[49]	*Molecular Therapy*	118	7.87	120	3
30	Schol J	2019	Cell therapy for intervertebral disc herniation and degenerative disc disease: clinical trials	[90]	*International Orthopaedics*	39	7.80	49	3
31	Acosta FL Jr	2011	Porcine Intervertebral Disc Repair Using Allogeneic Juvenile Articular Chondrocytes or Mesenchymal Stem Cells	[52]	*Tissue Engineering Part A*	101	7.77	115	4
32	Miyamoto T	2010	Intradiscal transplantation of synovial mesenchymal stem cells prevents intervertebral disc degeneration through suppression of matrix metalloproteinase-related genes in nucleus pulposus cells in rabbits	[50]	*Arthritis Research & Therapy*	105	7.50	108	3
33	Comella K	2017	Effects of the intradiscal implantation of stromal vascular fraction plus platelet rich plasma in patients with degenerative disc disease	[78]	*Journal of Translational Medicine*	52	7.43	66	97
34	Yim RL	2014	A Systematic Review of the Safety and Efficacy of Mesenchymal Stem Cells for Disc Degeneration: Insights and Future Directions for Regenerative Therapeutics	[58]	*Stem Cells and Development*	74	7.40	74	6

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
35	Zeng Y	2015	Injectable microcryogels reinforced alginate encapsulation of mesenchymal stromal cells for leak-proof delivery and alleviation of canine disc degeneration	[66]	*Biomaterials*	65	7.22	70	0
36	Leung VY	2014	Mesenchymal Stem Cells Reduce Intervertebral Disc Fibrosis and Facilitate Repair	[61]	*Stem Cells*	71	7.10	76	8
37	Zhang YG	2005	Bone mesenchymal stem cells transplanted into rabbit intervertebral discs can increase proteoglycans	[45]	*Clinical Orthopaedics and Related Research*	134	7.05	138	3
38	Sheyn D	2019	Human iPSCs can be differentiated into notochordal cells that reduce intervertebral disc degeneration in a porcine model	[94]	*Theranostics*	34	6.80	42	6
39	Pettine K	2016	Treatment of discogenic back pain with autologous bone marrow concentrate injection with minimum two year follow-up	[76]	*International Orthopaedics*	53	6.63	68	37
40	Yang H	2015	TGF-beta I Suppresses Inflammation in Cell Therapy for Intervertebral Disc Degeneration	[69]	*Scientific Reports*	59	6.56	46	1
41	Yang H	2010	Transplanted mesenchymal stem cells with pure fibrinous gelatin-transforming growth factor-beta 1 decrease rabbit intervertebral disc degeneration	[54]	*Spine Journal*	85	6.07	78	6
42	Jeong JH	2010	Regeneration of intervertebral discs in a rat disc degeneration model by implanted adipose-tissue-derived stromal cells	[55]	*Acta Neurochirurgica*	83	5.93	74	0
43	Wang H	2014	Utilization of Stem Cells in Alginate for Nucleus Pulposus Tissue Engineering	[71]	*Tissue Engineering Part A*	58	5.80	56	1
44	Hussain I	2019	Mesenchymal Stem Cell-Seeded High-Density Collagen Gel for Annular Repair: 6-Week Results From In Vivo Sheep Models	[101]	*Neurosurgery*	29	5.80	31	2
45	Feng G	2011	Transplantation of mesenchymal stem cells and nucleus pulposus cells in a degenerative disc model in rabbits: a comparison of 2 cell types as potential candidates for disc regeneration Laboratory investigation	[57]	*Journal of Neurosurgery: Spine*	74	5.69	76	0
46	Sakai D	2015	Migration of bone marrow-derived cells for endogenous repair in a new tail-looping disc degeneration model in the mouse: a pilot study	[80]	*Spine Journal*	49	5.44	50	1

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
47	Croft AS	2021	The Application of Mesenchymal Stromal Cells and Their Homing Capabilities to Regenerate the Intervertebral Disc	[123]	*International Journal of Molecular Sciences*	16	5.33	19	2
48	Migliorini F	2019	Autogenic mesenchymal stem cells for intervertebral disc regeneration	[106]	*International Orthopaedics*	26	5.20	31	2
49	Liang CZ	2013	Dual release of dexamethasone and TGF-beta 3 from polymeric microspheres for stem cell matrix accumulation in a rat disc degeneration model	[73]	*Acta Biomaterialia*	56	5.09	56	3
50	Zhou X	2018	Injectable decellularized nucleus pulposus-based cell delivery system for differentiation of adipose-derived stem cells and nucleus pulposus regeneration	[100]	*Acta Biomaterialia*	30	5.00	37	0
51	Wang F	2019	Injectable Hydrogel Combined with Nucleus Pulposus-Derived Mesenchymal Stem Cells for the Treatment of Degenerative Intervertebral Disc in Rats	[109]	*Stem Cells International*	25	5.00	32	0
52	Ishiguro H	2019	Intervertebral disc regeneration with an adipose mesenchymal stem cell-derived tissue-engineered construct in a rat nucleotomy model	[107]	*Acta Biomaterialia*	25	5.00	30	0
53	Wang Z	2015	Efficacy of intervertebral disc regeneration with stem cells - A systematic review and meta-analysis of animal controlled trials	[86]	*Gene*	44	4.89	50	23
54	Chun HJ	2012	Transplantation of Human Adipose-Derived Stem Cells in a Rabbit Model of Traumatic Degeneration of Lumbar Discs	[72]	*World Neurosurgery*	58	4.83	51	1
55	Pang X	2014	Human Umbilical Cord Mesenchymal Stem Cell transplantation for the Treatment of Chronic Discogenic Low Back Pain	[81]	*Pain Physician*	48	4.80	51	0
56	Silverman LI	2020	In vitro and in vivo evaluation of discogenic cells, an investigational cell therapy for disc degeneration	[113]	*Spine Journal*	19	4.75	18	52
57	Hoogendoorn RJ	2008	Adipose stem cells for intervertebral disc regeneration: current status and concepts for the future	[56]	*Journal of Cellular and Molecular Medicine*	74	4.63	75	3
58	Zeckser J	2016	Multipotent Mesenchymal Stem Cell Treatment for Discogenic Low Back Pain and Disc Degeneration	[92]	*Stem Cells International*	37	4.63	38	5

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
59	Oehme D	2014	Mesenchymal progenitor cells combined with pentosan polysulfate mediating disc regeneration at the time of microdiscectomy: a preliminary study in an ovine model	[84]	*Journal of Neurosurgery: Spine*	45	4.50	54	4
60	Wei A	2009	The Fate of transplanted Xenogeneic Bone Marrow-Derived Stem Cells in Rat Intervertebral Discs	[64]	*Journal of Orthopaedic Research*	66	4.40	65	0
61	Ho G	2008	Effect of severity of intervertebral disc injury on mesenchymal stem cell-based regeneration	[63]	*Connective Tissue Research*	69	4.31	64	3
62	Marfia G	2014	Potential use of human adipose mesenchymal stromal cells for intervertebral disc regeneration: a preliminary study on biglycan-deficient murine model of chronic disc degeneration	[87]	*Arthritis Research & Therapy*	43	4.30	43	6
63	Cai F	2015	Evaluation of intervertebral disc regeneration with implantation of bone marrow mesenchymal stem cells (BMSCs) using quantitative T2 mapping: a study in rabbits	[93]	*International Orthopaedics*	36	4.00	35	0
64	Haufe SM	2006	Intradiscal injection of hematopoietic stem cells in an attempt to rejuvenate the intervertebral discs	[62]	*Stem Cells and Development*	70	3.89	77	3
65	Allon AA	2010	Structured coculture of stem cells and disc cells prevent disc degeneration in a rat model	[75]	*Spine Journal*	54	3.86	61	0
66	Shu CC	2017	A Histopathological Scheme for the Quantitative Scoring of Intervertebral Disc Degeneration and the Therapeutic Utility of Adult Mesenchymal Stem Cells for Intervertebral Disc Regeneration	[104]	*International Journal of Molecular Sciences*	27	3.86	31	4
67	Chen X	2016	A comparison between nucleus pulposus-derived stem cell transplantation and nucleus pulposus cell transplantation for the treatment of intervertebral disc degeneration in a rabbit model	[97]	*International Journal of Surgery*	30	3.75	29	0
68	Murrell W	2009	Olfactory stem cells can be induced to express chondrogenic phenotype in a rat intervertebral disc injury model	[74]	*Spine Journal*	56	3.73	53	0

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
69	Freeman BJC	2016	Allogeneic Mesenchymal Precursor Cells Promote Healing in Postero-lateral Annular Lesions and Improve Indices of Lumbar Intervertebral Disc Degeneration in an Ovine Model	[102]	*Spine*	28	3.50	34	3
70	Wang W	2018	Transplantation of Hypoxic-Preconditioned Bone Mesenchymal Stem Cells Retards Intervertebral Disc Degeneration via Enhancing Implanted Cell Survival and Migration in Rats	[112]	*Stem Cells International*	21	3.50	30	0
71	Hiraishi S	2018	Discogenic cell transplantation directly from a cryopreserved state in an induced intervertebral disc degeneration canine model	[111]	*JOR Spine*	21	3.50	21	57
72	Feng G	2020	Nanofibrous spongy microspheres to deliver rabbit mesenchymal stem cells and anti-miR-199a to regenerate nucleus pulposus and prevent calcification	[128]	*Biomaterials*	14	3.50	18	1
73	Henriksson HB	2019	The Traceability of Mesenchymal Stromal Cells After Injection Into Degenerated Discs in Patients with Low Back Pain	[120]	*Stem Cells and Development*	17	3.40	19	3
74	Bendtsen M	2011	Autologous Stem Cell Therapy Maintains Vertebral Blood Flow and Contrast Diffusion Through the Endplate in Experimental Intervertebral Disc Degeneration	[85]	*Spine*	44	3.38	46	0
75	Jeong JH	2009	Human mesenchymal stem cells implantation into the degenerated coccygeal disc of the rat	[79]	*Cytotechnology*	49	3.27	45	0
76	Migliorini F	2016	Strategies in regenerative medicine for intervertebral disc repair using mesenchymal stem cells and bioscaffolds	[105]	*Regenerative Medicine*	26	3.25	26	1
77	Chiang ER	2019	Use of Allogeneic Hypoxic Mesenchymal Stem Cells For Treating Disc Degeneration in Rabbits	[122]	*Journal of Orthopaedic Research*	16	3.20	18	2
78	Ahn J	2015	Transplantation of human Wharton's jelly-derived mesenchymal stem cells highly expressing TGFβ receptors in a rabbit model of disc degeneration	[103]	*Stem Cell Research & Therapy*	28	3.11	32	4

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
79	Sun W	2014	Sox9 Gene Transfer Enhanced Regenerative Effect of Bone Marrow Mesenchymal Stem Cells on the Degenerated Intervertebral Disc in a Rabbit Model	[96]	*PLoS One*	31	3.10	26	0
80	Hee HT	2010	Effects of implantation of bone marrow mesenchymal stem cells, disc distraction and combined therapy on reversing degeneration of the intervertebral disc	[88]	*Journal of Bone and Joint Surgery: British Volume*	42	3.00	43	0
81	Gou S	2014	Stem Cell Therapy for Intervertebral Disk Regeneration	[98]	*American Journal of Physical Medicine & Rehabilitation*	30	3.00	33	3
82	Tam V	2014	A Comparison of Intravenous and Intradiscal Delivery of Multipotential Stem Cells on the Healing of Injured Intervertebral Disk	[99]	*Journal of Orthopaedic Research*	30	3.00	34	6
83	Sun Y	2019	Clinical trials of intervertebral disc regeneration: current status and future developments	[124]	*International Orthopaedics*	15	3.00	20	1
84	Omlor GW	2010	Methods to monitor distribution and metabolic activity of mesenchymal stem cells following in vivo injection into nucleotomized porcine intervertebral discs	[91]	*European Spine Journal*	39	2.79	41	0
85	Xu J	2016	BMP7 enhances the effect of BMSCs on extracellular matrix remodeling in a rabbit model of intervertebral disc degeneration	[110]	*FEBS Journal*	22	2.75	24	4
86	Maidhof R	2017	Timing of Mesenchymal Stem Cell Delivery Impacts the Fate and Therapeutic Potential in Intervertebral Disc Repair	[116]	*Journal of Orthopaedic Research*	19	2.71	21	1
87	Beeravolu N	2018	Human umbilical cord derivatives regenerate intervertebral disc	[121]	*Journal of Tissue Engineering and Regenerative Medicine*	16	2.67	20	13
88	Steffen F	2017	Bone Marrow-Derived Mesenchymal Stem Cells as Autologous Therapy in Dogs with Naturally Occurring Intervertebral Disc Disease: Feasibility, Safety, and Preliminary Results	[117]	*Tissue Engineering Part C: Methods*	18	2.57	20	70
89	Li YY	2014	Delivering Mesenchymal Stem Cells in Collagen Microsphere Carriers to Rabbit Degenerative Disc: Reduced Risk of Osteophyte Formation	[108]	*Tissue Engineering Part A*	25	2.50	35	1

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
90	James G	2016	Mesenchymal Stem Cell Treatment of Intervertebral Disc Lesion Prevents Fatty Infiltration and Fibrosis of the Multifidus Muscle, but not Cytokine and Muscle Fiber Changes	[115]	*Spine*	19	2.38	21	2
91	Liao JC	2016	Cell Therapy Using Bone Marrow-Derived Stem Cell Overexpressing BMP-7 for Degenerative Discs in a Rat Tail Disc Model	[114]	*International Journal of Molecular Sciences*	19	2.38	20	1
92	Wang YT	2010	Regeneration potential and mechanism of bone marrow mesenchymal stem cell transplantation for treating intervertebral disc degeneration	[95]	*Journal of Orthopaedic Science*	33	2.36	25	0
93	Daly CD	2018	Mesenchymal progenitor cells primed with pentosan polysulfate promote lumbar intervertebral disc regeneration in an ovine model of microdiscectomy	[127]	*Spine Journal*	14	2.33	21	3
94	Wei JN	2016	Transplantation of CXCR4 Overexpressed Mesenchymal Stem Cells Augments Regeneration in Degenerated Intervertebral Discs	[119]	*DNA and Cell Biology*	18	2.25	22	6
95	Wang SZ	2016	Intervertebral disc regeneration using platelet-rich plasma-containing bone marrow-derived mesenchymal stem cells: A preliminary investigation	[118]	*Molecular Medicine Reports*	18	2.25	16	1
96	Shu CC	2018	Efficacy of administered mesenchymal stem cells in the initiation and co-ordination of repair processes by resident disc cells in an ovine (Ovis aries) large destabilizing lesion model of experimental disc degeneration	[130]	*JOR Spine*	13	2.17	17	0
97	Anderson DG	2005	Cell-based therapy for disc repair	[89]	*Spine Journal*	41	2.16	47	0
98	Hang D	2017	One-Stage Positron Emission Tomography and Magnetic Resonance Imaging to Assess Mesenchymal Stem Cell Survival in a Canine Model of Intervertebral Disc Degeneration	[125]	*Stem Cells and Development*	15	2.14	18	0
99	Hou Y	2016	Study design: in vitro and in vivo assessment of bone morphogenic protein 2 combined with platelet-rich plasma on treatment of disc degeneration	[126]	*International Orthopaedics*	15	1.88	14	0

Table 2 (continued)

Rank	First Author	Year		Reference	Journal	WoS Citations	Wos Citations per year (since publication)	Dimensions	AAS
100	Zhou Y	2014	Effects of transplantation of hTIMP-1-Expressing Bone Marrow Mesenchymal Stem Cells on the Extracellular Matrix of Degenerative Intervertebral Discs in an In Vivo Rabbit Model	[129]	*Spine*	14	1.40	20	1

WoS Web of Science, *AAS* Altmetric Attention Score

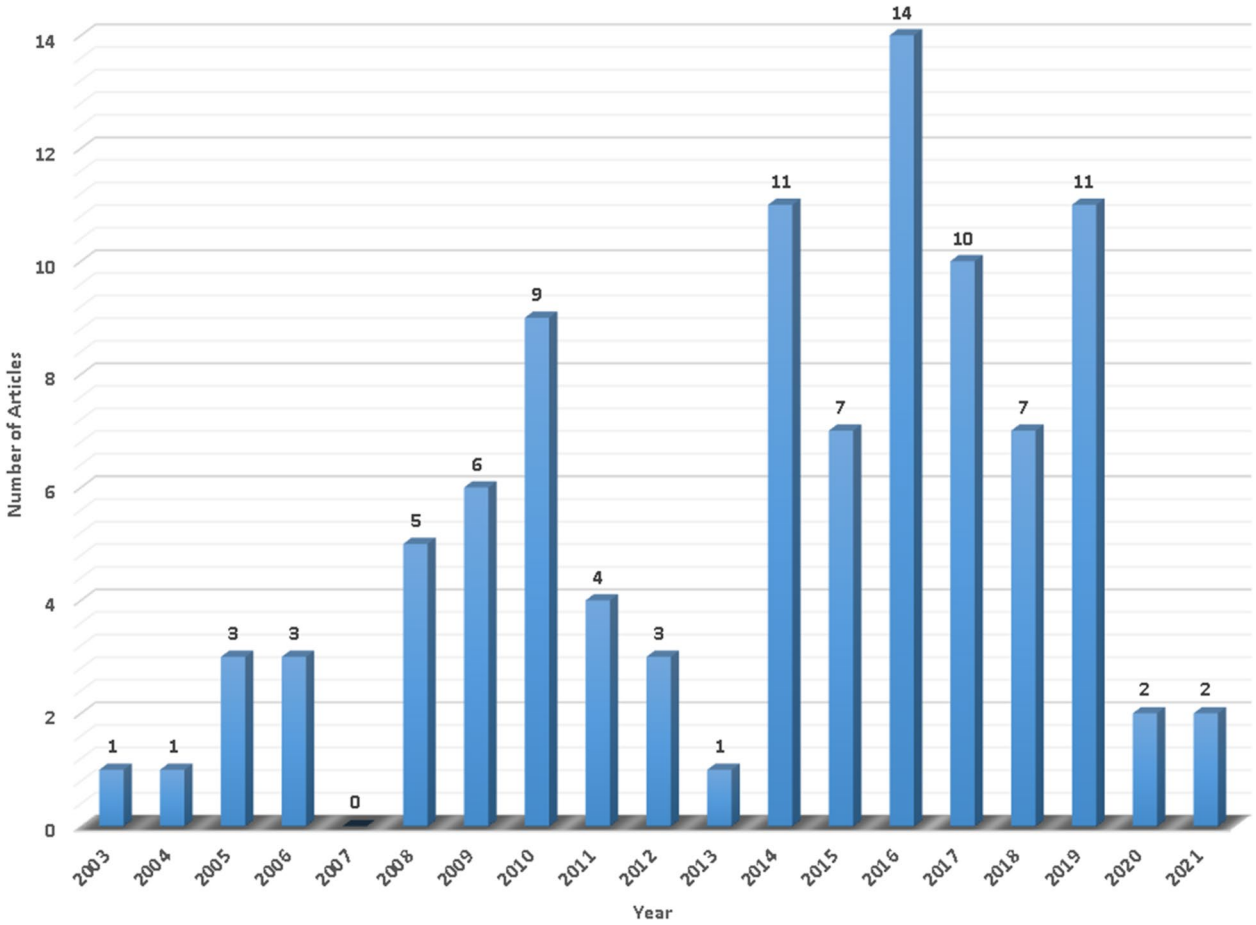

Fig. 2 Annual distribution of the top 100 works on SCT in IDD, showing that the peak publication year was 2016, followed by 2014 and 2019

IDD and restore disc functions [7, 8, 11, 12, 98]. The progress in SCT may provide potent strategies for treating IDD, while some of the most influential work may change clinical practice and motivate discussions, disputes, and further studies [8–10, 12, 98]. Although numerous publications analyzing the highest-cited works have been reported in many fields [13–30], there have been no such papers on SCT in IDD. Thus, this is the first study to determine and analyze the highest impact works on SCT in IDD.

The top 100 papers were published in English, demonstrating that English is the most important and influential language in the scientific community [16, 20–22, 24, 25]. *Spine* and *Spine Journal* published the largest number of works, followed by *International Orthopaedics*, and *Journal of Orthopaedic Research*, demonstrating that these journals have a strong influence on SCT in IDD. One reason for this observation may be that investigators tend to submit vital work to high-impact journals in their fields [20–25]. Another possibility is that investigators tend to cite papers published in important journals [13–19]. Moreover, journals with high impact factors, such as *Nature Reviews Rheumatology*, published at least one paper on stem cells in IDD. This finding suggests that some high-quality works on this topic could be accepted in high-impact journals [14, 16, 18, 19].

The 100 highest impact works were published by authors from 17 countries. The top three countries, including China, the United States, and Japan, produced 67 papers, accounting for about 70% of the top 100 works. This indicates that high-impact work is still concentrated in a few countries, most of which are developed, with the exception of China. This finding demonstrates that the economic status of a country is associated with the research output of high-impact works [13, 20, 22, 24]. Therefore, there is a need to improve the quality of work in non-developed countries.

It is surprising that China is the most fruitful country for the publication of research relating to SCT in IDD. Indeed, the high scientific productivity of the United States has been proven in many fields [13, 17, 18, 21–25]. This may be attributed to the advantages of the United

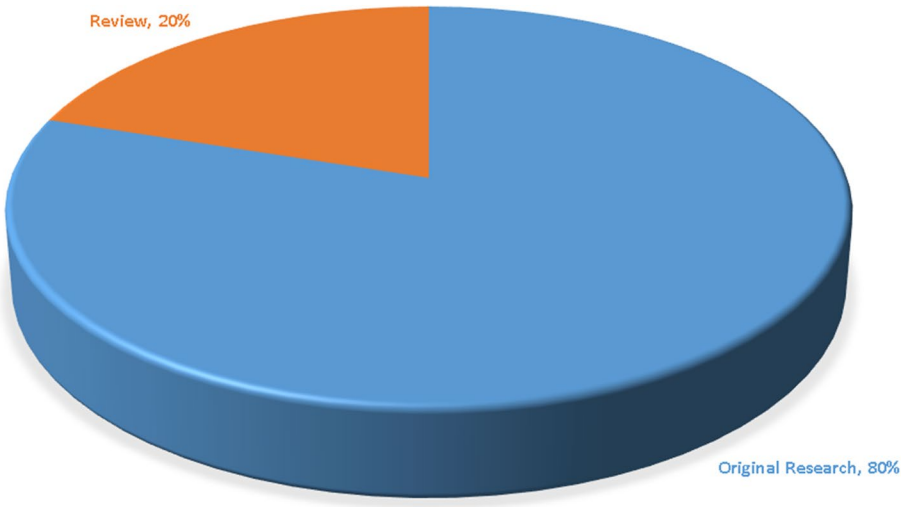

Fig. 3 Article types among the top 100 works, comprising 80 original research articles and 20 review articles

Table 3 Journals with two or more papers among the top 100 works

Journal Title	No. of Papers	Total WoS Citations	Average WoS Citations	Average AAS	Impact Factor
Spine	8	916	114.50	4.50	3.0
Spine Journal	8	490	61.25	8.38	4.5
International Orthopaedics	7	246	35.14	7.14	2.7
Journal of Orthopaedic Research	6	471	78.50	3.00	2.8
Biomaterials	4	776	194.00	4.00	14.0
Stem Cells and Development	4	176	44.00	3.00	4.0
Acta Biomaterialia	4	163	40.75	1.00	9.7
European Spine Journal	3	321	107.00	1.00	2.8
Tissue Engineering Part A	3	184	61.33	2.00	4.1
Journal of Translational Medicine	3	174	58.00	241.67	7.4
Stem Cells International	3	83	27.67	1.67	4.3
JOR Spine	3	79	26.33	19.00	3.7
International Journal of Molecular Sciences	3	62	20.67	2.33	5.6
Transplantation	2	446	223.00	26.00	6.2
Journal of Tissue Engineering and Regenerative Medicine	2	217	108.50	11.50	3.3
Stem Cells	2	173	86.50	7.00	5.2
Arthritis Research & Therapy	2	148	74.00	4.50	4.9
Stem Cell Research & Therapy	2	123	61.50	3.00	7.5
Journal of Neurosurgery: Spine	2	119	59.50	2.00	2.8

WoS Web of Science, *AAS* Altmetric Attention Score

States in terms of a large number of researchers and sufficient funds [13–22, 24, 25]. Our findings may indicate that China have played an increasingly important role in the field of SCT in IDD. However, when the research output was normalized by population or GDP, Australia, Switzerland, Sweden, and Ireland were more prolific. For each country, it may make more sense to adjust by the number of researchers and financial resources used on SCT in IDD, not the total population and GDP. However, it should be recognized that it is rather difficult to obtain these data from each country in the field of SCT in IDD. Nevertheless, when considering the population and economic status of these countries, the findings may reflect their relatively high research output on SCT in IDD.

Table 4 Countries of the top 100 works

Country[a]	No. of Papers	Total WoS Citations	Average WoS Citations	Average AAS	No. per Billion Populations	No. per $ 10,000 Billion GDP
China	31	1439	46.42	1.77	2.19	17.48
United States	22	1539	69.95	41.09	6.63	9.57
Japan	14	2264	161.71	8.64	11.14	28.35
Australia	9	294	32.67	1.89	34.97	58.34
South Korea	5	313	62.60	1.40	19.31	27.80
Italy	3	309	103.00	6.00	5.08	14.29
Switzerland	3	79	26.33	36.00	34.49	36.91
Spain	2	446	223.00	26.00	4.23	14.03
Sweden	2	178	89.00	4.50	19.20	31.88
Germany	2	65	32.50	1.00	2.41	4.74
Netherlands	1	74	74.00	3.00	5.70	9.82
Denmark	1	44	44.00	0.00	17.07	25.18
Singapore	1	42	42.00	0.00	18.34	25.19
Canada	1	34	34.00	6.00	2.61	5.02
Ireland	1	46	46.00	26.00	19.89	20.06
United Kingdom	1	270	270.00	7.00	1.49	3.14
France	1	71	71.00	2.00	1.48	3.40

WoS Web of Science, *AAS* Altmetric Attention Score, *GDP* Gross Domestic Product

[a] Population and GDP of each country for the year 2022 were obtained from the World Bank (www.worldbank.org)

Table 5 Institutions with two or more papers among the top 100 works

Institutions	No. of Papers	Total WoS Citations	Average WoS Citations
Tokai University School of Medicine	11	1950	177.27
The University of Hong Kong	8	550	68.75
Southeast University	4	105	26.25
Zhejiang University	3	138	46.00
University of California	3	422	140.67
Celling Biosciences	3	217	72.33
Kolling Institute	3	66	22.00
University of Valladolid and CSIC	2	446	223.00
Campus Bio-Medico University of Rome	2	266	133.00
Sahlgrenska Hospital	2	178	89.00
University of Ulsan	2	132	66.00
CHA University	2	123	61.50
Mayo Clinic	2	74	37.00
Monash University	2	59	29.50
Second Military Medical University	2	36	18.00

WoS Web of Science

Some institutions and authors have excellent records in the top 100 list. Sakai D from Tokai University School of Medicine ranks first with the highest total citations, indicating his significant influence in the field of SCT in IDD. Other notable authors such as Cheung KMC, Melrose J, Pettine K, Lotz JC, Murphy MB, Schol J, Vadalà G, and García-Sancho J also have impressive publication records. Our findings underscore the high quality of their work on SCT in IDD.

Table 6 First/corresponding authors with two or more papers of the top 100 works

Authors	As First Author	As Corresponding Author	No. of Papers	Total WoS Citations	Average WoS Citations	Average WoS Citations per Year (Since Publication)
Sakai D	7	9	10	1911	191.10	12.59
Cheung KMC		6	6	451	75.17	5.58
Melrose J	1	3	3	66	22.00	3.62
Pettine K	3		3	217	72.33	8.94
Lotz JC		3	3	422	140.67	8.33
Murphy MB		3	3	217	72.33	8.94
Schol J	1	2	2	111	55.50	9.04
Vadalà G	2		2	266	133.00	12.44
Leung VY	2		2	219	109.50	7.66
Henriksson HB	2		2	178	89.00	7.07
Yang H	2		2	144	72.00	6.31
Jeong JH	2		2	132	66.00	4.60
Feng G	2		2	88	44.00	4.60
Zhou X	2		2	82	41.00	6.83
Shu CC	2		2	40	20.00	3.01
García-Sancho J		2	2	446	223.00	21.18
Choi KH		2	2	132	66.00	4.60
Lee SH		2	2	123	61.50	8.34
Chen Q		2	2	108	54.00	6.88
Qu W		2	2	74	37.00	3.94
Wu XT		2	2	54	27.00	3.13

WoS Web of Science

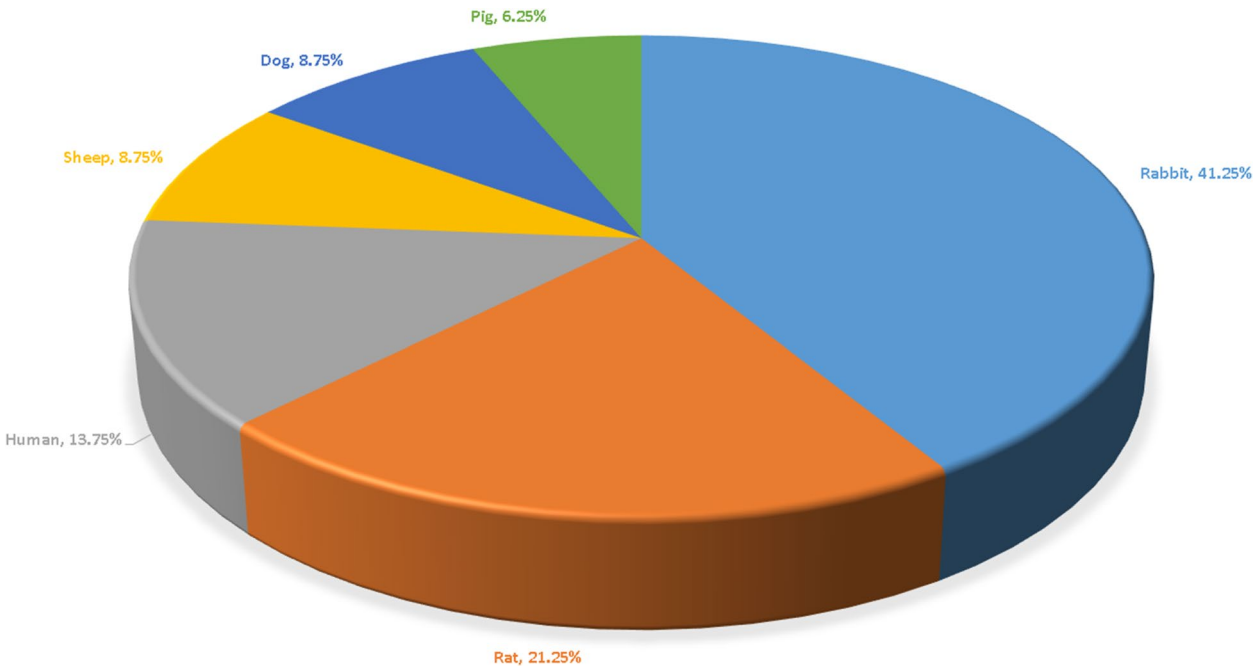

Fig. 4 Species examined in the original research studies. Six species were included, with rabbit being the most frequently studied (41.25%), followed by rat (21.25%), human (13.75%), sheep (8.75%), dog (8.75%), and pig (6.25%)

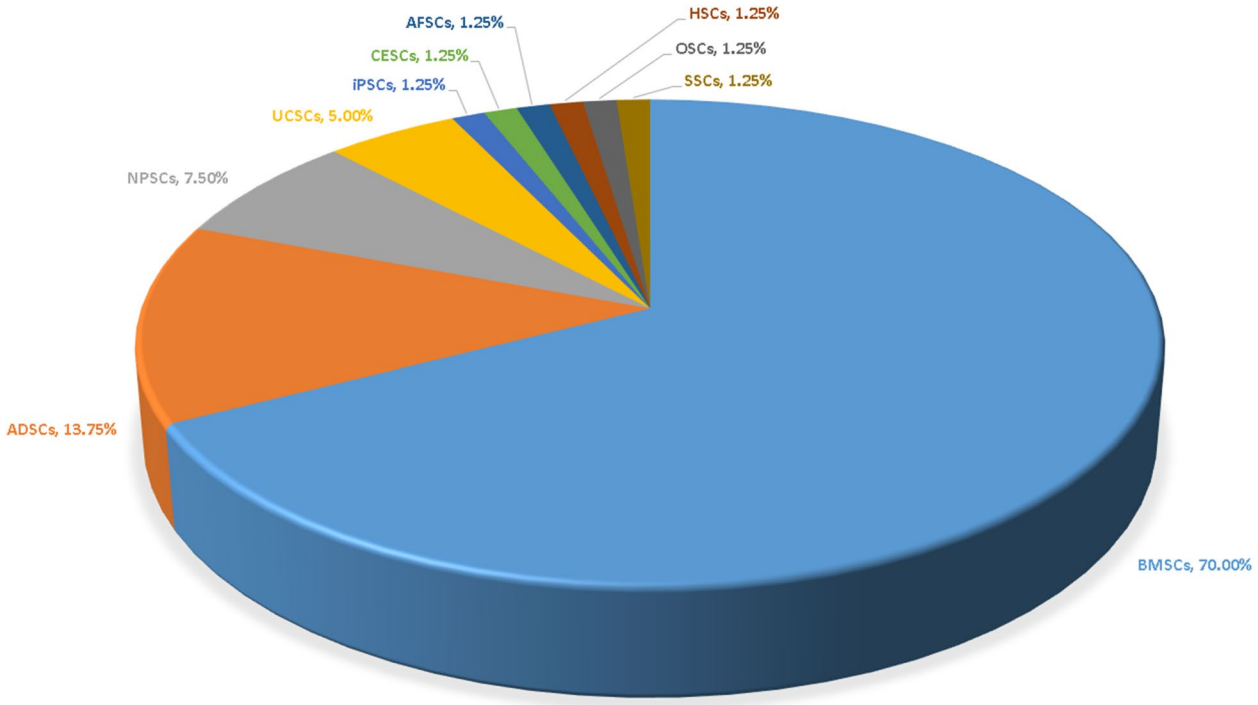

Fig. 5 Stem cell types discussed in the original research. Ten different types of stem cells were included, with BMSCs being the most frequently discussed (70.00%), followed by ADSCs (13.75%) and NPSCs (7.50%)

Citations per year (since publication) is calculated as an indicator that evaluates the relative influence of a paper, irrespective of the time elapsed since its publication [24, 25, 28, 30, 131]. We found that the top study based on citation per year (since publication) was a review on SCT in IDD. The second study, which investigated the transplantation of mesenchymal stromal cells, is notable for its high citation per year (since publication), likely because it represents the first human clinical study investigating SCT for the treatment of disc degeneration disease [3]. The 3rd, 4th, and 5th highest cited papers are also from Sakai D, further evidencing his significant impact in SCT on IDD. Given their high citation per year (since publication), these studies are expected to maintain strong citation records in the future [23, 132].

In our comprehensive analysis of the top 100 papers on SCT in IDD, a detailed comparison of total WoS citations and citations per year since publication reveals a dynamic landscape of research impact [24, 25, 28, 30, 131]. Notably, while papers with the highest total WoS citations indicate long-standing contributions to the field, their annual citations suggest varying levels of ongoing influence [18, 22, 28, 132]. For instance, the most cited paper, with 372 total citations, ranks only fifth when evaluated by its annual citation rate of 17.71, highlighting strong historical impact but a relatively moderated contemporary influence. Conversely, papers with fewer total citations but higher citations per year, such as those with 33.75, 24.92, and 23.50 citations per year, are emerging as significant recent contributors, emphasizing the importance of considering both longevity and immediacy in assessing research impact. Additionally, the integration of AAS alongside traditional citation metrics provides a layered understanding of research visibility and engagement [14, 15]. The highest recorded AAS was 535, indicative of substantial immediate attention and public engagement. Analyzing average AAS per year since publication offers further insight into the sustained impact of these studies over time. For instance, the top-ranked paper by AAS also shows a high annual engagement rate, suggesting ongoing discussions and relevance within the community long after publication. This dual perspective highlights not only the peak interest at the time of publication but also the enduring resonance of research in broader discussions, thereby enriching our understanding of both immediate and lasting scholarly influence [14, 15, 133]. Such analysis is crucial for discerning which topics capture transient attention versus those that foster prolonged academic and public discourse, thus providing a more nuanced view of the dynamics within scientific communication [14, 15].

Animal models play a pivotal role in advancing research on IDD, particularly in evaluating the safety and efficacy of SCT [134, 135]. These models provide

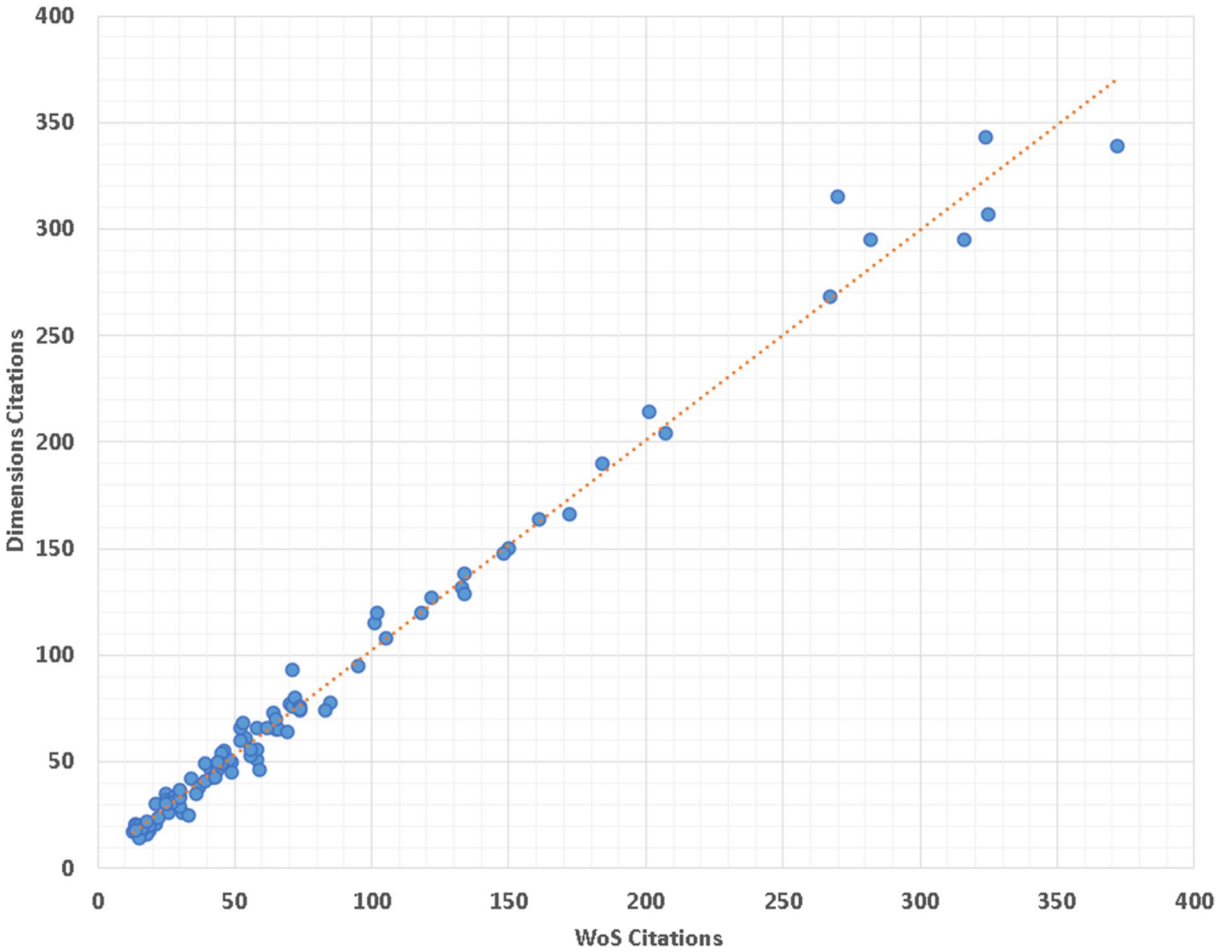

Fig. 6 Scatter plot illustrating the correlation between WoS and Dimensions citations, demonstrating a very high linear correlation ($r = 0.994$, $p < 0.001$)

researchers with valuable insights into the mechanisms of SCT and its potential therapeutic applications. Rabbits emerged as the most commonly used species in SCT research, appearing in 41.25% of the studies. Their relatively larger disc dimensions, compared to smaller models like rats, make them ideal for facilitating SCT [136]. Additionally, the cost-effectiveness and availability of rabbits, compared to larger animals like sheep or pigs, contribute to their popularity in this area of research [136, 137]. Despite the advantages of animal models, translating these findings to human clinical applications remains challenging. Humans constituted only 13.75% of the studies, reflecting the complexity of advancing preclinical data into clinical trials. Ethical concerns, safety considerations, and the inherent complexity of human spinal conditions create barriers to conducting large-scale human trials [136, 137]. While larger animals such as sheep and pigs could provide closer physiological similarities to humans, their high maintenance costs and limited availability reduce their use in SCT research [137].

In clinical trials, sample sizes were small, ranging from 2 to 33 participants, reflecting the early stages of SCT research [136, 138]. The trials addressed various spinal conditions, including low back pain and lumbar spinal stenosis, demonstrating the potential versatility of SCT. Follow-up durations from 1 to 6 years allowed researchers to assess both short-term and long-term outcomes, providing valuable insights into the sustained efficacy of these therapies. BMSCs were the most frequently used, employed in 7 of the 11 trials, likely due to their established regenerative potential and safety profile [11, 60]. Although alternative stem cell types are being explored, BMSCs remain the dominant choice, indicating a need for further research into the effectiveness of other cell sources. The results of the studies were largely positive, showing improvements in radiologic outcomes such as increased water content in the discs, improved Pfirrmann grading, and reduced disc bulge size as observed in MRI scans. Additionally, SCT was associated with improvements in lumbar function, reduced pain, and enhanced

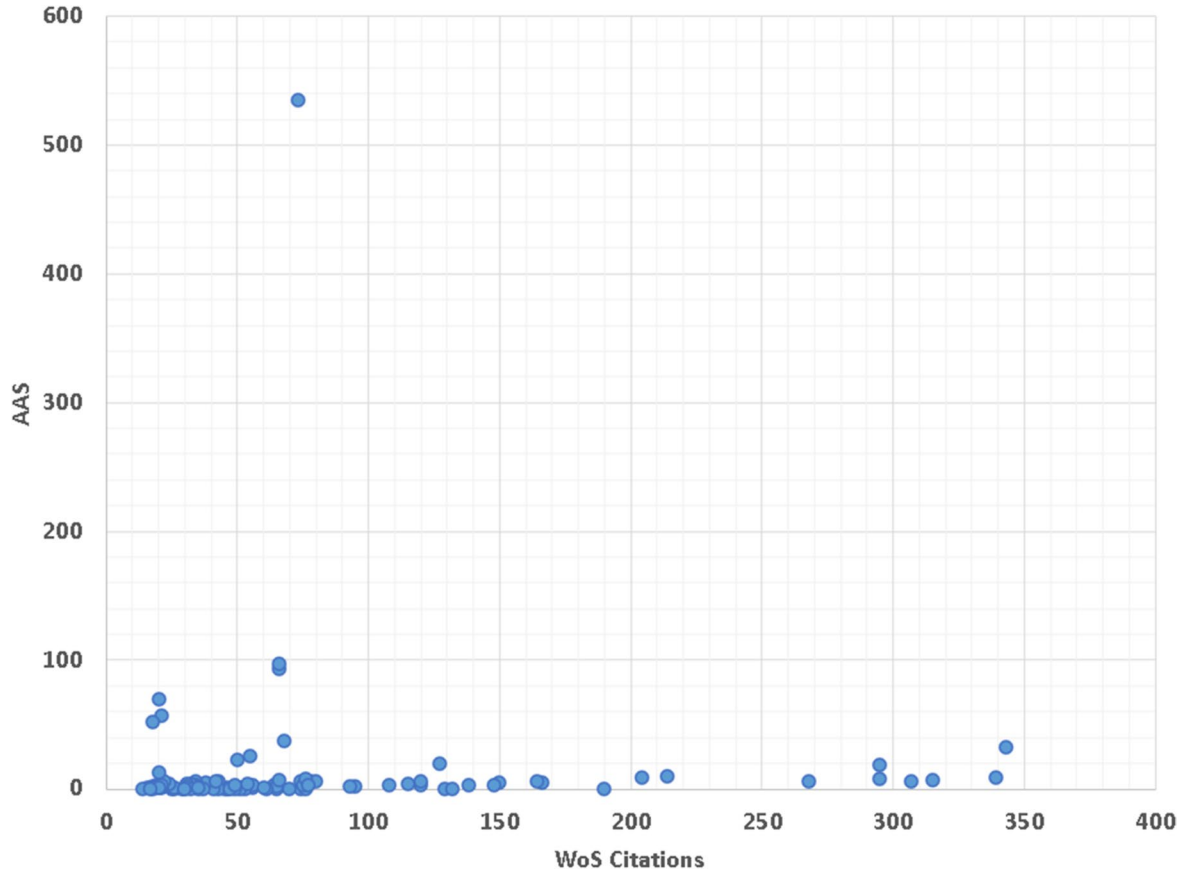

Fig. 7 Scatter plot assessing the correlation between WoS citations and AAS, showing no significant correlation between the two metrics ($r = 0.000$, $p = 0.996$)

quality of life for patients. Importantly, most studies reported minor or no adverse events, further supporting SCT's potential as a safe and effective treatment for IDD [9, 60, 138]. However, despite these promising findings, limitations remain. The small sample sizes and lack of large-scale randomized controlled trials limit the generalizability of the results [60, 138]. To confirm the safety and efficacy of SCT as a treatment for IDD, larger, well-designed RCTs are needed. These future studies should focus on expanding the sample sizes and exploring the use of different stem cell sources to ensure the broader applicability of SCT in clinical settings.

Some of the studies included in our analysis investigated multiple cell types, not just SC. These studies highlight that certain cell types, such as articular chondrocytes [52], may offer advantages in treating IDD compared to SC, as they are better suited to survive in the ischemic disc microenvironment [8, 11, 98]. We consider these findings highly significant for the field of SCT in IDD and have therefore included these studies in our top 100 list. These insights could encourage researchers to modify SC to enhance their adaptation to the challenging disc environment or to explore new stem cell types with superior regenerative potential. In addition, BMSCs are the most widely used stem cell type, likely due to their excellent biological properties and ease of harvesting with minimal harm [3, 98]. However, as our understanding of IDD deepens, increasing evidence suggests that the harsh microenvironment of degenerated discs limits the efficacy of BMSCs [10, 98]. Consequently, there is growing interest in utilizing resident stem cells, such as (NPSCs, AFSCs, and CESCs, which demonstrate better tolerance to disc conditions [9, 10]. We anticipate that research on resident stem cells in IDD will expand rapidly in the near future.

Traditional indicators of academic influence, largely comprising impact factors and citations, provide an important view of the quality of research [20, 21, 139]. Nevertheless, social media substantially alters the way in which knowledge is shared [14, 15, 133, 139]. Worldwide platforms such as X (formerly known as Twitter) and Facebook allow investigators to share their work with many more readers, many of whom will not be familiar with the academic field and may not be reflected by

traditional indicators [133, 139]. AAS is an indicator of the online sharing activities a paper has received [14, 15]. In this study, the AAS of 27% of the included studies was zero, meaning that these studies had no online activities. Moreover, the citation counts of the top 100 works in WoS were very high correlated with their citations in Dimensions ($r=0.994$, $p<0.001$). This result is similar to the findings for previous publications in other fields [14, 15]. This suggests that this new database could be an alternative to WoS and could compensate for the bias of Altmetric because of the rapid change in social media. Altmetrics can be used as a useful index to investigate the impact of work on society, but not as a reliable index of work quality [14, 15, 133, 139]. A poor correlation was demonstrated between the number of citations in WoS and AAS ($r=0.000$, $p=0.996$), which is similar to the findings of similar publications [14, 15]. Therefore, the number of WoS citations is not directly comparable to the AAS values; this may be attributed to the fact that different databases cover different journals, which may affect the citations of articles [139]. However, different databases can be used to assess different aspects of the work.

In our analysis of SCT research in IDD, the AAS may indicate geographic discrepancies that potentially challenge its universality and fairness [133, 140]. Altmetric's system, primarily monitoring Western-oriented platforms like X (formerly known as Twitter) and Facebook, biases engagement metrics towards American content, while popular platforms in Europe and Asia such as LinkedIn and Sina Weibo are underrepresented due to recent policy changes and data stream closures [140]. This skew may distort perceptions of the impact and relevance of research across different regions, potentially affecting academic recognition and funding decisions [131, 140]. To address these issues, it is essential for Altmetric to broaden its scope to include a more diverse array of data sources, ensuring that altmetrics provide a balanced view of global research impact [140]. As the academic and publishing communities become increasingly aware of these biases, there is a pressing need for altmetrics to evolve to reflect the diverse nature of scientific discourse more accurately, thereby enhancing the fairness and accuracy of research impact assessments and ensuring equitable recognition of scholarly contributions worldwide [131, 140].

This study has several limitations. First, although a comprehensive literature search has been performed, some papers may not be identified due to the intrinsic limitations of the search strategy. Second, the citation count is used as an indicator of the impact of a work, which may not be absolutely reliable. Indeed, as older works have more time to receive citations, influential papers published in recent years may have fewer citations, resulting in their exclusion from the top 100 list. Third, the number of citations is usually influenced by multiple factors, such as self-citation, and may not reflect the objective impact of the studies. Fourth, only the WoS database was retrieved to identify the top-cited publications. The high-impact works in other sources, such as books, websites, and other databases could not be included in this study. Fifth, our analysis was limited to first authors and corresponding authors, which is not without its shortcomings. This method may miss recognizing the important contributions of co-authors in collaborative studies, including those with shared first authorships. Sixth, reviewing the most highly cited papers in this field does not necessarily reveal how best stem cells might be used to affect disc repair. Seventh, our study employed a cross-sectional design with data collected at a single point in time. Consequently, it may not capture temporal changes in specific cell types, species, journals, countries, citations, or AAS. It is important to note that paper rankings could shift if the search is conducted at another time. Eight, our analysis incorporates AAS, which introduce another layer of temporal bias. These scores tend to favor recent publications due to their immediate visibility on social media platforms, potentially underrepresenting the historical impact of older research that predated the widespread use of these digital tools. Therefore, while AAS provide valuable insights into current public and scholarly engagement, they should be interpreted with caution. Despite these constraints, our study establishes a foundational baseline for future analyses, enabling subsequent studies to track longitudinal changes in the field's dynamics and the evolving impact of specific research outputs. This will allow for a more comprehensive understanding of how different factors influence research recognition over time.

Conclusions

For the first time, we provide an analytic study of the 100 highest impact works on SCT in IDD, thereby providing a list of the most influential publications in this field. The current study should disseminate beneficial knowledge to researchers and clinicians, expand the understanding of the historical works regarding SCT in IDD, and be helpful in guiding further research on this topic.

Abbreviations

SCT	Stem cell transplantation
IDD	Intervertebral disc degeneration
WoS	Web of Science
AAS	Altmetric Attention Score
LBP	Low back pain
SC	Stem cell
GDP	Gross domestic product
BMSCs	Bone marrow-derived stem cells
ADSCs	Adipose-derived stem cells

NPSCs Nucleus pulposus-derived stem cells
UCSCs Umbilical cord-derived stem cells
iPSCs Induced pluripotent stem cells
CESCs Cartilage endplate-derived stem cells
AFSCs Annulus fibrosus-derived stem cells
HSCs Hematopoietic stem cells
OSCs Olfactory stem cells
SSCs Synovial stem cells

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Statement of human and animal rights
Not applicable.

Authors' contributions
Study conception and design was performed by XL and QL. Acquisition of data was conducted by XC, HL, and BH, Analysis and interpretation of data was done by HL, BH, and JR. Drafting the manuscript was performed by XC, HL, and BH. Critical revision of manuscript was conducted by JR, XL, QL. All authors read and approved the final manuscript.

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Data availability
All data in this paper are available upon reasonable requests from corresponding author.

Declarations

Ethics approval and consent to participate
No approval of Institutional Reviewed Board was needed due to not involving human and animals in this study.

Consent for publication
There are no human subjects in this article, and informed consent is not applicable.

Competing interests
The authors declare no competing interests.

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