

# Trends in Anterior Cruciate Ligament Repair

## A Bibliometric and Visualized Analysis

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**Background:** Bibliometrics is a methodology that measures the scientific output of an author, institution, or country. Visualized analysis is the transformation of data into visible form by software, highlighting important features, including commonalities and anomalies, allowing users to easily and quickly perceive significant aspects of their data.

**Purpose:** To conduct a bibliometric analysis of the literature on anterior cruciate ligament (ACL) repair, with visualization of trends, in order to identify the areas of interest and the primary researchers involved in ACL repair.

**Study Design:** Cross-sectional study.

**Methods:** The PubMed database was queried on April 14, 2022, for publications that reported on ACL repair from 1960 onward. The initial search resulted in 1392 publications. Filter settings were applied to remove publications with weak correlation, such as those on meniscal repair and ACL reconstruction. Publication information, citations, authors, commonly used terms, and affiliated institutions and countries were analyzed by VOSviewer and Python.

**Results:** A total of 553 articles were included for analysis. Three techniques were visualized: bridge-enhanced ACL repair, internal brace, and dynamic intraligamentary stabilization. The most published authors were Martha Murray (51 articles), Gregory Difelice (35 articles), and Braden Fleming (31 articles). The most cited article was “Collagen–Platelet Rich Plasma Hydrogel Enhances Primary Repair of the Porcine Anterior Cruciate Ligament” by Murray et al. The journals with the most publications on ACL repair were the *American Journal of Sports Medicine* (n = 49); *Knee Surgery, Sports Traumatology, Arthroscopy* (n = 49); and *Arthroscopy* (n = 48). The top 3 institutions by publication number were the Hospital for Special Surgery (n = 51), Boston Children’s Hospital (n = 49), and Brown University (n = 31), with the most publications coming from the United States (n = 242), Germany (n = 83), and the United Kingdom (n = 47).

**Conclusion:** The results demonstrate that the research on ACL repair comes from a small number of authors and corresponding institutions; the top sports medicine journals and the developed countries have an interest in this topic.

**Keywords:** anterior cruciate ligament; ACL; bibliometrics; bridge-enhanced ACL repair; internal brace; dynamic intraligamentary stabilization

Although the existence of the anterior cruciate ligament (ACL) was recognized as early as the ancient Greeks,<sup>32</sup> operative treatment of ACL injury is not uncommon today. Mayo Robson<sup>20</sup> published a case report of the surgical repair of cruciate ligaments of a coal digger in 1903. ACL repair was sparingly performed over the remainder of the century, with Feagin and Curl<sup>8</sup> publishing a seminal report on the 5-year outcome of military cadets who underwent ACL repair, finding high rates of persistent instability with associated disability. Marshall et al<sup>19</sup> published a similar case series in 1982 but found more favorable outcomes using their described repair technique. However, the

advent and refinement of ACL reconstruction offered more consistent outcomes than ACL repair. In a long-term study comparing 3 techniques for treating ACL injury, Drogset et al<sup>6</sup> found that the rate of revision after 1-stage ACL repair was much higher than that after ACL reconstruction with bone–patellar tendon–bone autograft. This coincided with the continued refinement of knee arthroscopy,<sup>25</sup> ushering in an era during which ACL reconstruction become standard of care for patients with ACL injuries who intended to return to sports.

Despite the advances made in ACL reconstruction, graft failure rates of approximately 5% are commonly reported, with higher rates noted in younger, competitively athletic populations.<sup>9</sup> Furthermore, radiographic evidence of osteoarthritis is found in more than 20% of patients at a minimum of 10 years after ACL reconstruction.<sup>29</sup> These

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limitations in contemporary ACL reconstruction have motivated continued research on novel methods to improve outcomes after ACL injury, with renewed interest in ACL repair. Indeed, publications on ACL repair have increased in recent years, including reports on novel surgical techniques and fixation devices,<sup>11,16,18</sup> biologic scaffolds,<sup>17</sup> and suture tape augmentation.<sup>4</sup>

In this study, we sought to capture the trends in ACL repair by use of bibliometric analysis,<sup>2,3</sup> which more easily allows visualization of publication trends compared with systematic reviews. We aimed to trace the evolution of ACL repair in the literature, with a particular focus on the frequency and connectivity of keywords, authors, journals, publications, institution, and countries.

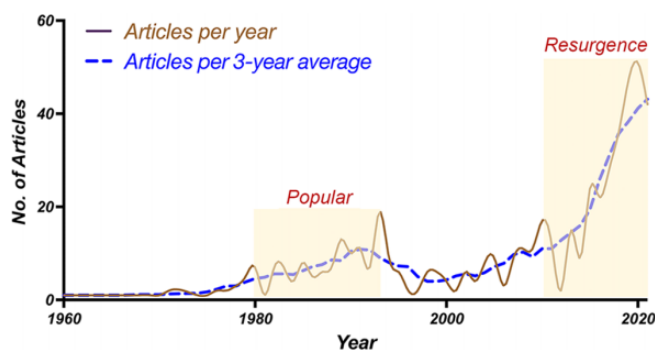
## METHODS

### Search Strategy

We queried the PubMed database on April 14, 2022, for publications that reported on ACL repair from 1960 onward; the search strategy is detailed in Supplemental Table S1, available separately. All types of studies were considered in the initial screening, including those with evidence levels from 1 (high-quality prospective randomized trials) through 5 (expert opinions). The initial search resulted in 1392 publications, after which publications were further screened by title and abstract. Publications principally focused on techniques other than ACL repair, such as meniscal repair and ACL reconstruction, were excluded. Original articles, case reports, rapid communication, letters to the editor, comments, narrative reviews, systematic reviews, and meta-analyses focused on primary ACL repair were all included. Papers identified in searches were reviewed by the corresponding author (with more than 10 years of sports medicine experience). Journal Citation Reports 2021 was used to obtain the impact factor (IF) and the category quartile (Q) of relevant journals.

### Data Processing

Python, GraphPad Prism, and VOSviewer were applied to analyze and plot the annual publication output. Python<sup>28</sup> (version 3.9.6; Guido van Rossum) was used to extract relevant characteristics of publications, including authors, institution, journal, and country. The code to perform this function is included in Supplemental Table S2. GraphPad Prism<sup>21</sup> (version 9.2.0) was used to visualize trends and to map the number of articles published by different authors.



**Figure 1.** Yearly trend in publications on anterior cruciate ligament repair, 1960–2020, by articles per year and articles per 3-year average.

VOSviewer software<sup>35</sup> (version 1.6.17; Leiden University) was applied for constructing and visualizing bibliometric networks.

## RESULTS

A total of 553 publications were included in the final analysis. Two fit lines indicated the arithmetic distribution of the number of publications per year and the average number of publications per 3 years (Figure 1). There were 2 epochs of increasing publication frequency. From 1980 to 1993, the 3-year average number of articles on ACL repair increased before diminishing near the turn of the century. A second rise in publication frequency began in 2010 and continues through the present. Information on relevant authors and institutions for the 2 epochs of increasing publication frequency is provided in Supplemental Table S3.

No consistent contribution trend from a single author was noticed. However, during the period from 1982 to 1993, among the top 10 researchers, 2 were from the Hospital for Special Surgery. Among the top 20 authors in terms of publication volume during the period from 2010 to 2022, 3 were from the Hospital for Special Surgery.

VOSviewer was used to determine the occurrence and relevance of the most frequent terms used in the title or abstract of publications of ACL repair (Table 1). The most commonly used terms were “cruciate ligament,” “healing,” “score,” “tear,” and “week.” VOSviewer was also used to visualize the connectivity of terms. In Figure 2, the changes in commonly used terms from 2000 to 2020 are shown. For example, “proximal tear” and “primary ACL repair” appeared more frequently in recent years, while

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Ethical approval was not sought for the present study.

TABLE 1  
Frequency of Commonly Used Terms in ACL Repair Publications (top 46 terms)<sup>a</sup>

Term	Occurrence	Relevance	Term	Occurrence	Relevance
Cruciate ligament	382	0.02	Degree	39	0.31
Healing	119	0.55	Study design	39	0.29
Score	114	0.65	Suture repair	39	0.86
Tear	99	0.63	Arthroscopy	37	0.65
Week	83	0.44	Cell	37	2.62
Effect	78	0.91	Examination	37	0.56
Tissue	77	0.55	Response	37	1.95
Primary ACL repair	76	0.79	ACL tear	35	0.87
Use	75	0.41	Interest	35	0.29
Lysholm	56	1.47	Control	33	0.45
Scaffold	51	1.25	Clinical outcome	33	0.93
Fixation	49	0.35	Development	33	0.77
Change	48	0.29	Flexion	33	0.5
Instability	48	0.6	Lachman test	33	1.07
Mean	44	1.19	Posterior cruciate ligament	33	0.73
Addition	43	0.45	Dog	32	0.77
Pain	43	0.56	Approach	31	0.59
Literature	42	0.35	Article	31	0.26
Fracture	41	0.58	Case series	31	1.03
Hypothesis	41	0.48	Tegner	31	1.36
IKDC	41	1.53	Proximal tear	30	1.3
Load	41	1.67	Role	30	0.24
Management	40	0.4	DIS	29	0.55

<sup>a</sup>The occurrence attribute indicates the number of articles in which the term occurs at least once. Terms with a high relevance score tend to represent specific topics covered by the text data, while terms with a low relevance score tend to be of a general nature and not representative of any specific topic. ACL, anterior cruciate ligament; DIS, dynamic intraligamentary stabilization; IKDC, International Knee Documentation Committee.

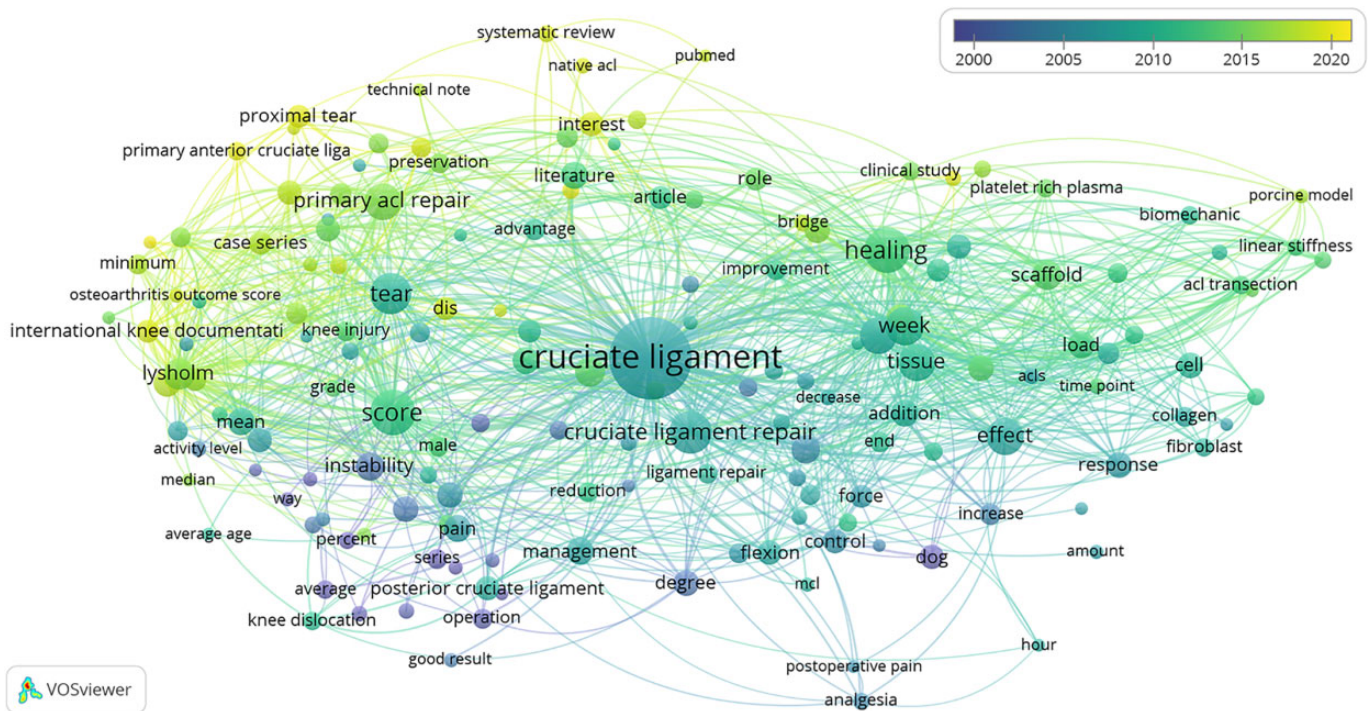
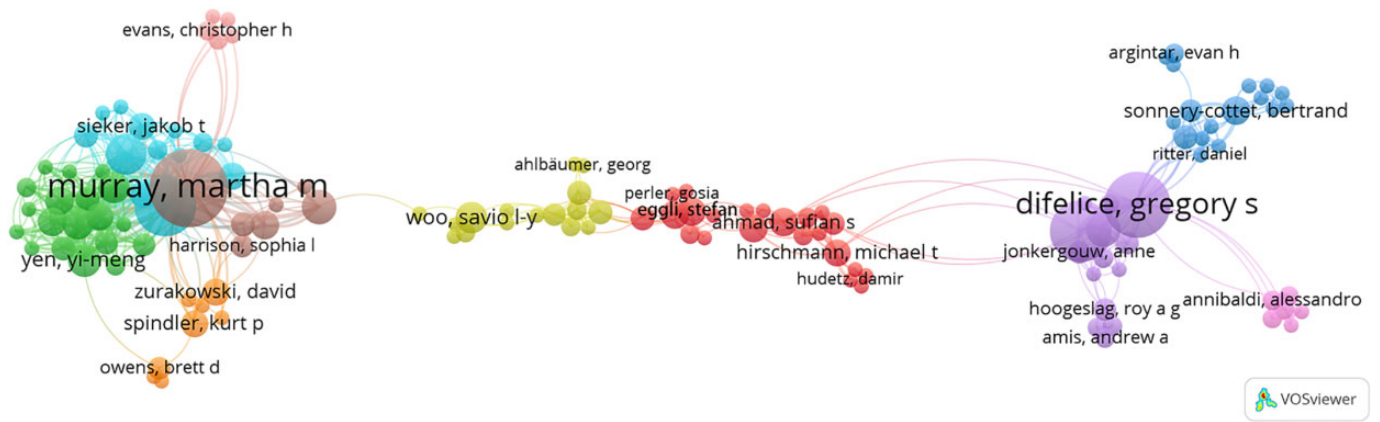


Figure 2. Distribution of commonly used terms according to time of appearance, 2000-2020. Blue indicates the terms that appeared earlier, whereas yellow reflects a later occurrence.



**Figure 3.** The visualization of authors involved in anterior cruciate ligament (ACL) repair publications was roughly divided into 3 clusters. The left cluster principally involved work on bridge-enhanced ACL repair, the central cluster involved dynamic intraligamentary stabilization, and the right cluster was related to the study of anchors and suture tape augmentation (internal bracing).

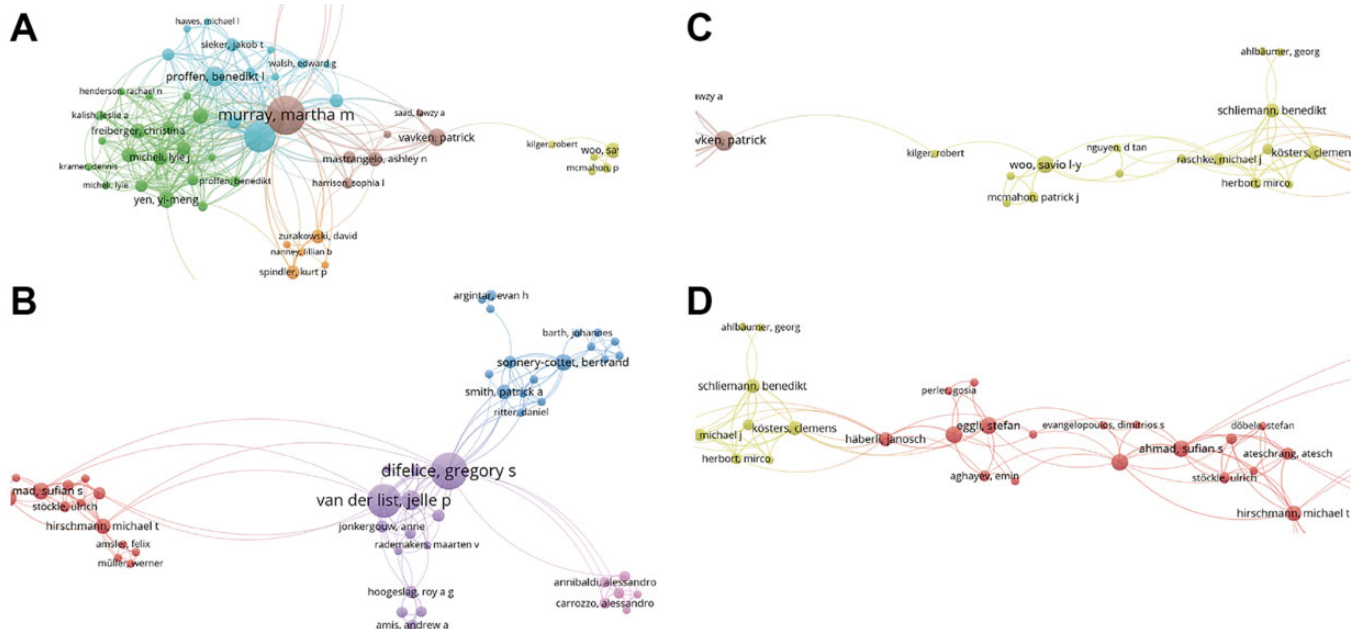
“instability” and “operation” were more frequently used in older publications.

There were 1747 unique authors who contributed to the included publications on ACL repair, 250 of whom had written more than 2 articles, 43 more than 5 articles, and 7 more than 10 articles. The visual results of VOSviewer show 3 clusters of authors, corresponding primarily to 3 different ACL repair techniques: bridge-enhanced ACL repair (BEAR), dynamic intraligamentary stabilization (DIS), and anchors and suture tape augmentation (ie, internal bracing) (Figure 3). Author groupings were most commonly centered around 4 corresponding authors: Martha Murray, Gregory Difelice, Stefan Eggli, and Savio Woo (Figure 3).

The network of authors for each of these corresponding authors is shown in Figure 4. As shown in Figure 5, the most published authors were (in descending order) Martha Murray, Gregory Difelice, and Braden Fleming.

The top 10 journals with the most publications related to ACL repair are listed in Table 2. The *American Journal of Sports Medicine* (IF, 7.01; Q1) and *Knee Surgery, Sports Traumatology, Arthroscopy* (IF, 4.11; Q1) had the largest number of publications, followed by *Arthroscopy* (IF, 5.97; Q1).

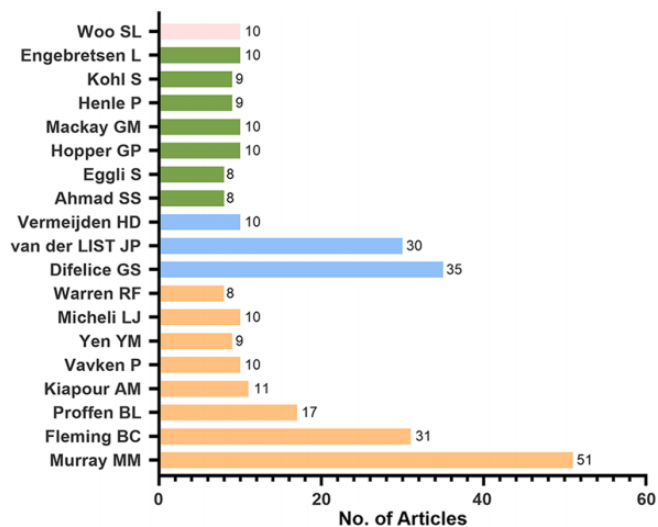
The 16 most cited publications in descending order are listed in Appendix Table A1. The most highly cited publication was “Collagen–Platelet Rich Plasma Hydrogel



**Figure 4.** Networks of authors publishing on anterior cruciate ligament repair surgery. Shown are coauthors who published with (A) Martha Murray, (B) Gregory Difelice, (C) Savio Woo, and (D) Stefan Eggli.

Enhances Primary Repair of the Porcine Anterior Cruciate Ligament” by Murray et al,<sup>24</sup> with 119 citations. This study demonstrated that biomechanical properties measured after primary repair of the ACL transection in a porcine model were enhanced with use of a collagen–platelet-rich plasma hydrogel placed within the repair site. These results supported the hypothesis that an important mechanism for failure of the ACL to heal was a lack of appropriate provisional scaffold. The second most cited article was “Isolated Tear of the Anterior Cruciate Ligament: 5-Year Follow-up Study” by Feagin and Curl,<sup>8</sup> with 113 citations. In this study, the authors found that the failure rate of primary ACL repair with suture was high at the 5-year follow-up. A follow-up study on this small series<sup>33</sup> indicated that the patients had progressive knee deterioration, in part supporting the adoption of ACL reconstruction as the standard of care in the decades that followed.

Table 3 lists affiliated institutions by number of publications. The Hospital for Special Surgery, Boston Children’s



**Figure 5.** Number of articles on anterior cruciate ligament repair published by 19 authors. Affiliated coauthors are depicted by the same bar color.

Hospital, and Brown University produced the most publications. Brown University is affiliated with the Rhode Island Hospital. All 4 organizations are located in the United States. The majority of publications were from the United States (n = 242) and Germany (n = 83), followed by the United Kingdom (n = 47), the Netherlands (n = 24), France (n = 16), Canada (n = 6), and China (n = 6) (Figure 6).

DISCUSSION

In this study, we visualized the trends in research on ACL repair, finding periods of increased publication numbers from 1980 to 1993 and again from 2010 until the present day. The downward trend in the curve after 2020 was presumed to be due to the impact of the COVID-19 pandemic. Renewed interest in ACL repair has principally come from 3 surgical techniques, BEAR, DIS, and suture tape augmentation (internal bracing), which are associated with corresponding authors Martha Murray, Stefan Eggl, and Gregory Difelice, respectively. The *American Journal of Sports Medicine*; *Knee Surgery, Sports Traumatology, Arthroscopy*; and *Arthroscopy* had the most publications on ACL repair. The Hospital for Special Surgery, Boston Children’s Hospital, and Brown University represented the top 3 institutions by publication number, with the most publications coming from the United States, Germany, and the United Kingdom.

The BEAR technique, associated with Martha Murray, entails augmentation of an ACL repair with a collagen-platelet scaffold.<sup>27</sup> Numerous preclinical studies demonstrated that the BEAR technique reliably increased tissue formation at the tear site, largely restoring ACL structure and function, thereby restoring knee stability and diminishing osteoarthritic changes predicably seen with ACL insufficiency.<sup>1,14</sup> A first-in-human cohort study compared 10 patients undergoing BEAR matched with 10 patients who underwent ACL reconstruction with hamstring tendon autograft, finding no failures in either group with similar patient-reported outcomes and knee stability and function between the groups at the 2-year follow-up.<sup>23</sup> A subsequent prospective randomized controlled trial comparing BEAR (n = 65) against ACL reconstruction with hamstring tendon

TABLE 2  
Top 10 Journals With the Most Publications Related to ACL Repair<sup>a</sup>

Rank	Journal	No. of Publications
1	<i>American Journal of Sports Medicine</i>	49
2	<i>Knee Surgery, Sports Traumatology, Arthroscopy</i>	49
3	<i>Arthroscopy</i>	48
4	<i>Arthroscopy Techniques</i>	36
5	<i>Journal of Orthopaedic Research</i>	31
6	<i>Clinical Orthopaedics and Related Research</i>	20
7	<i>Journal of Bone &amp; Joint Surgery—American Volume</i>	19
8	<i>Knee</i>	19
9	<i>Orthopaedic Journal of Sports Medicine</i>	16
10	<i>Veterinary Surgery</i>	9

<sup>a</sup>ACL, anterior cruciate ligament.

autograft (n = 35) found noninferiority in patient-reported outcomes and knee laxity with improved hamstring strength in the BEAR group, while 14% of patients who underwent BEAR and 6% of patients who underwent ACL reconstruction required a second ipsilateral ACL surgery.<sup>22</sup>

Primary repair of proximal ACL tears with or without suture tape augmentation (internal bracing) has been recently advanced by the Gregory Difelice and colleagues. In 1991, Sherman et al<sup>31</sup> suggested that primary ACL suture repair yielded good results with particular ACL injury characteristics, notably, older patients with proximal ACL tears, good residual tissue quality, and “tight-jointedness” with mild preoperative flexion contracture. Building on this work, Vermeijden et al<sup>36</sup> demonstrated

that ACL tear location and remnant length could be reliably measured on magnetic resonance imaging. In a cohort study of 56 consecutive patients with proximal ACL tears that underwent primary ACL repair with suture anchor fixation, good objective and subjective outcomes were obtained at the average 3.2-year follow-up, with 6 patients (10.7%) experiencing repair failure.<sup>13</sup> Of the first 11 consecutive patients, clinical outcomes were maintained at an average follow-up of 6 years.<sup>5</sup>

DIS has been most commonly investigated in Europe by Stefan Eggli and colleagues. DIS employs a dynamic spiral spring mechanism to reduce aberrant anterior tibial translation in the ACL-injured knee, which is often combined with biological augmentation (eg, microfracture and/or platelet-rich plasma) at the tear site in an effort to promote neotissue formation.<sup>7</sup> DIS-mediated ACL healing was demonstrated first in a preclinical sheep model in 2013.<sup>15</sup> A subsequent case series of 105 patients who underwent DIS reported failure with a revision rate of 16.3% and residual side-to-side anterior-posterior laxity  $\geq 3$  mm in 18.2% of cases, which the authors noted were higher than the values typically reported after ACL reconstruction.<sup>30</sup> Similarly, Osti et al<sup>26</sup> found an overall complication rate of 57.9% in a case series of 59 patients undergoing DIS, with complications including rerupture (17.5%), new meniscal tear (15.4%), cyclops formation (30.8%), and restricted range of motion (53.8%). On the other hand, in a prospective randomized controlled trial comparing DIS versus ACL reconstruction, there was no statistically significant difference in failure requiring revision surgery (DIS 16.3% vs ACL reconstruction

TABLE 3  
Ranking of ACL Repair Documents in Each Organization<sup>a</sup>

Rank	Institution	No. of Publications
1	Hospital for Special Surgery	51
2	Boston Children's Hospital	49
3	Brown University	31
4	University of Bern	17
5	University of Antwerp	17
6	University of Amsterdam	17
7	University of Pittsburgh	15
8	University Hospital Münster	9
9	Cedars-Sinai Kerlan-Jobe Institute	8
10	Sonnenhof Orthopaedic Center	9

<sup>a</sup>ACL, anterior cruciate ligament.

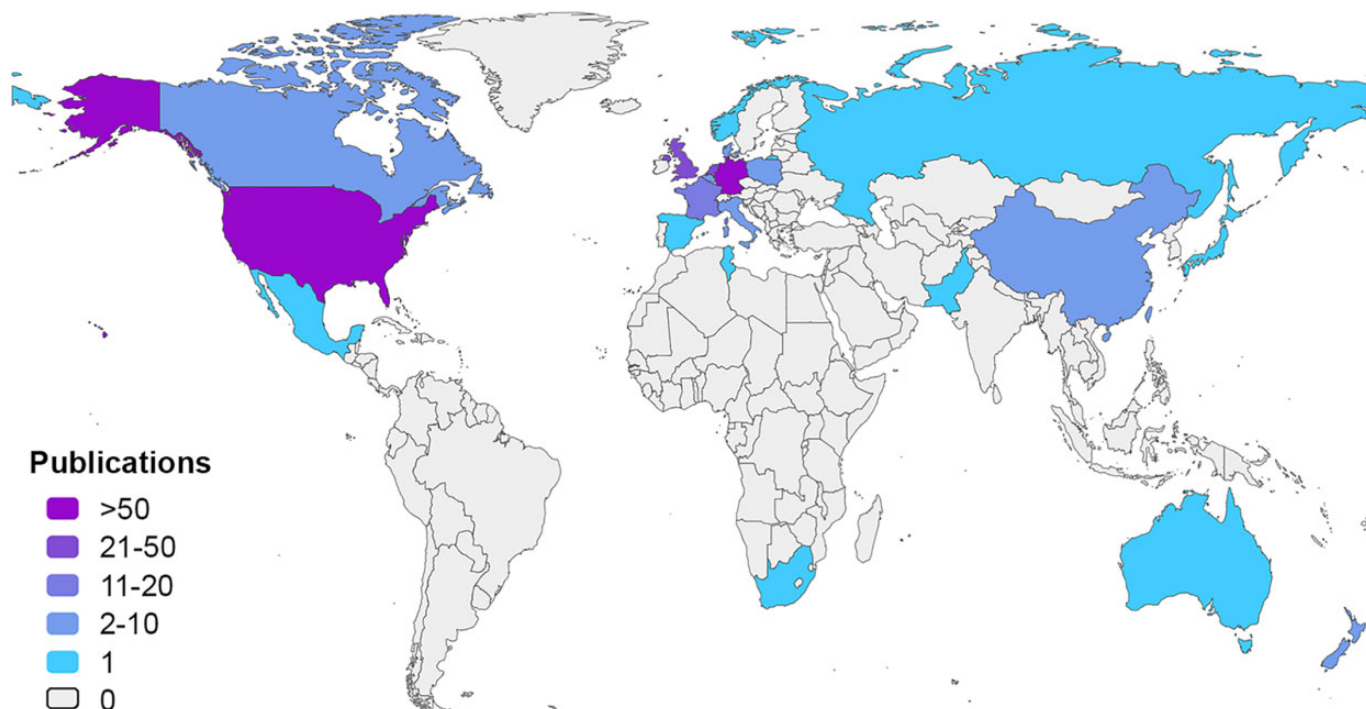


Figure 6. Distribution by country of publications on anterior cruciate ligament repair.

12.5%) nor rates of recurrent objective or subjective instability or patient-reported outcome measures (ie, Tegner, International Knee Documentation Committee, or Lysholm score).<sup>16</sup>

As visualized through this bibliometric analysis of the literature on ACL repair, the recent rise in publications on the topic has largely come from a small number of corresponding authors and their associated coauthors. Overcoming the past limitations of ACL repair to achieve a viable clinical strategy equal or superior to ACL reconstruction will require the involvement of more research groups, with collaboration and exchange among investigators. While the recent innovations in surgical techniques, devices, and biomaterials have likely contributed to the renewed interest in ACL repair, there is no consensus on indications for surgical repair, surgical technique, or rehabilitation protocols.<sup>37</sup> The level of evidence is low and there are limited studies reporting medium- or long-term outcomes.<sup>12,34</sup>

### Limitations

This study has some limitations. First, the analysis of global ACL research is somewhat flawed, as published articles are mostly written in English and there are many journals in other languages that are worth studying. Second, authors prefer to cite articles from the journal in which they intend to publish. This might bring in the bias of “incomplete citing” and “omission bias.” Finally, authors tend to use widely cited literature that they think is more reliable. This is called the snowball effect and tends to be biased.

### CONCLUSION

This article summarized research topics, trends, and sources for ACL repair as well as outlined global research on its impact. It allows researchers who want to understand ACL repair to quickly grasp the development history, current status, and trends of the research field, and have a macro understanding of global ACL repair research. It also provides a general understanding of the current mainstream surgical methods and allows comparisons among authors and institutions with greater academic influence around the world, in turn guiding further study and research cooperation. Consequently, ACL reconstruction remains the gold-standard surgical option for patients with ACL tears.<sup>12</sup> An ongoing prospective randomized clinical trial comparing BEAR, DIS, internal brace augmentation, and ACL reconstruction will help clarify the relative merit of each approach.<sup>10</sup>

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## APPENDIX

TABLE A1  
Most Cited Articles on ACL Repair<sup>a</sup>

Title	Authors	No. of Citations	
		Overall	Excluding Self-Citations
Collagen-platelet rich plasma hydrogel enhances primary repair of the porcine anterior cruciate ligament	Murray MM, Spindler KP, Abreu E, Muller JA, Nedder A, Kelly M, Frino J, Zurakowski D, Valenza M, Snyder BD, Connolly SA,	119	66
Isolated tear of the anterior cruciate ligament: 5-year follow-up study	Feagin JA Jr, Curl WW	113	113
Enhanced histologic repair in a central wound in the anterior cruciate ligament with a collagen-platelet-rich plasma scaffold	Murray MM, Spindler KP, Ballard P, Welch TP, Zurakowski D, Nanney LB	99	55
Use of a collagen-platelet rich plasma scaffold to stimulate healing of a central defect in the canine ACL	Murray MM, Spindler KP, Devin C, Snyder BS, Muller J, Takahashi M, Ballard P, Nanney LB, Zurakowski D	74	39
Long-term results after primary repair or non-surgical treatment of anterior cruciate ligament rupture: a randomized study with a 15-year follow-up	Meunier A, Odensten M, Good L	73	73
The long-term follow up of primary anterior cruciate ligament repair. Defining a rationale for augmentation	Sherman MF, Lieber L, Bonamo JR, Podesta L, Reiter I	73	72
Use of a bioactive scaffold to stimulate anterior cruciate ligament healing also minimizes posttraumatic osteoarthritis after surgery	Murray MM, Fleming BC	63	29

(continued)



Table A1 (continued)

Title	Authors	No. of Citations	
		Overall	Excluding Self-Citations
Basic science of anterior cruciate ligament injury and repair	Kiapour AM, Murray MM	79	72
Collagen–platelet composite enhances biomechanical and histologic healing of the porcine anterior cruciate ligament	Joshi SM, Mastrangelo AN, Magarian EM, Fleming BC, Murray MM	67	37
Untreated ruptures of the anterior cruciate ligament. A follow-up study	McDaniel WJ Jr, Dameron TB Jr	56	56
The anterior cruciate ligament: a technique of repair and reconstruction	Marshall JL, Warren RF, Wickiewicz TL, Reider B	62	61
Platelet-rich plasma alone is not sufficient to enhance suture repair of the ACL in skeletally immature animals: an in vivo study	Murray MM, Palmer M, Abreu E, Spindler KP, Zurakowski D, Fleming BC	61	30
Ligament repair and reconstruction in traumatic dislocation of the knee	Liow RY, McNicholas MJ, Keating JF, Nutton RW	58	58
Biomechanical outcomes after bioenhanced anterior cruciate ligament repair and anterior cruciate ligament reconstruction are equal in a porcine model	Vavken P, Fleming BC, Mastrangelo AN, Machan JT, Murray MM	55	31
Indications for surgical treatment of tibial condyle fractures	Honkonen SE	51	51
Current status and potential of primary ACL repair	Murray MM	49	41

<sup>a</sup>ACL, anterior cruciate ligament.