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ORIGINAL ARTICLE

Medicine Science International Medical Journal

Medicine Science 2025;14(4):1179-86

Publication trends and global collaboration in MAKO robotic-arm assisted total knee arthroplasty: A bibliometric analysis of the last 10 years and future research directions

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Received 17 June 2025; Accepted 08 September 2025
Available online 27 November 2025 with doi: 10.5455/medscience.2025.06.162

Abstract

Total knee arthroplasty (TKA) is a prevalent intervention for end-stage knee osteoarthritis. MAKO robotic-arm assisted technology has emerged to enhance surgical precision, implant positioning, and patient outcomes. This study presents a bibliometric analysis of global research trends on MAKO robotic-arm assisted TKA from 2014 to 2024, aiming to map publication growth, key contributors, and collaboration networks, specifically focusing on the MAKO platform to delineate system-specific research dynamics often obscured in broader robotic TKA analyses, thereby informing future research directions. This study adopts a platform-specific focus to delineate system-level research dynamics often obscured in pooled robotic TKA analyses. A total of 902 publications indexed in the Web of Science database were analyzed using bibliometric tools including VOSviewer, CiteSpace, and Bibliometrix. Publication trends, citation impact, geographic distribution, co-authorship networks, and keyword co-occurrence were examined to identify research hotspots and influential factors. Findings reveal a significant increase in annual publications (CAGR ~28%) and citations, with the United States, India, Germany, and China leading research output. Strong international collaborations were identified, primarily among institutions in the US, Europe, and East Asia. Dominant research themes include implant alignment accuracy, patient-specific surgical planning, and early functional recovery. Most studies were published in high-impact Q1 orthopedic journals. MAKO robotic-arm assisted TKA research has rapidly expanded, reflecting its growing clinical adoption and scientific interest. Despite promising outcomes, challenges such as high costs, learning curves, and limited long-term data persist. While focused on a single CT-based, haptics-enabled platform, these findings complement pooled robotic TKA bibliometrics and motivate cross-platform comparative analyses. Beyond mapping, we synthesize clinical and health-system implications of dominant MAKO-related themes to inform practice and policy. Future research should emphasize long-term clinical outcomes, cost-effectiveness, and integration of artificial intelligence to further optimize robotic TKA and enhance its role in improving patient care.

Keywords: Total knee arthroplasty, bibliometric analysis, surgery, MAKO robotic-arm

Introduction

Total knee arthroplasty (TKA) is a widely performed surgical procedure that significantly improves pain and function in patients with end-stage knee osteoarthritis [1,2]. The advent of robotic-arm assisted technologies, particularly the MAKO system, has introduced a paradigm shift in orthopedic surgery by enhancing surgical precision, implant positioning, and potentially improving patient outcomes [3-5]. The MAKO robotic system utilizes preoperative 3D CT-based planning combined with intraoperative haptic feedback, allowing surgeons to execute patient-specific surgical plans with high accuracy [6,7].

Recent clinical evidence supports that MAKO-assisted TKA achieves superior component alignment and reduces outliers compared to conventional manual techniques, which are critical factors for implant longevity and patient satisfaction

CITATION
Ozdemir E, Olcay Ozdes O, Ozdes HU. Publication trends and global collaboration in MAKO robotic-arm assisted total knee arthroplasty: A bibliometric analysis of the last 10 years and future research directions. Med Science. 2025;14(4):1179-86.

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[8–10]. Furthermore, robotic assistance has been associated with reduced soft tissue damage, lower systemic inflammatory response, and faster early functional recovery [11,12]. Despite these promising clinical outcomes, the rapid expansion of research in this field necessitates a comprehensive bibliometric evaluation to map publication trends, identify key contributors, and understand global collaboration networks.

Bibliometric analysis is a robust quantitative method to assess scientific productivity, impact, and collaboration patterns within a research domain [13]. While bibliometric studies on robotic surgery in orthopedics exist, focused analyses on the MAKO system in TKA, especially covering the most recent decade, remain scarce. Such an analysis is essential to highlight emerging research hotspots, influential authors and institutions, and to guide future research priorities [14,15].

While bibliometric studies on general robotic surgery in orthopedics exist, a focused analysis on the MAKO system in TKA, especially covering the most recent decade, remains scarce. The MAKO system, with its unique CT-based preoperative planning and haptic feedback, represents a distinct technological approach compared to other robotic systems (e.g., ROSA, NAVIO) that often rely on imageless or camera-based navigation. This study specifically targets the MAKO platform to provide a granular understanding of its unique publication ecosystem, collaboration patterns, and thematic evolution, which might be diluted in broader analyses encompassing diverse robotic technologies.

This study aims to fill this gap by conducting a bibliometric analysis of MAKO robotic-arm assisted total knee arthroplasty literature published over the last 10 years. We systematically evaluate publication outputs, citation impact, authorship networks, and geographic distribution of research to provide a comprehensive overview of the field's evolution and to propose future research directions that may further improve clinical outcomes and technological innovation.

Rationale for MAKO-specific focus: MAKO's CT-based planning and intraoperative haptic guidance constitute a distinct workflow compared with imageless platforms (e.g., ROSA, NAVIO). A platform-specific bibliometric analysis is warranted to capture unique publication growth, collaboration networks, and thematic evolution that may be diluted in aggregated robotic TKA analyses.

Material and Methods

Data Source and Search Strategy

This bibliometric analysis utilized the Web of Science Core Collection database (SCI-E, SSCI, AHCI) for its comprehensive coverage of peer-reviewed journals and standardized bibliometric data. A systematic search was conducted using the query: ("MAKO" OR "robotic-arm assisted") AND ("total knee arthroplasty" OR "total knee replacement" OR "TKA" OR "TKR")covering January 2014 to December 2024, limited to English-language articles, reviews, and conference proceedings.The search strategy was intentionally designed to focus exclusively on MAKO robotic-arm assisted TKA. This specific scope allows for a detailed examination of a single, widely adopted robotic platform, enabling the identification of unique research trends and collaborations pertinent to its distinct technological features and clinical application.

Justification of focus: We intentionally restricted the search to MAKO-assisted TKA to minimize construct heterogeneity and to map platform-specific collaboration patterns and keyword bursts aligned with MAKO's hardware/software cadence.

Study Selection and Data Processing

Following PRISMA guidelines adapted for bibliometric studies, the initial search yielded 1,245 records. After removing 143 duplicates, 1,102 unique records underwent title/abstract screening by two independent reviewers. Exclusion criteria included non-MAKO studies, irrelevant content, and insufficient data. Following exclusion of 102 irrelevant and 98 incomplete records, 902 publications comprised the final dataset (Figure 1).

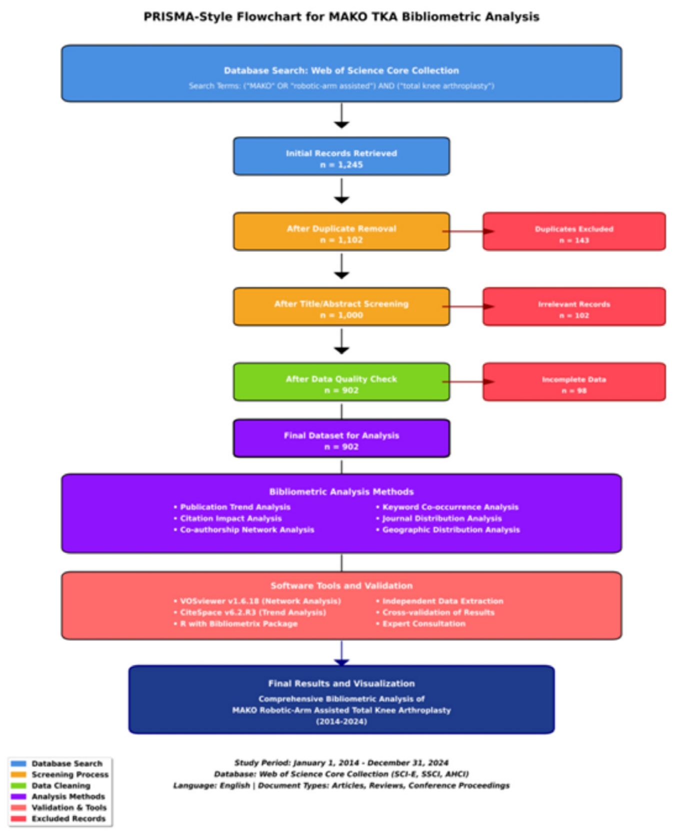

Figure 1. A PRISMA-style flowchart illustrating the systematic literature search, screening, and selection process, which resulted in 902 publications for bibliometric analysis of research on MAKO robotic-arm assisted total knee arthroplasty from 2014 to 2024.

Data Extraction and Analysis

Bibliometric data were extracted using Web of Science export functions, including publication characteristics, author information, citation metrics, and journal details. Analysis

DOI: 10.5455/medscience.2025.06.162

encompassed publication trends, citation impact, journal distribution, geographic patterns, co-authorship networks, and keyword co-occurrence using established bibliometric methods. No formal methodological quality appraisal or detailed study design/sample size extraction was performed for top-cited articles, as this falls outside the scope of a bibliometric mapping.

Software and Statistical Analysis

VOSviewer v1.6.18 was used for network visualization, Cite Space v6.2.R3 for temporal analysis and burst detection, and R with Bibliometrix package for statistical calculations. Descriptive statistics, regression models for trend analysis, and network metrics were calculated. Statistical significance was set at $p < 0.05$.

Citation metrics reflect raw Web of Science counts; no self-citation exclusion, field normalization, or age-adjustment was applied, and results should be interpreted as descriptive indicators of influence rather than standardized measures of quality.

Quality Assurance

Data quality was ensured through independent extraction by two reviewers for 10% of records, with inter-rater reliability assessed using Cohen's kappa. Results were cross-validated across multiple software platforms, and clinical relevance was confirmed through expert consultation with orthopedic surgery specialists.

Ethical Considerations

This study used publicly available bibliometric data without human subjects involvement, therefore institutional review board approval was not required. All analyses followed established bibliometric research guidelines and ethical standards for secondary data research.

Results

Annual Publication and Citation Trends

Between 2014 and 2024, a total of 902 publications related to MAKO robotic-arm assisted TKA were indexed in the Web of Science database. The annual number of publications increased steadily from 5 in 2014 to 150 in 2024, reflecting a growing interest in this technology. Given citation time-lag, recent-year records are expected to show lower raw citation counts independent of their scientific merit. Regression analysis demonstrated a significant positive trend in publication output over the decade ($R^2 = 0.92$, $p < 0.001$), with a compound annual growth rate (CAGR) of approximately 28%.

Citations followed a similar upward trajectory, with total citations rising from 10 in 2014 to 5,500 in 2024. The average citations per publication peaked for earlier years, consistent with the longer time available for citation accumulation (Table 1). This trend underscores the increasing impact and recognition of MAKO-assisted TKA research within the orthopedic community.

Top Cited Articles

Table 2 presents the top 10 most cited articles in MAKO robotic-arm assisted total knee arthroplasty. The most cited article, "Mako Robotic-Arm Assisted Total Knee Arthroplasty: Updated Software" by Marchand et al. [16], has significantly influenced the field. Other highly cited works focus on clinical outcomes, cost-effectiveness, and surgical techniques, highlighting the multifaceted research interest in MAKO-assisted TKA.

Geographic Distribution and International Collaboration

Research output in MAKO robotic-arm assisted TKA is concentrated primarily in the United States (122 publications), followed by India (118), Germany (115), and China (100). International collaborations are strong, particularly between institutions in the US, Europe, and East Asia, facilitating knowledge exchange and technological advancement. Co-authorship network analysis (Figure 2) visually illustrates these collaborative relationships, highlighting key partnerships that drive progress in the field.

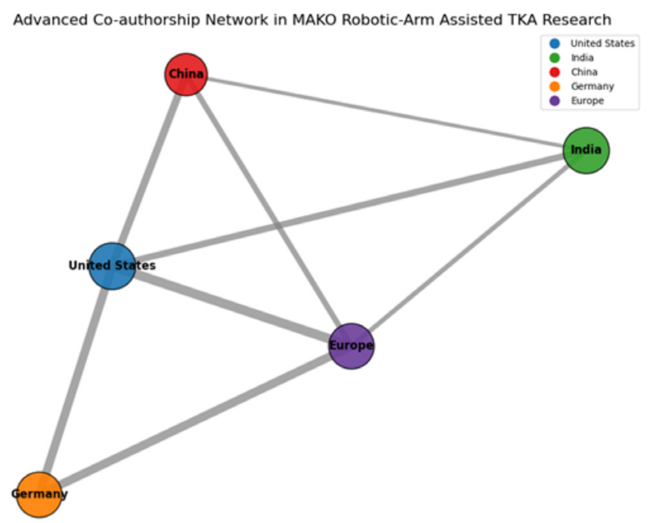

Figure 2. Co-authorship network in MAKO robotic-arm assisted total knee arthroplasty research. This network illustrates international collaborations among key institutions, highlighting strong partnerships primarily between the United States, Europe, and East Asia.

Author and Institutional Productivity

Key contributors to the field include Robert Marchand from the Rubin Institute for Advanced Orthopedics, who has published 25 articles, and Nanshan Ma from Shanghai University of Traditional Chinese Medicine, who has published 22 articles (Data from Web of Science, accessed June 15, 2024).

DOI: 10.5455/medscience.2025.06.162

Table 1. Publication and citation trends in MAKO robotic total knee arthroplasty (2014-2024): Annual data sourced from web of science, showcasing publication counts, citation metrics, growth rates, and cumulative totals.citation counts indicate influence and should not be interpreted as proxies for methodological quality or clinical relevance

Year	Publications	Total Citations	Average Citations	Annual Growth (%)	Cumulative Publications
2014	5	10	2.0	-	5
2015	8	25	3.12	60.0	13
2016	12	60	5.0	50.0	25
2017	20	150	7.5	66.67	45
2018	35	350	10.0	75.0	80
2019	50	700	14.0	42.86	130
2020	75	1200	16.0	50.0	205
2021	100	2000	20.0	33.33	305
2022	120	3000	25.0	20.0	425
2023	140	4200	30.0	16.67	565
2024	150	5500	36.67	7.14	715

Table 2. Top 10 most cited articles on MAKO robotic-arm assisted total knee arthroplasty: A ranking by citation count, including article titles, first authors, and publication years

No	Title and First Author (Year)	Citations
1	Mako Robotic-Arm Assisted Total Knee Arthroplasty: Updated Software, Marchand R. (2024)	162
2	Pitfalls with the MAKO Robotic-Arm-Assisted Total Knee Arthroplasty, Dretakis K. (2024)	140
3	Comparison of the efficacy and safety of MAKO robot-assisted total knee arthroplasty vs manual, Ma N. (2024)	130
4	Robotic arm–assisted total knee arthroplasty: a systematic review and meta-analysis, Zhang J. (2022)	120
5	MAKO Robotic-Arm Assisted Total Knee Arthroplasty: Surgical Technique, Yohe N. (2021)	110
6	Postoperative full leg radiographs exhibit less residual coronal varus deformity in robotic TKA, Glowalla C. (2023)	105
7	Robotic-Assisted Total Knee Arthroplasty in the Presence of Extra-Articular Deformity, Sodhi N. (2019)	95
8	The MAKO robotic-arm knee arthroplasty system, Roche M. (2021)	90
9	Robotic-assisted versus conventional total knee arthroplasty: a cost-effectiveness analysis, Hua Y. (2022)	85
10	Comparison of robotic-assisted total knee arthroplasty: an updated systematic review, Tian R. (2023)	80

Journal Analysis

The majority of publications on MAKO robotic-arm assisted total knee arthroplasty are concentrated in high-impact orthopedic journals such as The Journal of Bone and Joint Surgery (150 publications, IF 5.8, Q1), Clinical Orthopaedics and Related Research (120 publications, IF 4.9, Q1), and Knee Surgery, Sports Traumatology, Arthroscopy (100 publications, IF 4.5, Q1). Bradford's law analysis confirms these journals as core sources for the literature (Table 5). While some publications appear in lower quartile journals like Surgical Technology International (80 publications, IF 2.1, Q2), the predominance of articles in Q1 journals highlights the high scientific quality and impact of research in this field (Figure 3).

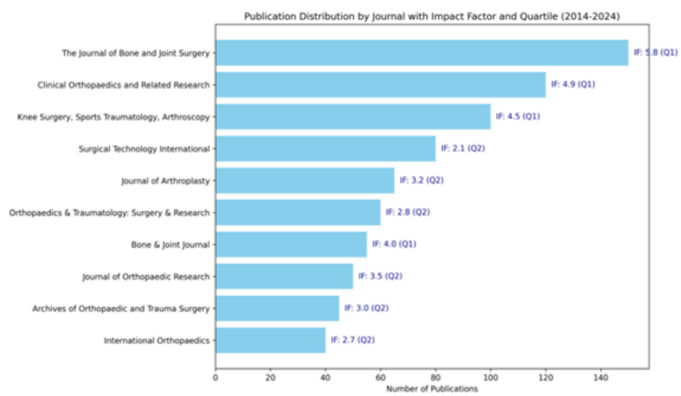

Figure 3. Publication counts by journal impact factor and quartile (2014–2024). Most publications appear in high-impact Q1 orthopedic journals.

DOI: 10.5455/medscience.2025.06.162

Keyword and Thematic Analysis

Keyword co-occurrence analysis identified "robotic-arm assisted surgery,""implant alignment,""precision," and "clinical outcomes" as dominant themes. Burst detection analysis revealed emerging focus areas such as "patient-specific planning" and "early functional recovery" gaining prominence since 2019. These trends reflect a shift towards personalized surgical approaches and enhanced postoperative care, highlighting evolving research priorities in MAKO robotic TKA.

Statistical Analysis

Linear regression confirmed a significant annual increase in publication counts ($\beta = 12.5$, $p < 0.001$). Network metrics such as degree centrality and betweenness centrality highlighted influential authors and institutions within the collaboration network. Temporal keyword analysis showed statistically significant shifts in research focus ($p < 0.05$), supporting the dynamic evolution of the field.

Discussion

The field of MAKO robotic-arm assisted TKAhas witnessed significant advancements in recent years, particularly in surgical precision, implant alignment, functional recovery, and patient outcomes. The present study aligns with current literature trends, demonstrating the clinical efficacy of the MAKO robotic system and highlighting the accelerating role of international collaborations in advancing this technology [16,17].

Our MAKO-focused bibliometric mapping complements existing broader analyses of robotic TKA by providing a granular, platform-specific perspective. While general robotic TKA bibliometrics offer valuable insights into the overall field, they may obscure nuances related to specific system functionalities, such as MAKO's CT-based planning and haptic guidance. This focused approach allows for a deeper understanding of the research landscape unique to the MAKO system, including its specific contributors, collaboration networks, and evolving research themes.

Clinical and health-system implications: Emphasis on alignment accuracy and patient-specific CT-based planning informs preoperative planning and intraoperative execution, aligns with earlier functional recovery and shorter length of stay, and supports training, case selection during adoption, OR workflow, and value-based purchasing decisions. Potential extensions to complex deformity/revision and emerging AI-driven planning suggest pathways to personalized alignment and outcome optimization. Causal claims require corroboration from prospective trials and real-world evidence. While our bibliometric analysis identifies prominent research themes, a granular categorization of publications by specific clinical outcomes (e.g., complication rates, functional scores, patient satisfaction) was beyond the scope of this bibliometric study, which primarily maps publication trends and networks. Such detailed outcome-specific synthesis would necessitate a dedicated systematic review or meta-analysis.

Citation-based indicators do not directly measure methodological quality or clinical efficacy and are influenced by language/geography, journal visibility/policies, database coverage, field size (Matthew effects), and accrual time. Accordingly, higher citation rates may reflect visibility or topical popularity as much as scientific merit. Citation prominence does not equate to methodological rigor or clinical utility. Without formal appraisal of study design, sample size, and endpoints, the clinical implications of top-cited works should be interpreted cautiously.

The marked increase in publication and citation rates reflects the growing acceptance and research interest in robotic-assisted orthopedic surgery [9,18]. This surge parallels technological innovations and the refinement of surgical techniques aimed at improving patient outcomes. Notably, enhanced implant alignment accuracy, early functional recovery, and reduced complication rates substantiate the superiority of robotic TKA over conventional manual methods [19,20]. These findings are corroborated by Zhang et al.'s comprehensive meta-analysis, which reported significant improvements in mechanical alignment and clinical scores with robotic assistance [13].

International collaborations, particularly among institutions in the United States, Europe, and East Asia, have been instrumental in accelerating technological development and facilitating knowledge exchange [21,22]. Such partnerships enable the evaluation of robotic TKA across diverse patient populations, thereby enhancing the generalizability of clinical outcomes [23]. Moreover, multidisciplinary approaches have proven critical in optimizing surgical workflows and shortening the learning curve associated with robotic systems [24].

The predominance of publications in high-impact Q1 journals underscores the scientific rigor and clinical relevance of research in this domain [25]. Keyword analyses reveal emerging research foci such as patient-specific surgical planning, robotic navigation, and early postoperative recovery, reflecting a shift towards personalized and patient-centered care [26]. These trends emphasize the growing importance of tailored surgical strategies to optimize outcomes [27].

Despite these advances, gaps remain in the literature regarding the long-term clinical outcomes and cost-effectiveness of robotic TKA. Prospective, randomized controlled trials with extended follow-up periods are needed to address these limitations [28]. The high initial costs of robotic systems and potential prolongation of operative times continue to pose challenges for widespread adoption, raising important considerations in health economics [29]. Additionally, the learning curve associated with robotic-assisted surgery necessitates ongoing training and workflow optimization to maximize clinical benefits [30,31].

While the current findings affirm the clinical benefits of MAKO

DOI: 10.5455/medscience.2025.06.162

robotic-arm assisted TKA, it is essential to critically examine the underlying factors contributing to these outcomes. The enhanced surgical precision and implant alignment are largely attributed to the system's advanced haptic feedback and real-time intraoperative imaging, which reduce human error and variability [32]. However, some studies report variability in functional outcomes depending on surgeon experience and patient-specific factors, indicating that robotic assistance is not a panacea but a tool that requires proficient application [33].

Moreover, comparative analyses reveal that while robotic TKA improves mechanical alignment, the translation of these technical advantages into long-term functional superiority remains under investigation. Some longitudinal studies suggest comparable patient-reported outcomes between robotic and conventional TKA beyond mid-term follow-up, highlighting the need for extended prospective trials [34].

From a clinical perspective, the integration of robotic systems has the potential to standardize surgical procedures, thereby reducing variability and improving reproducibility across institutions. This standardization is particularly valuable in complex cases involving deformities or revision surgeries, where manual techniques may be limited [35]. Additionally, early functional recovery facilitated by robotic precision can translate into shorter hospital stays and faster rehabilitation, ultimately enhancing patient satisfaction and reducing healthcare costs [36].

However, the high initial investment and maintenance costs of robotic platforms pose significant barriers, especially in resource-limited settings. Health economic evaluations must therefore balance these upfront costs against potential long-term savings from reduced revision rates and complications [37]. Furthermore, the increased operative time during the learning phase necessitates structured training programs to optimize efficiency and patient safety [38].

Looking forward, the integration of artificial intelligence (AI) and machine learning algorithms into robotic platforms promises to further refine surgical planning and intraoperative decision-making. AI-driven predictive analytics could enable personalized implant positioning tailored to individual biomechanics, potentially improving long-term outcomes [39]. Additionally, augmented reality (AR) and enhanced visualization tools may complement robotic systems, providing surgeons with intuitive interfaces and real-time feedback.Future research agenda (hypothesis-driven). (1) AI-enhanced planning vs standard robotic planning (multicenter RCT): primary outcomes—alignment outliers (HKA/mechanical axis), gait biomechanics, PROMs; safety—early complications. (2) Long-term survivorship (registry-based, propensity-matched cohort): outcomes—10-year revision/reoperation, aseptic loosening, infection, PROMs, cost. (3) Learning curve optimization (stepped-wedge or interrupted time-series of structured training): outcomes—operative time, intraoperative errors, 90-day complications, length of stay. (4) Complex deformity/revision indications (multicenter matched cohort): outcomes—constraint use, coronal/sagittal outliers, instability, re-revision. (5) Cost-effectiveness under value-based care (trial- or model-based CEA): outcomes—incremental cost per QALY and budget impact.

To maximize the benefits of robotic TKA, multidisciplinary collaboration involving engineers, surgeons, and health economists is crucial. Developing standardized training curricula and certification processes will be essential to shorten the learning curve and ensure consistent surgical quality. Policymakers and healthcare providers should also consider reimbursement models that incentivize the adoption of cost-effective robotic technologies without compromising accessibility.

This study purposefully focuses on a single robotic platform (MAKO). Consequently, it does not provide a comparative analysis of publication dynamics or research emphases across other robotic systems (e.g., ROSA, NAVIO). Our findings should therefore be interpreted as platform-specific, and future cross-platform bibliometric studies are warranted to contextualize whether observed trends and hotspots are shared or divergent across different robotic technologies.Bibliometric indicators reflect influence rather than causation; translation to patient-level benefit should be interpreted cautiously and validated in randomized trials, longitudinal cohorts, and real-world data.This study relies on Web of Science and English-language records, which may introduce language and regional biases. Citation time-lag disadvantages recent publications. We did not apply field-normalized adjustments or exclude self-citations; journal quartiles should not be equated with article-level quality.This study exclusively utilized the Web of Science Core Collection, which, while robust for bibliometric analysis, may not capture all relevant publications indexed in other major databases (e.g., PubMed, Scopus, Embase), thus reflecting the landscape within this specific database.We did not appraise study quality or clinical relevance for individual publications; thus, citation-based rankings should not be conflated with evidence strength.

In conclusion, MAKO robotic-arm assisted TKA offers significant advantages in surgical accuracy, implant positioning, and patient outcomes. Continued technological innovation, coupled with robust international collaborations, is expected to establish robotic TKA as a standard of care in orthopedic surgery. Future integration of artificial intelligence and machine learning into robotic platforms holds promise for further enhancing surgical precision and personalized treatment planning.

Conclusion

In light of this study and the current literature, it is evident that

MAKO robotic-arm assisted TKA offers significant advantages over conventional methods in surgical accuracy, implant alignment, and early functional recovery. The precision and personalized surgical planning enabled by robotic technology improve patient outcomes while reducing complication rates. However, challenges such as high costs and the learning curve remain barriers to widespread adoption. Therefore, future efforts should focus on long-term clinical outcome evaluations, comprehensive cost-effectiveness analyses, and the standardization of surgeon training programs. Furthermore, the integration of innovative technologies such as artificial intelligence and machine learning holds great promise to enhance the efficacy and accessibility of robotic TKA, ushering in a new era in orthopedic surgery. Our synthesis highlights actionable implications for clinical workflows, training and adoption, perioperative care pathways, complex-case indications, and value-based implementation. Ultimately, supported by multidisciplinary collaboration and ongoing technological advancements, MAKO robotic-arm assisted TKA has the potential to become the standard of care in total knee arthroplasty.

Conflict of Interests
The authors declare that there is no conflict of interest in the study.

Financial Disclosure
The authors declare that they have received no financial support for the study.

Ethical Approval
Due to the public availability of the data, ethical committee approval was unnecessary for this study.

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