JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-19, No.-5, May (2024) pp 81-100 ISSN (Print) 0973-8975

EVOLUTION AND ANALYSIS OF SINGLE-DEGREE-OF-FREEDOM WALKING MECHANISMS IN LEGGED ROBOTS: A BIBLIOMETRIC STUDY

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https://doi.org/10.26782/jmcms.2024.05.00006

(Received: February 22, 2024; Revised: April 20, 2024; Accepted: May 03, 2024)

Abstract

This study conducts a bibliometric analysis to explore the evolution and practical applications of legged robots equipped with single-degree-of-freedom mechanisms from 2010 to 2023. Through comprehensive methodologies involving renowned academic databases such as Scopus, the research examines 127 relevant articles, employing statistical analysis and network assessments to discern trends and contributors in the field. Results indicate a peak in publication volume in 2019, with India emerging as the leading contributor, followed by Romania and China. The findings provide valuable insights into the global research landscape of legged robotics, highlighting key advancements and contributors and paving the way for future developments in the field.

Keywords: Citation, Co-occurrences, Degrees of Freedom, Legged Robots, Walking Mechanisms.

I. Introduction

Equipped with the unique ability to traverse tough terrain inaccessible to normal vehicles with wheels or tracks, legged robots represent a significant advancement in the field of robotics. This capability is especially crucial in tasks like search and rescue missions, where swift access to remote or hazardous locations can

save lives. The key benefit of these robots stems from their advanced walking systems, designed to mimic the movement of living creatures, enabling them to navigate various landscapes smoothly and effectively [XXII, XV, IV]. Fascinating for their ability to replicate biological locomotion, walking robots can be categorized based on their degrees of freedom (DoF), which refers to the number of independent movements the robot can make. A single degree of freedom in walking mechanisms implies simple motion, often linear or rotary, without the complexity seen in multi-DoF systems. Beyond the single DoF, the complexity and capabilities of walking robots expand significantly [III]. In the category of single-degree-of-freedom (DoF) walking robots, the development of Theo Jansen's walking mechanism [VII], powered by a single-degree-of-freedom crank, has played a crucial role in advancing the design of walking machines. Focusing on further investigation of the Theo Jansen mechanism, Shah, R. et al. [XX] aim to enhance the capabilities of walking robots through innovative approaches to optimize performance. Their research focuses on proposing novel design modifications and cutting-edge control strategies, all aimed at maximizing stability and efficiency in robotic locomotion. In pursuit of these goals, researchers aspire to push the boundaries of robotic mobility, opening up new horizons for applications in various fields. The enhancement of the Theo Jansen mechanism has significantly advanced robotics, particularly in walking rehabilitation and terrain adaptability. By closely mimicking human ankle trajectories, the mechanism now offers improved rehabilitation tools and increased walking efficiency for robots navigating various terrains, highlighting its extensive applicability in healthcare and environmental exploration [XIX, XXIII]. Continuing with the advancement of robotic mechanisms, Patnaik, L. et al. [XVII], through continuous improvement of the Jansen mechanism, have expanded its application into the domain of Araneae, thereby advancing the design of walking robots. This research leveraged the Jansen mechanism for the selection of optimal motors, enabling the construction of more robust and efficient spider-like robots, marking a significant contribution to the advancement of biomimetic robotics. Additionally, the J. C. Klann [VIII] mechanism introduces a novel approach to mimicking natural walking movements, enhancing robotic mobility and efficiency through its innovative linkage design. Building on this mechanism, the study presents a reconfigurable four-legged robot that can execute six bio-inspired gaits. It is designed for easy control in difficult terrains, featuring efficient servo control and maintaining stability across various walking patterns. Simulations validate its performance on uneven terrain, emphasizing its potential for advanced robotic applications [XXI, XXII]. Kim, HyunGyu, et al. [XI] successfully applied the Klann mechanism to bio-inspired amphibious applications, markedly improving the running speed of a robot on both water and land through advanced modelling and optimization techniques. Expanding on this success, Kashem, S. B. et al. [IX, X] developed a compact amphibious robot equipped with bio-inspired webbed feet for the Klann linkage. This innovative design facilitates efficient navigation across a variety of terrains and aquatic environments, representing a significant advancement in the exploration of challenging areas and suggesting promising avenues for future robotic innovations. Furthermore, the Klann mechanism's applications were extended to araneae, leading to the development of a spider robot. This robot was successfully integrated into various environments, showcasing the versatility and potential of the enhanced Klann mechanism in bio-

inspired robotics. [XVIII, XIV] Under the category of single degree of freedom robots, the pantograph mechanism presents an intriguing subject. Manuel A. Armada et al. [I] analyze the kinematics and dynamics of a 1-DOF Pantograph leg, emphasizing modularity, compactness, light weight, and minimal degrees of freedom to improve walking capabilities. To continues the research on pantograph mechanism walking robots Ben Sheng Lin et al. [XIII] investigate how pantograph mechanisms have notably enhanced the performance and efficiency of walking robots, setting the stage for future technological advancements. Their innovative efforts, particularly in combining these mechanisms with the Chebyshev-Pantograph design, have resulted in the development of more streamlined and economical biped robots. To elevate the capabilities of pantograph mechanism-based walking robots, Ishihara, H. et al. [VI] introduce a 4-legged locomotion mechanism incorporating a pantograph-jack leg design, tailored for heavy load-carrying tasks like disaster relief. This jack-like leg efficiently grasps and lifts heavy objects with minimal energy consumption or active control. The prototype achieves crawl walking resembling reptilian movement, boasting a walking speed of 0.001 m/s and a payload capacity of 45 kg. The paper details the locomotion concept, prototype design, and significant experimental findings. The Peaccular-Lipkin walking mechanism robot, due to its flexible design, is classified within the category of single-degree-of-freedom walking robots. JC Godoy et al. [V] introduce a novel non anthropomorphic biped exoskeleton to assist individuals with walking difficulties. Rooted in an eight-bar mechanism, with a focus on the Peaucellier-Lipkin mechanism, the exoskeleton's innovative design emphasizes its effectiveness in facilitating translation movements through polynomial functions of time. With ongoing research on Peaucellier-Lipkin mechanism walking robots, Núñez-Altamirano, Diego A. et al. [XVI] introduce a new reconfigurable robotic leg based on the inverse Peaucellier-Lipkin mechanism, tailored for walking machines. This leg can traverse both straight and curved paths, determined by the ratio between two of its links and its kinematics. In parallel, Desai, S. G. et al. [II] present a novel single-degree-of-freedom crank-driven walking leg mechanism for walking machines and robots. This mechanism, refined from a planar Peaucellier-Lipkin type with eight links, undergoes kinematic analysis, with optimal design achieved using the Genetic Algorithm (GA) to determine link lengths. Practical accuracy is validated through an experimental model, and an eight-legged walking machine employing this mechanism undergoes successful testing. Comparative analysis with Jansen's and Klann's mechanisms highlights the effectiveness of the proposed design, indicating significant potential for the development of highly efficient single degree-of-freedom walking robots.

II. Background

The Modified Peaucellier-Lipkin mechanism marks a significant advancement in the field of robotics, particularly for single-movement robots. Its ability to extend the stride length and enable movement in all directions sets it apart from older mechanisms like those by Jansen and Klann. What makes this mechanism unique is its clever design that simplifies complex walking motions, enhancing robot versatility and efficiency. This innovation has generated considerable interest for its application in robots designed for challenging terrains, such as those in rescue operations or exploration missions. The focus on refining this mechanism highlights

its importance in the evolution of robot design, pointing towards a future where robots are more capable of navigating diverse environments.

III. Document analysis

In our analysis of single degrees of freedom (DOF) walking mechanisms, we delved into the evolution, key contributors, leading research institutions, and interdisciplinary nature of the field. By examining publications over time, we identified trends, pivotal advancements, and the diverse types of documents that form the research landscape. We also highlighted the financial and geographical facets driving this area forward, uncovering the global collaboration and innovation hubs. This streamlined approach offers a clear view of the field's development and current state, guiding future research and technological advancements in single DOF walking mechanisms. Document analysis in terms of year: From 2010 to 2023, documents were collected from various sources such as conferences, journals, and book chapters. The statistics are presented in the table, with the graph illustrating the distribution of documents across these sources. The year 2019 saw the highest number of publications, followed by 2022. Figure1 provides a graphical representation of this distribution.

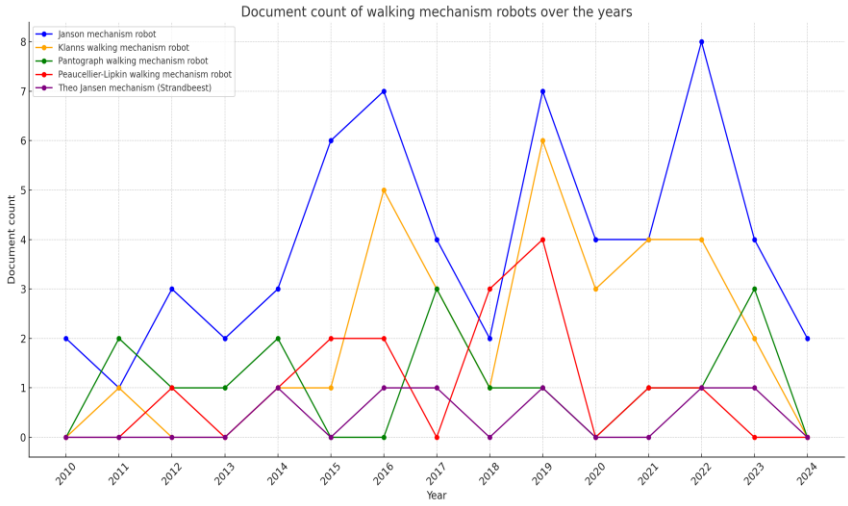

Fig. 1. Documents by year.

Documents by authors: In this analysis centered on author contributions within this domain, we meticulously compared the publication output of the top 15 authors. The data reveals that Dolga V. and Bhavsar K. are at the forefront, each having published a remarkable total of seven articles in this specific area of study. It is observed that, on average, the majority of these leading authors have made contributions of 3 to 4 articles, highlighting their significant involvement and consistent contributions to the field of single degree of freedom walking

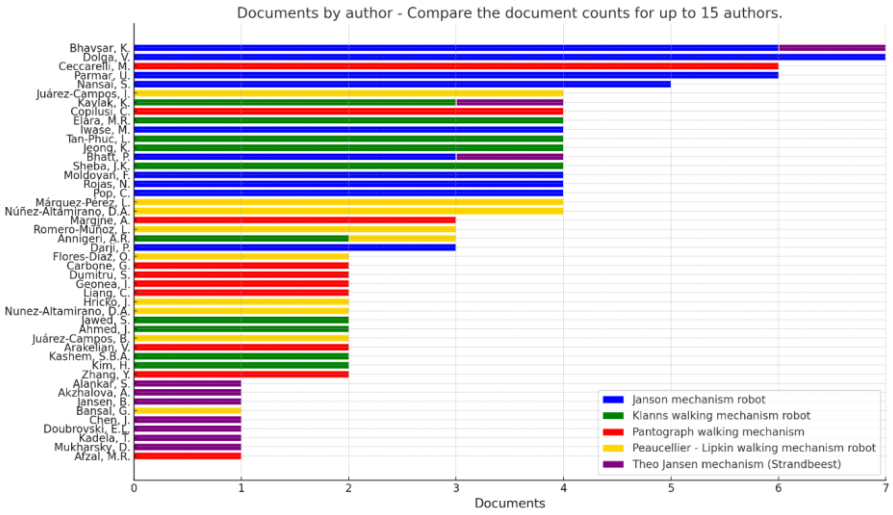

Fig. 2. Documents by authors.

Documents in terms of affiliations: In our analysis of the top 15 affiliations, the United States leads with 9 publications. Close behind, institutions from Italy, Japan, Mexico, and Universitatea Politehnica Timișoara each have eight publications. This shows a wide international effort in researching single-degree freedom walking mechanisms.

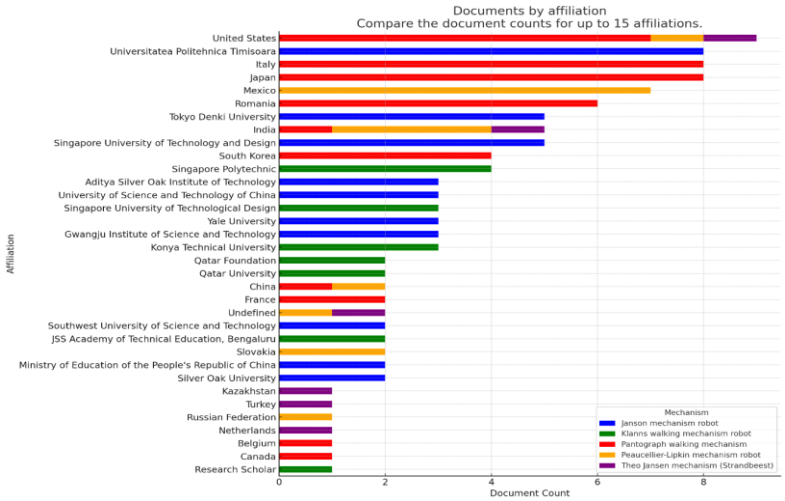

Fig. 3. Documents by authors.

Documents by subject area: In our analysis of documents by subject area, we found that robotics, which is encompassed by the broader term mechatronics, is primarily categorized under Engineering, accounting for 39.2% of the documents. This is succeeded by computer science with 30.4% and mathematics with 11.7%, indicating a multidisciplinary interest in the field, particularly within these three domains.

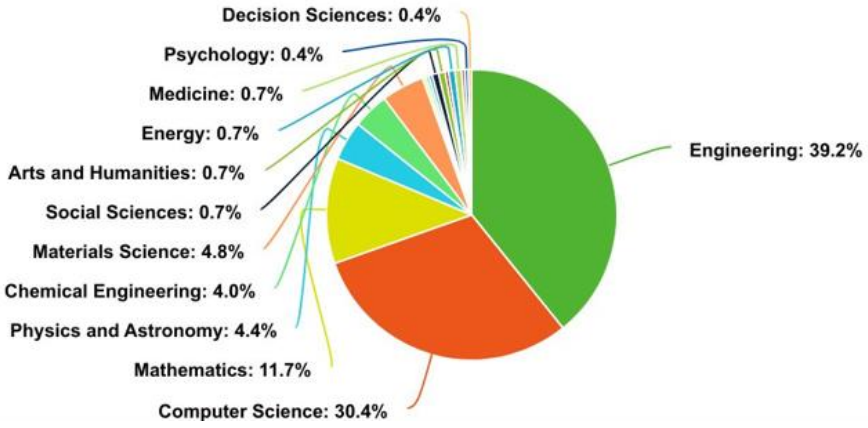

Fig. 4. Documents by subjected area.

Documents by type: Based on the analysis, journal articles represent the largest portion of publications in this area, making up 55.5% of the total. Conference papers are the next most common type of publication, accounting for 40% of the output. This highlights the predominant channels through which research on this topic is disseminated.

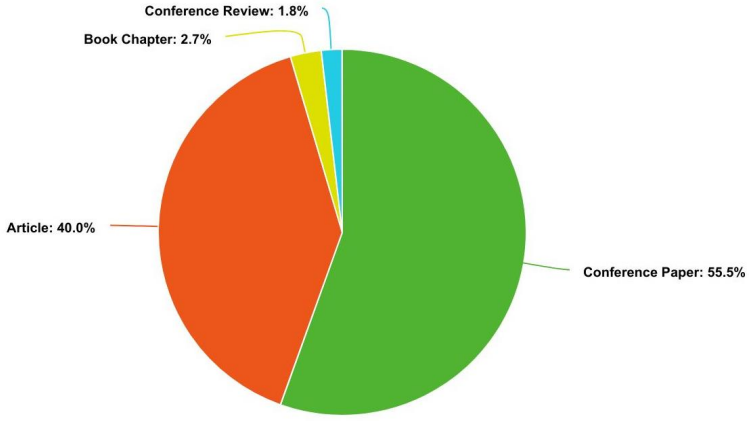

Fig. 5. Documents by subjected area.

Documents by funding sponsors: In the analysis of documents by funding sponsors, the Unitatea Executivă pentru Finanțarea Învățământului Superior, a Cercetării, Dezvoltării și Inovării (UEFISCDI) emerges as the top contributor. It is followed by the Ministerul Cercetării, Inovării și Digitalizării, and the National Research Foundation of Korea. These organizations lead in funding support, highlighting their significant roles in fostering research and development in this field.

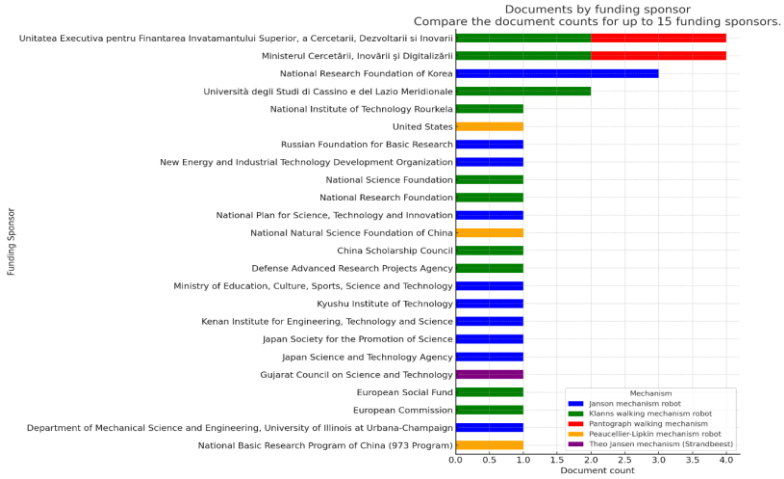

Fig. 6. Documents by subjected area.

Analysis of publications by country or territory : Upon evaluating the documents in the Scopus database, it is apparent that India emerges as the largest contributor, followed by Romania, with China securing third place.

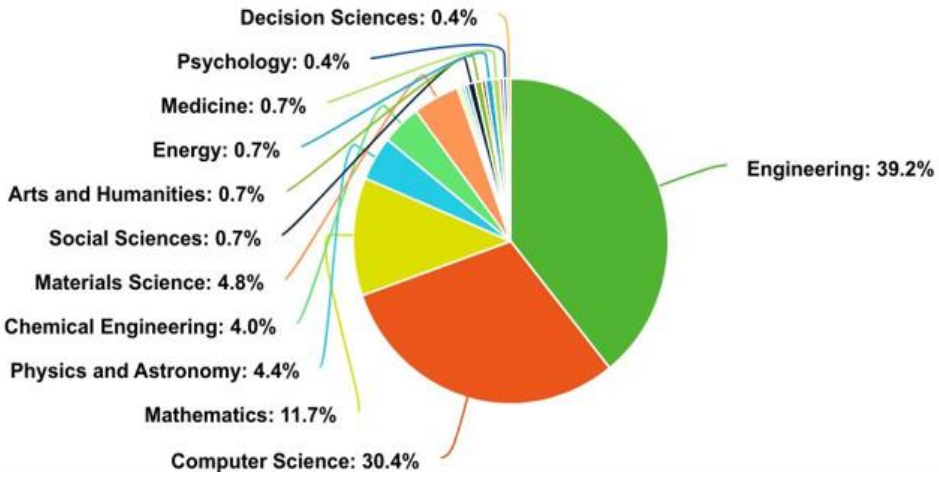

Fig. 7. Documents by subjected area.

Documents by type: Based on the analysis, journal articles represent the largest portion of publications in this area, making up 55.5% of the total. Conference papers are the next most common type of publication, accounting for 40% of the output. This highlights the predominant channels through which research on this topic is disseminated.

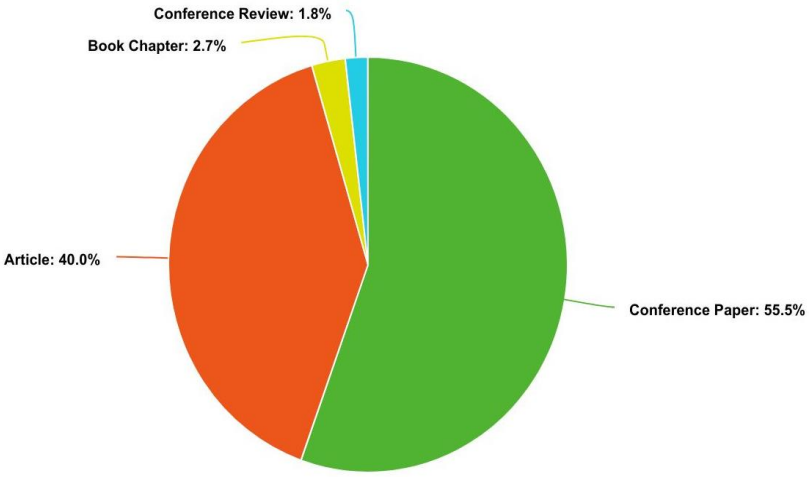

Fig. 8. Documents by type.

Documents by funding sponsors: In the analysis of documents by funding sponsors, the Unitatea Executivă pentru Finanțarea Învățământului Superior, a Cercetării, Dezvoltării și Inovării (UEFISCDI) emerges as the top contributor. It is followed by the Ministerul Cercetării, Inovării și Digitalizării, and the National Research Foundation of Korea. These organizations lead in funding support, highlighting their

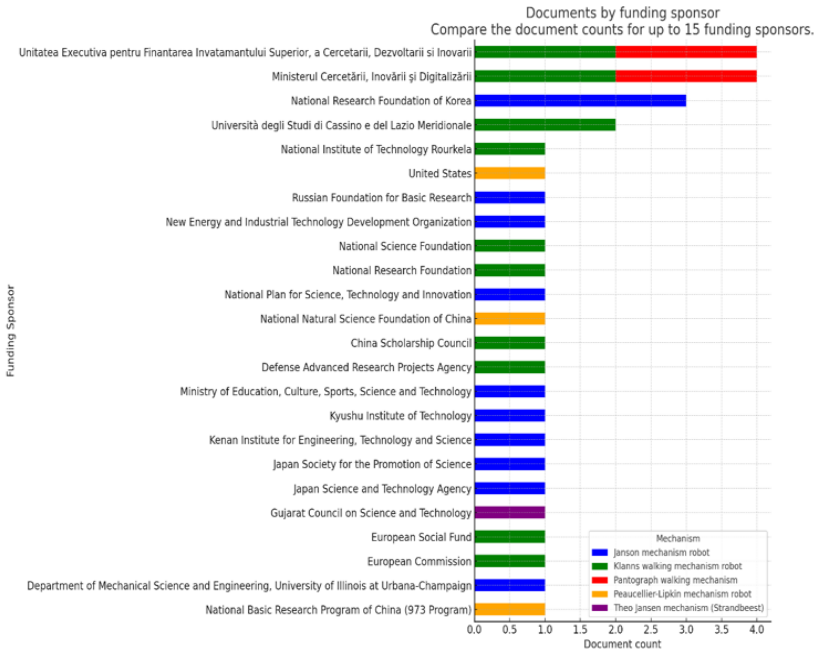

Fig. 9. Documents by funding sponsor.

Analysis of publications by country or territory : Upon evaluating the documents in the Scopus database, it is apparent that India emerges as the largest contributor, followed by Romania, with China securing third place

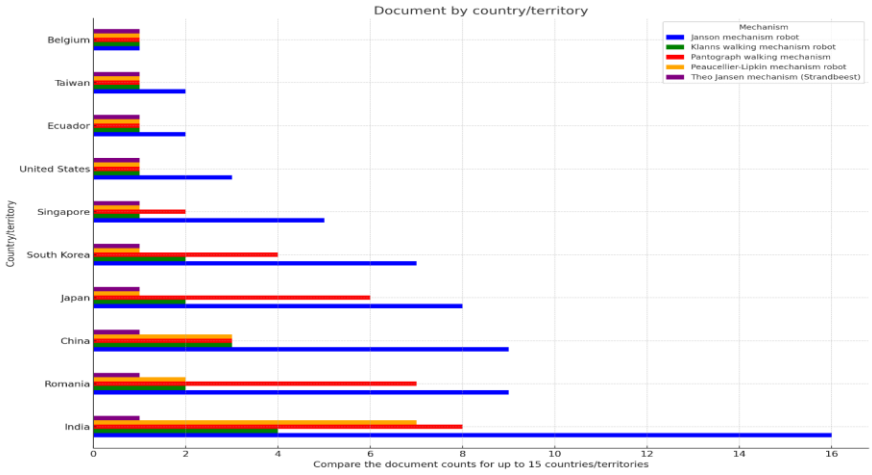

Fig. 10. Documents by funding sponsor.

IV. Network analysis

Co-authorship in terms of authors: Out of 127 authors, 12 meet the established criteria of having a minimum of 4 documents and at least 2 citations each. Among these, 'elara, mohan rajesh' has the highest number of documents at 8, with 149 citations, and 'nansai, shunsuke' follows with 6 documents and 157 citations.

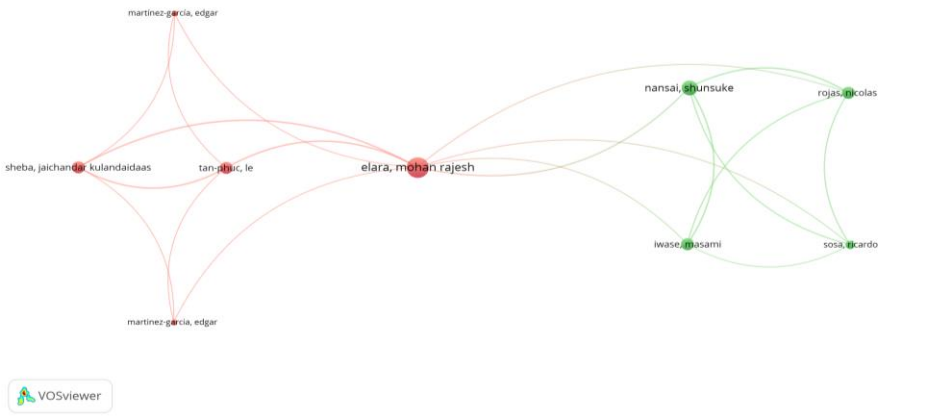

Fig. 11. Co-authorships with respect to authors.

CO-authorship with respect to organizations: In the analysis focusing on co-authorship linked to organizations, applying a threshold of at least 2 citations and 2 documents per organization, only 12 out of 192 organizations met this criterion. Among these, Konya Technical University stands out with 4 documents, followed by

institutions specializing in nuclear convergence technology. This highlights a selective yet impactful group of organizations making significant contributions within the specified criteria.

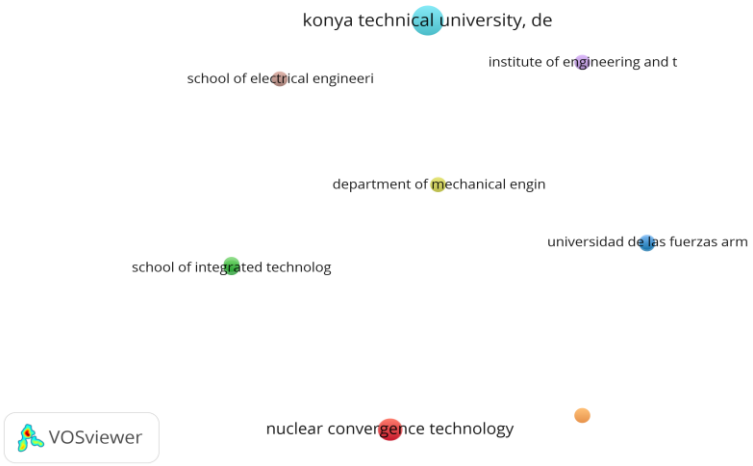

Fig. 12. Co-authorship with respect to organizations.

Co-authorship with respect to country: In the analysis focusing on countries, with a minimum of 2 documents, 18 out of 30 countries met the criteria. Japan leads with 14 documents and 224 citations, followed by the United States with 11 documents and 407 citations, showcasing significant contributions and international collaboration in research.

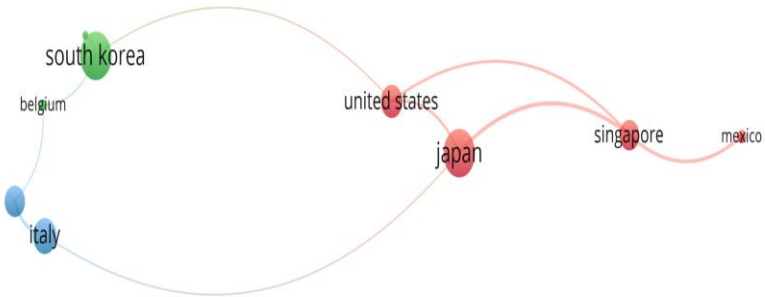

Fig. 13. Co-authorship with respect to country.

Co-occurrence with respect to all keywords: In the keyword analysis, with a threshold of 3 occurrences, 92 out of 946 keywords were significant. These keywords primarily focus on machine design, mobile robots' kinematics, leg mechanisms, and degrees of freedom (DOF), indicating key research areas.

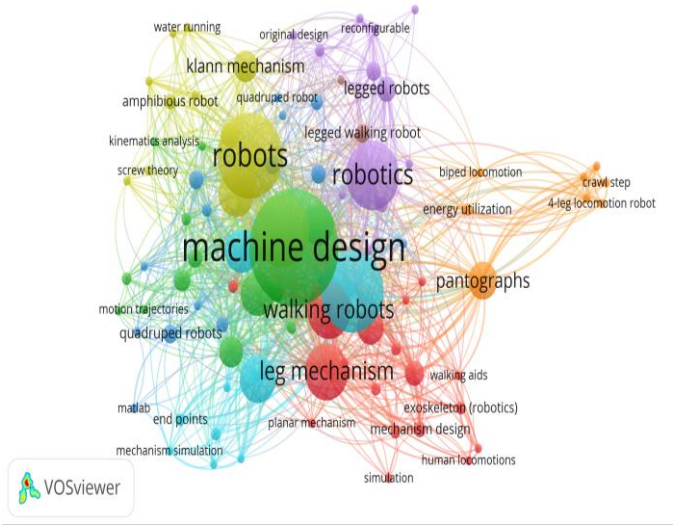

Fig. 14. Co-authorship with respect to country.

Co-occurrence with respect to index keywords: In the analysis of index keywords, applying a threshold of 5 occurrences, only 28 out of 784 keywords met this threshold. This indicates a focused set of topics that are central to the research field under study.

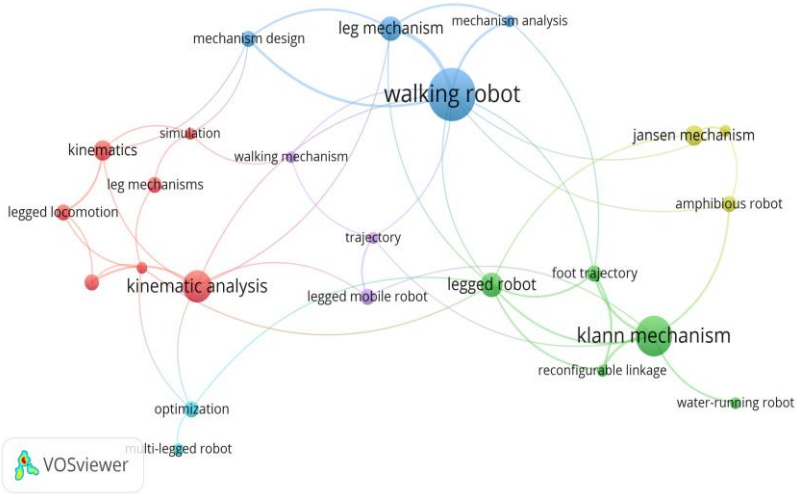

Fig. 15. Co-occurrence with respect to indexed keywords.

Citation analysis in terms of documents: In the citation analysis, with a threshold of 2 citations per document, 78 documents qualified. The most cited authors are Liang (2012) and Nansai (2015).

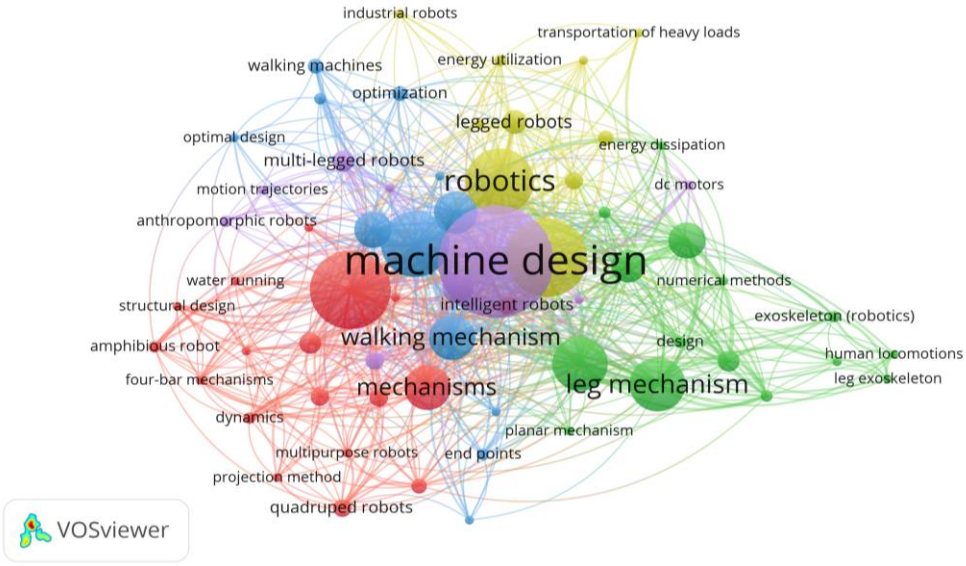

Fig. 16. Citation analysis in terms of documents.

Citation analysis in terms of sources: In the analysis of citations by sources, with a criterion of at least 2 documents per source, 19 out of 80 sources met this threshold. "Advances in Mechanical Engineering" leads with 56 citations, followed by "Mechanisms and Machine Science" with 34 citations, highlighting their influence in the field.

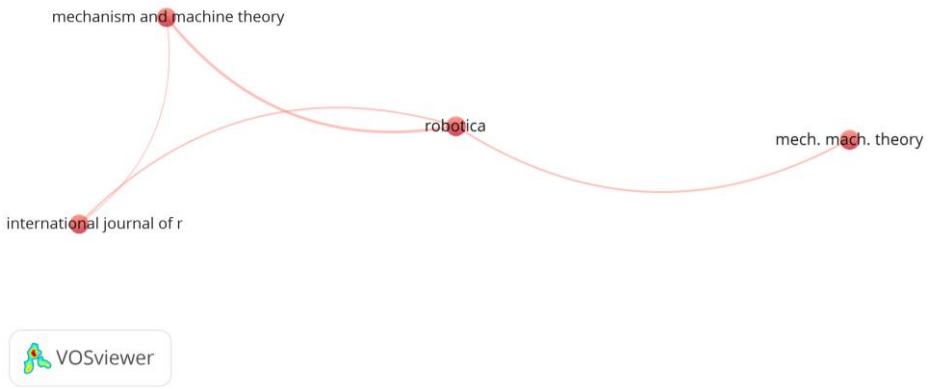

Fig. 17. Citation analysis in terms of sources.

Citation analysis in terms of authors: In the citation analysis focused on authors, with a minimum of 2 documents per author and at least 2 citations per author as the criteria, 62 authors met this threshold. GAO.L stands out with the highest number of citations, totalling 801, showcasing significant impact within the research community.

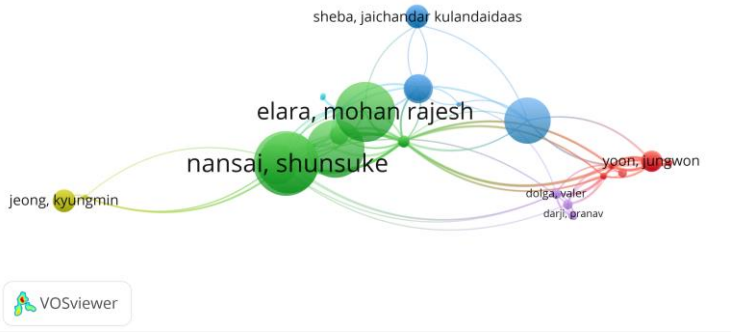

Fig. 18. Citation analysis in terms of sources.

Citation analysis in terms of organization: In the organizational citation analysis, with a threshold of 2 documents and citations, 12 out of 192 organizations qualified. The Department of Mechanical Engineering recorded the highest citations, highlighting its significant impact.

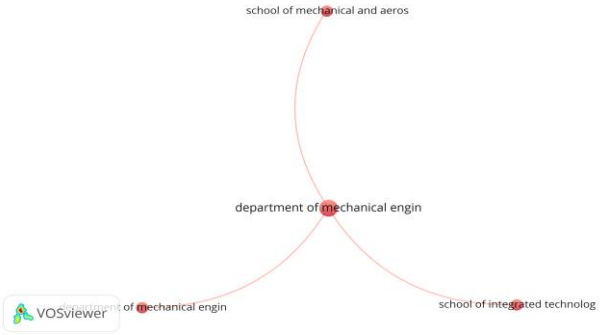

Fig. 19. Citation analysis in terms of organizations.

Citation analysis in terms of country: with a minimum of 2 documents per country, 18 out of 30 countries met the threshold. The United States led with 407 citations, followed by Japan with 224, showcasing their leading contributions to the field.

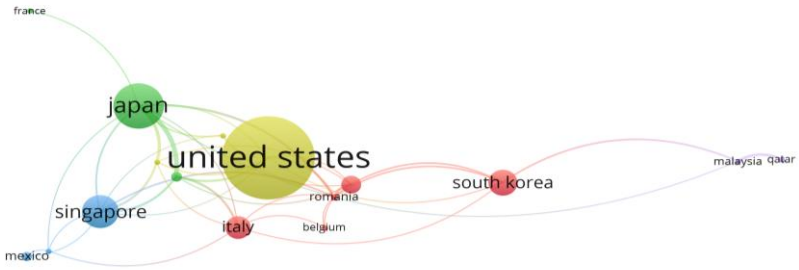

Fig. 20. Citation analysis in terms of country.

Bibliographic coupling in terms of documents and sources: consideration of minimum citations of the documents 5and 48 met the threshold value.

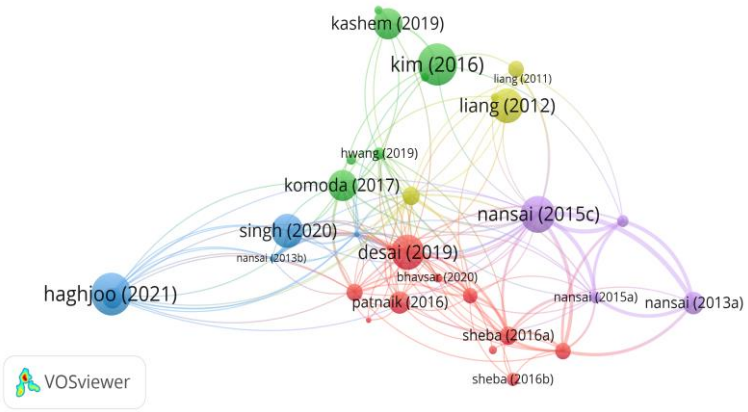

Fig. 21. Bibliometric coupling in terms of documents and sources.

Bibliographic coupling in terms of documents: In the bibliographic coupling analysis, applying thresholds of at least 2 documents per source and 2 citations, 17 sources qualified. "Mechanism and Machine Sciences" leads with 12 documents and 34 citations, highlighting its key role in the field.

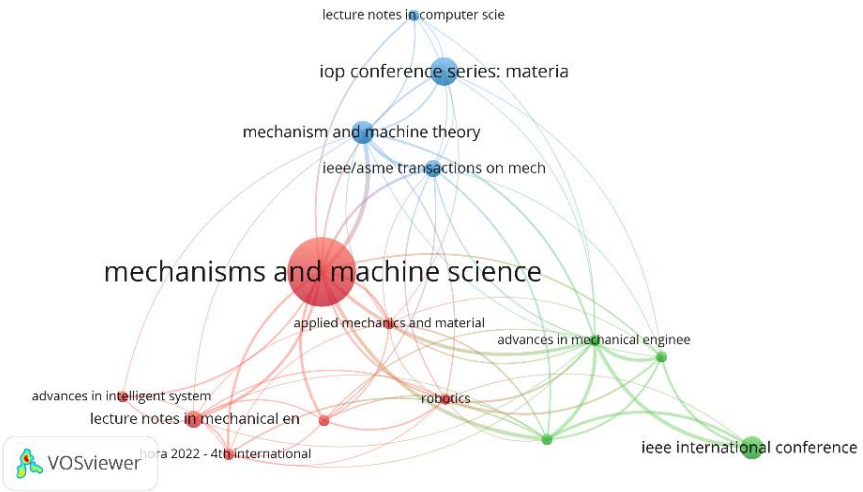

Fig. 22. Bibliometric coupling in terms of documents.

Bibliographic coupling in terms of and sources: consideration of minimum number of documents of a source 2 and minimum citation 2 so 62 meet the threshold. earla, mohan rajesh having 7 documents with 111 citations.

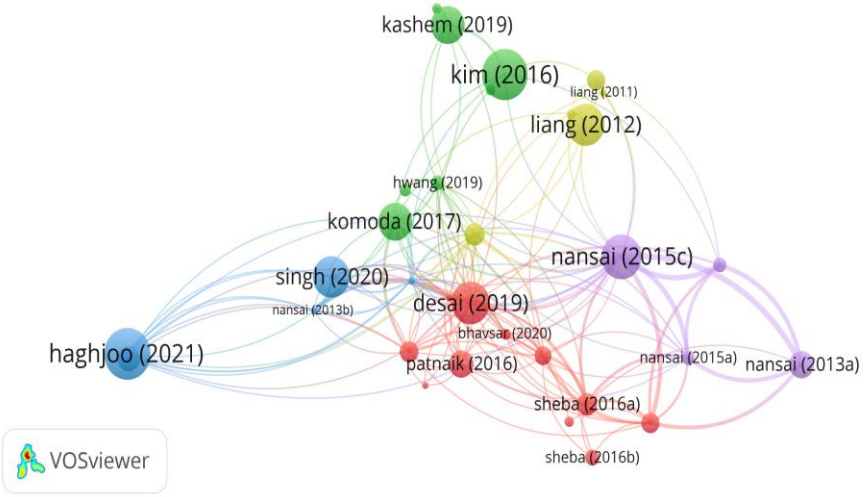

Fig. 23. Bibliometric coupling in terms of and sources.

Bibliographic coupling in terms of country: consideration of minimum number of documents of country 2 and 2 minimum citations 2 meet the threshold values is 17.

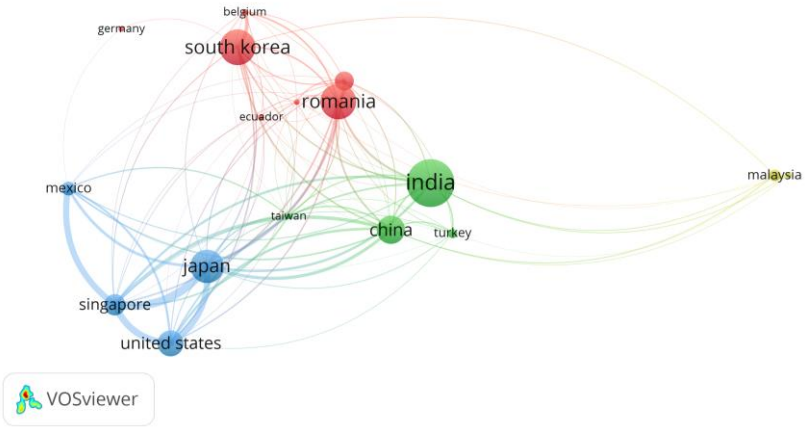

Fig. 24. Bibliographic coupling in terms of country.

Co-citations in terms of cite reference's: In the co-citation analysis for cited references, with a threshold of 2 citations, 81 out of 2019 references qualified. "Jansen T., The Great Pretender, (2007)" leads with 13 citations and a link strength of 25, while "Klann J.C., Walking Device, (2002)" has 5 citations and a link strength of 28, highlighting their key impact.

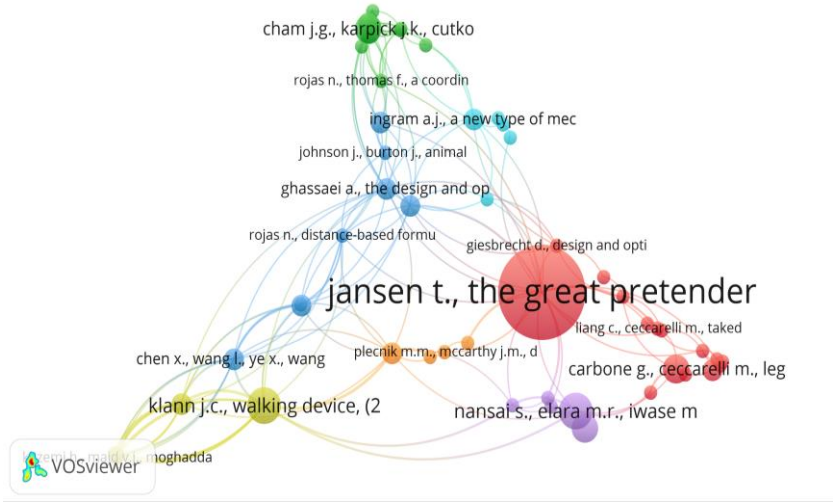

Fig. 25. Co-citations in terms of cite reference's.

In the co-citation analysis of authors, with a 20-citation minimum, 13 out of 3534 authors met this mark. 'Nansai S.' leads with 41 citations, followed by 'Elara M.R.' with 39, and 'Iwasae M.' with 38, indicating their significant impact.

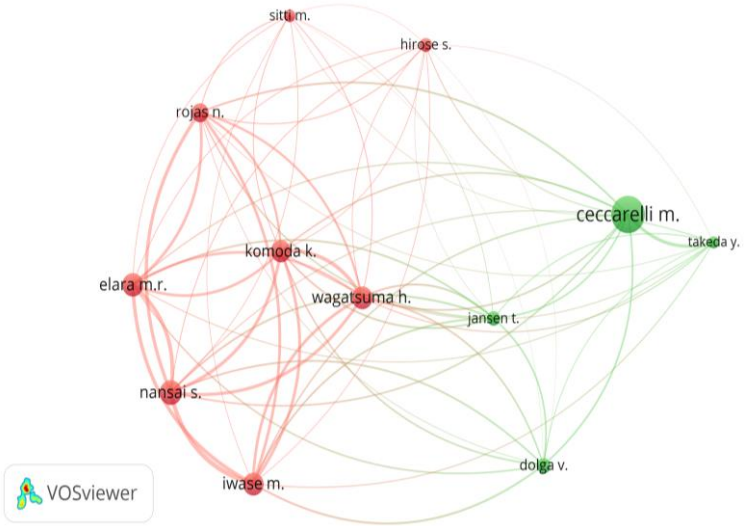

Fig. 26. Co-citations in terms of authors.

Co-citations in terms of sources: Minimum number of citations of a source is 20 of 1270 sources four meet their threshold in that robotics having highest citations with respect to 22 link strength.

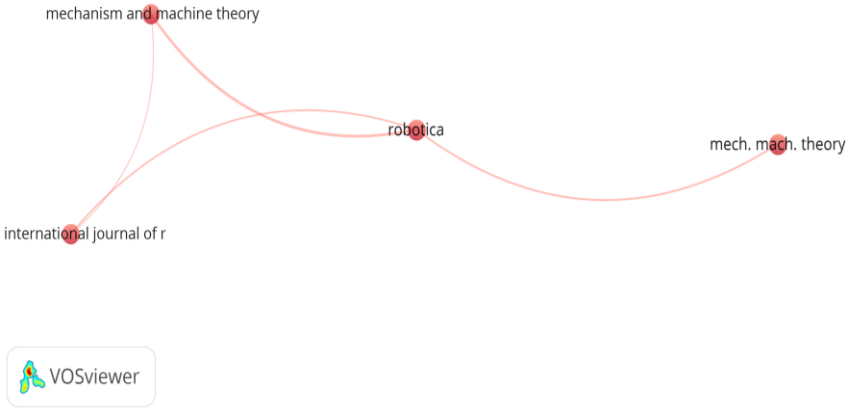

Fig. 27. Co-citations in terms of authors.

Method: This study obtained research articles from renowned academic databases such as Scopus, encompassing publications from 2010 to 2023. Scopus, known for its extensive analytical tools, enabled the categorization and assessment of documents based on factors like their origin, publication date, and the country of publication. The analysis incorporated several methodologies, including the examination of co-authorship networks, the occurrence of keywords in conjunction with each other, and the analysis of citations. The bibliometric analysis was carried out using Vosviewer version 1.6.20.

Results: The study examined 127 articles on single degrees of freedom leg mechanisms and their advancements from 2010 to 2023. According to statistical and network analyses, 2019 experienced a peak in publication volume, with India emerging as the leading contributor, followed by Romania and China.

IV. Conclusions

Following an exhaustive review within the Scopus database, we have identified a total of 127 scholarly articles pertaining to five key types of single-degree freedom walking mechanisms. This discovery underscores the significant research interest in single-degree freedom walking mechanisms, with English emerging as the primary language for these publications. Our statistical analysis spanned various dimensions, including authorship, document types, geographical distribution, and institutional affiliations, revealing the vast potential inherent in this research area. Moreover, our network analysis on these dimensions strongly indicates that there is considerable scope for further investigations into single-degree-of-freedom walking mechanism robots. These insights align well with the research goals we initially set, highlighting the promising avenues for future exploration in this field.

Keynote: The modified Peaucellier-Lipkin mechanism stands out for its superior benefits compared to mechanisms like Jansen's and Klann's, among others. Key

advantages include a remarkable stride length, bidirectional crank rotation, and improved kinematic adjustability and simplicity. These attributes highlight its significance in advancing mobile robot development, particularly for single degrees of freedom applications. Given its unique advantages, this mechanism is poised to be a primary subject of ongoing research in the field.

Conflict of Interest:

The author declares that there was no conflict of interest regarding this paper.

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