

Review Article

Robotic and Navigation-Assisted Knee Arthroplasty: Understanding Research Funding Allocation and Innovation Using a Modern Linked Data Network

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Background

An abundance of research has been published recently regarding robotic and navigation-assisted knee arthroplasty. Dimensions is a modern-linked database that uses machine-learning and cloud-computing to aggregate grants, publications, citations, clinical trials, and patents in one place. Using Dimensions data, this study examines the evolution of knowledge and funding for robotic/navigated knee arthroplasty.

Methods

Dimensions was queried for publications, grants, patents, and clinical trials related to knee arthroplasty and robotics/navigation. There were no geographic or date-range restrictions. Search results were manually screened for accuracy and resulted in 2,590 publications, 23 grants, 110 patents, and 166 clinical trials beginning in 2004. 2023 inflation-adjusted US Dollars (USD) were reported. Descriptive statistics and temporal analyses were performed.

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Results

Since 2004, approximately \$260M has been allocated for robotic/navigated knee arthroplasty. Largest contributors are the International Cancer Research Partnership (ICRP) and National Institutes of Health (NIH). Most funding was granted by the United States (\$3M), United Kingdom (\$1.5M), and Norway (\$1.3M). 2,590 publications were identified, with the majority (63%) being clinical research, 32% basic-science, and 5% combined. Top publications were found to have widespread scientific reach, with the top 5 articles having more than 300 citations. Among 110 patents filed, there was a bimodal distribution with peaks in the early 2000's and a resurgence from 2018-2022. 132 (80%) of the clinical trials identified were interventional.

Conclusion

Using a modern-linked data network, we have identified that the US and UK are primary funders of robotic arthroplasty research followed by Norway. Publications and patents about robotic knee arthroplasty have risen since 2018, and 166 clinical trials have been registered. These results provide an overview of the funding and publication landscape and may serve as a basis for institutions to direct their efforts for further trials.

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INTRODUCTION

Traditionally, total knee arthroplasty (TKA) has been performed with the assistance of various manually adjusted cutting guides and alignment systems. However, the relatively recent introduction of robotic and navigation technologies aims to enhance the precision of osteotomies and implant alignment, minimize soft tissue disruption, and possibly improve patient outcomes (Buza et al., n.d.; Christ et al. 2018; Jacofsky and Allen 2016; Liow et al. 2014). Although robotic knee arthroplasty was first described in 1993,(Matsen et al. 1993) it has not been until the last decade that we have seen a dramatic upsurge in interest from both surgeons and patients in robotic and navigation-assisted TKA and unicompartmental knee arthroplasty (UKA) (Lieberman, Chen, and Iorio 2022). Despite the potential benefits of these technologies, questions still remain regarding cost-effectiveness, the procedural learning curve, and resulting impact on education of trainees who may not experience adequate training with manual techniques (Kolesar et al. 2022; Jung et al. 2023; Morrissey et al. 2023; Schopper et al. 2023).

Recently, a plethora of research has emerged which attempts to assess the value of these new technologies in knee arthroplasty. Therefore, it is essential to evaluate the progress made thus far and explore the trajectory of future developments in robotic and navigation-assisted knee arthroplasty. As such, this study was designed to leverage a modern linked research data infrastructure to analyze multiple data sources including publications, patents, clinical trials, and grants relating to robotic and navigation-

assisted knee arthroplasty. Through this investigation, we sought to provide a comprehensive overview of the field, identifying innovation via patents and grant funding, as well as research throughput via clinical trials and publications. Our hope is that this analysis may offer a resource to researchers and institutions alike, helping to guide future efforts in this rapidly developing field.

METHODS

DATA SOURCE

Developed in 2018, the Dimensions database is a modern linked research data network which uses various modern technologies such as machine learning and cloud computing to aggregate grants, publications, citations, clinical trials, patents, and policy documents in one place. Dimensions provides a uniquely comprehensive approach to research discovery and access compared to traditional databases such as PubMed, Google Scholar, Scopus or Web of Science (Dimensions Analytics 2022). Dimensions data can be accessed either for free or through a paid subscription, with the level of access and the decision to utilize the algorithm application programming interface (API) influencing the choice of subscription. For this study, a paid Dimensions data subscription was utilized via our institution's library, allowing us access through the API. The data includes over 100 million indexed publications, 4.6 million grants, 38 million patents, 455,000 clinical trials and 422,000 policy documents (Dimensions Analytics 2022). The Dimensions database establishes links between grants, patents and publications using several methodologies. Natural language processing is employed to extract and analyze the acknowledgements section of publications, and any specific grants or funding organization names identified within these sections allow Dimensions to create a direct connection between a specific grant and the resulting publication. The database also taps into authoritative sources like PubMed and CrossRef to further enhance the grant-publication linkage (Dimensions Analytics 2022). Although

the Dimensions resource is relatively new, Dimensions data have been accepted in the peer-reviewed literature with several published studies utilizing this data source (Ravi et al. 2024; Raman 2023; Beinat et al. 2024).

The Dimensions data also includes data such as the Altmetric score, which is a numerical representation of the visibility and impact of a scholarly article or research output on social media platforms, news articles, online discussions, and other online platforms (Martins and Wasif 2023). It measures the attention and engagement received by the scholarly work, including the number of times it has been shared, liked, commented on, and cited in various online sources. Altmetric scores can be useful in assessing the broader impact of research outputs (Collins et al. 2021).

RETRIEVAL OF ROBOTIC AND NAVIGATION-ASSISTED KNEE ARTHROPLASTY RELATED DATA

The Dimensions database was queried for all information regarding robotic and navigation-assisted total and partial knee arthroplasty without geographic or date-range restrictions. Initial retrieval included publications, grants, patents, and clinical trials related to knee arthroplasty that had any aspect of robotics or navigation. The search process involved scanning for keywords in the title or abstract including “knee arthroplasty” AND (“robotic” OR “navigation” OR navigat*). Grants, peer- publications, patents and clinical trials were gathered for all available time periods through the time the search was performed on February 17, 2023.

Two researchers (A.B.H, X.S) performed a manual screening of the titles and abstracts of 2,876 items from the initial search. Items were excluded that did not directly focus on robotic and navigation-assisted knee arthroplasty or grants directed towards conference or symposium awards, travel, and/or clinical fellowships. Also excluded were any basic science/non-clinical research entries that lacked a genuine focus on knee arthroplasty.

DATA VERIFICATION AND SCREENING

The initial search resulted in 2,616 publications, 24 grants, 110 patents, and 166 clinical trials. All results were initially manually screened by a single author (X.S.) to confirm the inclusion/exclusion criteria and verified by a second author (A.B.H.). Ultimately, 2,590 (99%) of publications met inclusion criteria, 22 (92%) of grants, and all patents/clinical trials originally identified were also included in the final study. Further, all publications/grants/patents were classified as either clinical, non-clinical, or both. Clinical publications/grants/patents were defined as those involving human subjects as part of the primary research. Non-clinical publications/grants/patents included biomechanical studies, robotic engineering projects, and animal-based studies.

For grant funding amounts, the monetary values were adjusted for inflation using the Consumer Price Index at the beginning of each year of the grant. This adjustment nor-

malized all funding to the value of the USD in 2023, ensuring comparability across the years.

STATISTICAL ANALYSIS

Descriptive statistics were used to analyze the number of publications, grants, patents, and clinical trials. This analysis further categorized these values by funder, region of grant, and topic. All statistical analyses were performed using Stata Statistical Software: Release 17 (StataCorp. 2021; College Station, TX). Significance was defined as $p < 0.05$.

RESULTS

GRANTS

The majority of the 22 grants identified (55%) were for non-clinical projects including robotic/engineering and biomechanical grants. 41% were for clinical studies, and a small fraction (5%) were for studies that involved both clinical and non-clinical research. Of the 19 grants for which funding amounts could be obtained, the amount of funding ranged from \$17,705.64 to \$1,522,259 (interquartile range (IQR): \$32,536.68 to \$470,049.5) with a mean funding amount of \$350,316.

Grants were provided by various funders from different countries, with the highest mean funding amount attributed to grants from Norway (\$1,292,344.9). However, the largest proportion of the grants (47.37%) originated from the United States, having a mean funding amount of \$325,822.68 per grant. The National Institute of Arthritis contributed the highest total funding with \$2446K across three grants, followed by the Orthopaedic Research and Education Foundation with \$230K across five grants. When examining contributions from larger umbrella organizations, the International Cancer Research Partnership (ICRP) had the highest total funding of \$2640K, followed by cOAlition S with \$1292K, and the National Institute of Health (NIH) with \$1431K, [Figure 1](#).

PUBLICATIONS

Of the 2,590 peer-reviewed publications identified in the final analysis, articles were cited a mean of 17 ± 36 times. 45% of publications were Open Access (OA). The publications spanned from 1993 to 2023, with an increasing trend in the number of publications over time. The highest number of publications were seen in 2022 with 294 papers (11% of the total) while the least number was seen in 1993, 1995, 1996, 1998, and 1999 with just one paper each year. 2022 had the highest number of publications (294, 11% of the total), [Figure 2](#). In terms of Altmetric scores, there were observations for 639 of the publications. The mean Altmetric score was approximately 6.3 ± 23.4 (Range 1-400).

Regarding the countries of the research organizations involved, the United States was the most represented with 541 publications (25.57% of the total). This was followed by Japan (192 publications, 9.07%), Germany (123 publi-

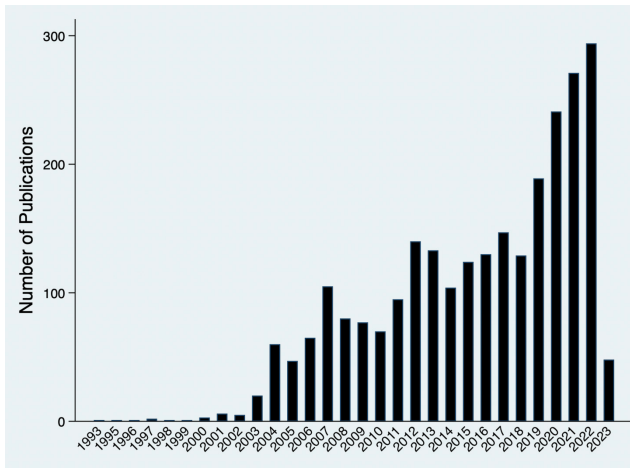


Figure 1. Number of Publications per Year with a Primary Focus on Robotic and Navigated Knee Arthroplasty

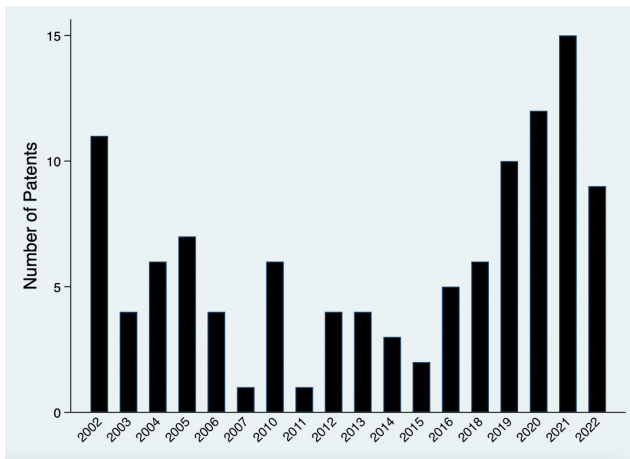


Figure 2. Number of Patents Filed per Year with a Primary focus on Robotic or Navigated Knee Arthroplasty.

cations, 5.81%), the United Kingdom (118 publications, 5.58%), and South Korea (102 publications, 4.82%). Finally, categorization based on whether the research was clinical, non-clinical, or both showed that 32% of the papers were non-clinical, a substantial majority of 63% were clinical, and the remaining 5% encompassed both clinical and non-clinical research. The top 10 most cited peer-reviewed publications had between 262-646 citations, and an overview of all of the 10 most cited publications is provided in [Table 1](#).

PATENTS

There were a total of 110 patents filed from 2002 to 2022. The statuses of these patents varied with 34 (31%) being pending, 21 (19%) granted, 19 (17%) abandoned, 11 (10%) active, and 9 (8%) were published applications. The remaining patents were listed as N/A, expired (either due to fees or end of lifetime), or withdrawn. The largest number of patents were filed in 2021 (15 patents, 14% of the total),

closely followed by the year 2020 with 12 patents (11%). The least patents were filed in the years 2007 and 2011, each with just one patent filing, [Figure 3](#).

Of the 21 patents that were granted, the years each patent was granted ranged from 2004 to 2022. The year 2013 and 2014 had the most granted patents with 2 each, representing 13% of all granted patents. Regarding the location of the assignees, most patents were associated with the United States, with 58 patents (59%) having their assignees based there. This was followed by Canada with 20 patents (20%), China with 6 patents (6%), and Israel with 5 patents (5%). The remainder of the patents had assignees located in various countries, with a several being assigned to multiple countries.

CLINICAL TRIALS

The clinical trials data consisted of a total of 166 trials from 2000 to 2023. These trials had a mean of 140 ± 117 participants (range 9-674). 34 of the 166 trials were able to be directly linked to funding data. Of these 34 trials, the United States had the largest proportion of the overall funded clinical trials (18 trials, 53% of the total). Taiwan and China each funded 4 trials (12%), followed by India and Italy each funding 2 trials (6%). The remaining trials were funded by Belgium, Canada, Norway, and Singapore, each funding one trial.

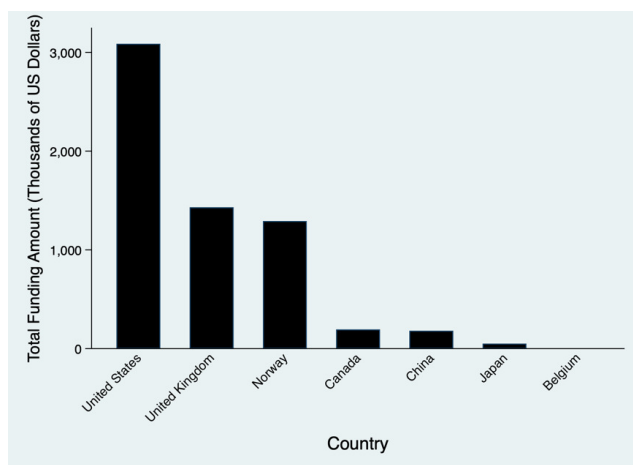
DISCUSSION

Overall, the purpose of this study was to provide a clear outline of the innovation and research output in robotic and navigation-assisted total knee arthroplasty. The results of our investigation offer a perspective on the progression of knowledge and funding, with several important and novel discoveries. Our analysis identified a substantial increase in patents and publications since 2018, as well as a marked increase in patents filed since 2015, underscoring the escalating interest and advancement in this field. This trajectory suggests an accelerated pace of innovation and inquiry, fueled by the potential end enthusiasm for robotic and navigation technologies to revolutionize knee arthroplasty. We believe that this study is relevant because it quantifies the increasing interest and prevalence of this technology throughout the entire spectrum from idea development to translational research. Our findings of rapid growth without signs of slowing should instill confidence in innovators who wish to make continued advances in robotic and navigation-assisted knee arthroplasty.

Interestingly, our data highlights the United States and the United Kingdom as the top funders for research in this domain, followed by Norway. This highlights the geographical distribution of research efforts, emphasizing the regions which have taken the lead in propelling the development of robotic and navigated knee arthroplasty. It also reveals potential areas for other countries to expand funding and research activities on this topic. When examining the top countries/regions overall for medical research funding, it should also be noted that the top regions of the world

Table 1. Top 10 Most Cited Peer-Reviewed Publications on Robotic and Navigated Knee Arthroplasty

Rank	Citations	Title			
1	646	Effect of Postoperative Mechanical Axis Alignment on the Fifteen-Year Survival of Modern, Total Knee Arthroplasties	Journal of Bone and Joint Surgery	2010	Parratte, S., Pagnano, M.W., Trousdale, R.T., Berry, D.J.
2	527	Alignment in total knee arthroplasty: A Comparison of Computer-Assisted Surgery with the Conventional Technique	The Bone & Joint Journal	2004	Bäthis, H., Perlick, L., Tingart, M., Lüding, C., Zurakowski, D., Grifka, J
3	474	Positioning of Total Knee Arthroplasty with and Without Navigation Support. A Prospective, Randomised Study	The Bone & Joint Journal	2003	Sparmann, M., Wolke, B., Czupalla, H., Banzer, D., Zink, A
4	370	A Prospective, Randomized Study of Computer-Assisted and Conventional Total Knee Arthroplasty	Journal of Bone and Joint Surgery	2007	Matziolis, G., Kroker, D., Weiss, U., Tohtz, S., Perka, C.
5	320	Computer-Assisted Navigation Increases Precision of Component Placement in Total Knee Arthroplasty	Clinical Orthopaedics and Related Research	2005	Haaker, R.G., Stockheim, M., Kamp, M., Proff, G., Breitenfelder, J., Ottersbach, A.
6	280	Navigated Total Knee Replacement	Journal of Bone and Joint Surgery	2007	Bauwens, K., Matthes, G., Wich, M., Gebhard, F., Hanson, B., Ekkernkamp, A., Stengel, D.
7	273	Hands-on Robotic Unicompartmental Knee Replacement	The Bone & Joint Journal	2006	Cobb, J., Henckel, J., Gomes, P., Harris, S., Jakopc, M., Rodriguez, F., Barrett, A., Davies, B.
8	273	Navigated Total Knee Replacement. A Meta-analysis	Journal of Bone and Joint Surgery	2007	Bauwens, K., Matthes, G., Wich, M., Gebhard, F., Hanson, B., Ekkernkamp, A., Stengel, D.
9	266	Meta-Analysis of Navigation vs Conventional Total Knee Arthroplasty	The Journal of Arthroplasty	2012	Hetaimish, B.M., Khan, M.M., Simunovic, N., Al-Harbi, H.H., Bhandari, M., Zalzal, P.
10	262	Navigation Improves Accuracy of Rotational Alignment in Total Knee Arthroplasty	Clinical Orthopaedics and Related Research	2004	Stöckl, B., Nogler, M., Rosiek, R., Fischer, M., Krismer, M., Kessler, O.


Figure 3. Funding Provided by Countries Sponsoring Research on Robotic and Navigated Knee Arthroplasty.

are North America, Europe, with much smaller contributions coming from Africa, the majority of Asia, and the Middle East (Petersen 2021). In addition, the United States and United Kingdom are also the top 2 leaders in worldwide oncology research (McIntosh, Alam, Adams, et al. 2023). Thus, our findings may also be an artifact of countries with larger research funding infrastructure in general.

The substantial and consistent growth in annual publications on robotic and navigation-assisted knee arthroplasty observed in our study corroborates the conclusions of two recent bibliometric analyses by Boddu et al (Boddu et al. 2023). and Mahmoud et al (Mahmoud et al. 2022). Both of these analyses identified a significant increase in influential literature pertaining to robotic arthroplasty, particularly over the last decade, which they attributed largely to contributions from the United States. Mahmoud et al. emphasized the frequent citation of papers focusing on clinical outcomes (Mahmoud et al. 2022). The alignment of these findings accentuates the growing importance of ro-

botic and navigation assistance in knee arthroplasty, underscoring the need for continued investigation and the value of analyses like ours in guiding future research endeavors. Our study can also be compared to an analysis of the PatentInspiration database performed by Dalton et al. in 2016, in which the authors identified the largest technology clusters within knee arthroplasty to be Unicompartmental, Patient-Specific Instrumentation (PSI), Navigation, and Robotic knee arthroplasty. They were able to correlate patents in these areas with publication productivity to suggest that PSI was undergoing a period of exponential growth (Dalton et al. 2016). While our study focused solely on robotic and navigated knee arthroplasty as a whole, it seems that the trends in patents and publications in this field have continued since 2016.

Beyond publications, our study additionally highlighted a surge in the number of clinical trials in this area, implying what appears to be a translation of research interest into clinical practice. Singh et al. noted similar trends in the field of neurosurgery, with an increasing number of clinical trials focusing on robotic procedures (Singh, Wang, Qureshi, et al. 2022). However, their findings also suggest that while there is a growth in the field, robotics in neurosurgery is still in its infancy, with less than half of the top programs offering robotic procedures (Singh, Wang, Qureshi, et al. 2022). Our findings also indicate that the majority of clinical trials are interventional rather than observational in nature. This aligns with the broader objective of integrating and evaluating the efficacy of these advanced technologies in actual surgical procedures, moving beyond basic-science research into real-world applications. Yet, as Robinson et al. pointed out in their systematic review of 388 randomized clinical trials in surgery, the quality and design of these trials often lack standardization, with significant discrepancies in trial registration and protocol adherence. Few trials controlled for surgeon experience or assessed the quality of the intervention, suggesting an area that needs improvement in clinical trials in order to reliably evaluate the efficacy of new surgical technologies (Robinson, Fremes, Hameed, et al. 2021). Future studies may seek to assess the quality of clinical trials performed in robotic knee arthroplasty in order to guide future directions for high-quality studies to be designed where needed.

This study presents several limitations which should be acknowledged. Our reliance on the Dimensions database, despite its comprehensive nature, may exclude data from less recognized data sources or uncatalogued research. While this study offers an in-depth examination of robotic and navigation-assisted knee arthroplasty research trends, it does not extend its analysis to the quality or outcomes of the clinical trials, patents, or interventions under study, limiting the interpretation of the translational aspect of these advancements. The additional manual screening process of search results, although meticulously performed, also carries an inherent risk of human error. Our categorization of data into clinical and non-clinical also assumes a clear delineation between the two could also oversimplify complex, multi-disciplinary projects. Lastly, inflation adjustment for grant funding was based on the Consumer Price Index, which may not fully account for the variations in funding value across different regions and time periods. Despite these limitations, we believe that this study provides an invaluable overview of the trends in research related to robotic and navigation-assisted knee arthroplasty.

CONCLUSION

Our results underscore the increasing interest and investment in the field of robotic and navigation-assisted knee arthroplasty, with a notable increase since 2018. We identified the United States and United Kingdom as leading funders supporting research activities and innovation within this field. With 80% of clinical trials being interventional, these technologies are rapidly transitioning from the laboratory to the operating room. For arthroplasty surgeons and researchers, these findings provide a map of the current landscape, identifying areas of high activity, potential collaboration, and future exploration, thereby assisting in shaping the next phase of research and clinical practice in robotic knee arthroplasty.

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