Scientific Production of Exoskeleton: A Scientometric Analysis

Chithiraivel S[1], Loganayaki R[2], Saravanan K[3], Sharmila R[4], Sivankalai S[5], Sivasekaran K[6]

[1]Librarian, SRM Madurai College for Engineering and Technology, Sivagangai, spchithiraivelphd@gmail.com Orcid Id: 0009-0007-1998-5865

[2]Librarian, Mannar Thirumalai Naicker College, Madurai, loganayakivnr@gmail.com Orcid: 0009-0002-6545-1884

[3]Deputy Librarian, kkpsaro@gmail.com Orcid: 0009-0001-7179-6152

[4]Librarian, Lakshmi School (ICSE), TVS Schools Group, Madurai, sharminethra@gmail.com Orcid Id: 0000-0001-9449-1135

[5]Assistant University Librarian, 4&5Anna University Chennai, skysivan@gmail.com Orcid Id: 0000-0002-1174-7594

[6]Librarian, Ayya Nadar Janaki Ammal College, Sivakasi, sivasekarank@gmail.com Orcid Id: 000003-0021-7819

Abstracts: The history of exoskeleton-like contraptions traces back to 1890 when Russian inventor Nicholas Yagin created the first passive gadget that required human intervention. Over the years, academic and industrial organizations have shown great interest, resulting in numerous studies, prototypes, and commercialized products. In this publication, we present a scientometrics investigation focusing on exoskeleton research. The analysis encompasses exoskeleton publications published from 1989 to 2022 year. Various scientometrics metrics were employed to explore different aspects of the field, including authors, nations, affiliations, keywords, citations, and collaboration networks. Among the Nation's leading in this sector, the United States stands at the forefront with an extensive collaboration network involving other countries. Harvard University emerges as a critical contributor to exoskeleton research, leading in the number of publications, total citations per article (Vitiello N), h-index, g-index, and m-index. Over the past years, the Journal of Neuroengineering and Rehabilitation has experienced a significant surge in manuscripts related to exoskeletons, signifying the growing interest in the field since 2006. According to the author's keyword analysis, most studies focus on exoskeletons and their uses in rehabilitation. This comprehensive report provides an in-depth assessment of the current state of exoskeleton research and collaboration networks. It is a valuable resource for researchers to guide their projects or discover potential collaborators.

Keywords: Exoskeletons, Robotics, Rehabilitation, Human-Robot Interaction, Scientometrics.

1. INTRODUCTION

An exoskeleton is an exterior skeleton that supports and protects an animal's body, as opposed to the inside skeleton (endoskeleton). It was the animal's outward skeleton, as opposed to the interior skeletin (endoskeleton) of, say, a human. The exoskeleton is a skeleton that is found outside the body. Exoskeletons are wearable devices that work in tandem with the user. Exoskeletons are implanted on the user's body and function as amps to improve, strengthen, or restore human performance. A mechanical protest, on the other hand, would be employed as a robot arm or leg, replacing the original portion of the body. The exoskeleton robotic business is still in its early stages, although it is expanding steadily as technology advances. An exoskeleton, as the name indicates, is a skeleton that exists outside of the body. Of course, humans have endoskeletons. Exoskeletons are used to support body weight, raise, maintain load, or stabilise the user's body. A powerful exoskeleton is mobile wearable equipment that uses an electric motor, pneumatic systems, heels, hydraulics, or a mix of technologies to provide limb motion. It also has strong armour, powered armour, a strong suit, cybernetic armour, cybernetic Armor, an exosuit, hardsuit, or an exoframe.

1.1 Exoskeleton (Robotics)

The robotic knee orthosis has reduced excessive trunk movement, pain, and metabolic expenditure in terms of most notably, the robotic knee orthosis assisted customers to walk normally again and could be useful in helping with everyday tasks. The robotic knee orthosis worked well for both individuals in this paper. The control algorithm can be improved by providing training in common activities of daily life situations while utilising the robotic knee orthosis this orthosis can aid those with lower limb paralysis or stroke and even training. Additional study and testing are required to prove this. Additional research is required to establish the long-term effects of using the robotic knee orthosis. In tandem with the human body, wearable robotic exoskeletons assist or retrain impaired human gait. Muscle force can be generated using transcutaneous electrical stimulation in a variety of application settings. A hybrid robotic exoskeleton combines motor neuroprosthesis with smart exoskeletons. Several strategies for artificial compensation have been proposed, including using diverse approaches. This paper focuses on the latest in hybrid robotics, as well as new insights on assistive and neurorehabilitation applications. them provide an up-to-date overview of the technology as well as guidance for future research into this subject. A case study discusses a generic framework for coordinating several gait-regulating muscles with electric motors using a muscle synergy-inspired control technique. Semiglobal asymptotic stability is supported with a novel method for adjusting the PID controller parameters. This is used on an upper limb exoskeleton. Results demonstrate that this novel PID tuning technique is straightforward, systematic, and successful for robot control. Exoskeleton components: sensing, decision-making, and physical actions. Designing robotic exoskeletons includes technologies for function of each module.

2. RESEARCH METHODOLOGY

The study in question utilizes scientometric analysis, a widely employed method to assess research performance in various scientific fields and support the development of appropriate governmental policies. The researchers utilized the WoS Core Collection (Web of Science) as the primary source for their research. This database is known for covering many international periodicals in various disciplines. As the data used in the study was obtained from Anna University, the researchers searched using specific keywords. The keywords "Exoskeletons" and "Exoskeleton" were used to find relevant exoskeleton-related papers published in the WoS database between 1989 and 2022, which revealed 8,436 records. To ensure the accuracy of the research output, the researchers searched for keywords in the article titles. They adopted a basic search approach to include all published publications that met the inclusion criteria. Specifically, the study focused on English articles falling under the "Original articles" and "Editorial material" categories in the WoS databases for analysis. The analysis, the researchers primarily used "Biblioshiny Tools" (R version 4.1.0). This tool enabled them to classify and analyze individual research trends and selected publication features from the WoS databases. The researchers examined the distribution of prolific authors, nationalities, journals, institutions, research topics, and keywords. Additionally, they considered essential metrics like the h-index, impact factor, and total citations to assess the significance and impact of the research. The h-index, a widely recognized metric for measuring research impact, was obtained using the "Histcite program". The researchers also employed Microsoft Excel to further their analysis for data mining, mapping, and network visualization. These tools helped in presenting and understanding the findings visually. The study utilized a comprehensive approach, combining scientometric analysis, keyword searches, data mining, and visualization techniques to examine the exoskeleton research landscape and relevant metrics from the WoS database.

3. RESULTS AND DISCUSSIONS

The scientometric examination of exoskeletons uncovers noteworthy trends and patterns in research productivity, collaborative networks, and the influence of citations. The talks emphasize the increasing significance of exoskeleton research across several scientific fields, emphasising its potential uses and drawing attention to significant hurdles. In summary, the results provide valuable insights into the changing field of exoskeleton technology and its influence on scientific discussions.

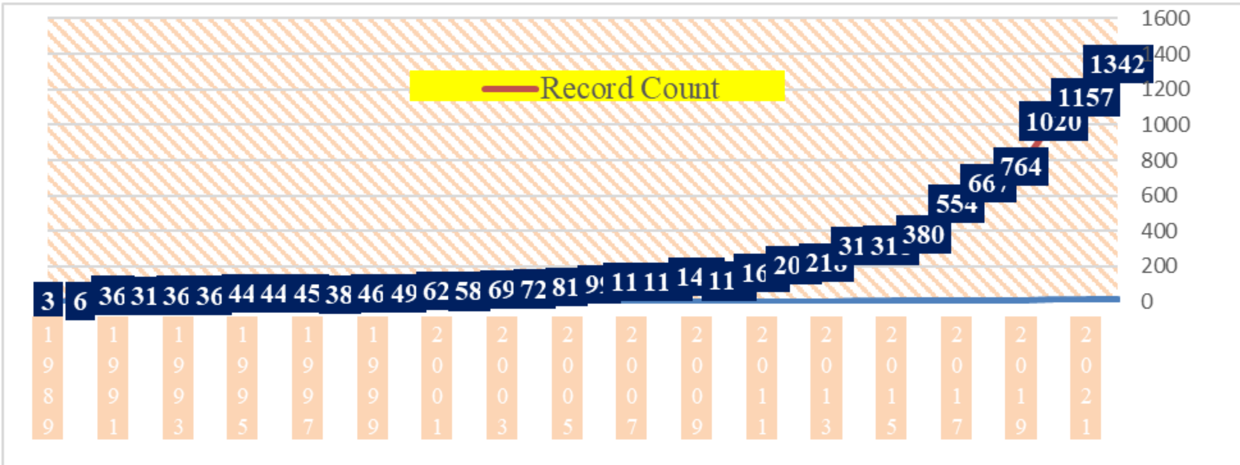

Figure 3.1. Yearly wise number of published articles related to exoskeletons.

Figure 3.1 shows the yearly number of published articles related to exoskeletons and the percentage of the total count (8,436 articles). The data spans from 1989 to 2022. The key findings from the data are: The year 2022 had the highest number of published articles related to exoskeletons, with 1,342 articles accounting for 15.908% of the total count. There has been a significant increase in published articles in recent years, with 2021 and 2020 also having a substantial number of articles at 1,157 (13.715%) and 1,020 (12.091%), respectively. The number of published articles has generally increased, indicating a growing interest in exoskeleton research. In the early years (1989 to the early 2000s), they had a relatively minor number of articles, with less than 1% of the total count each year. 1991, 1993, and 1994 had the same number of published articles (36), the highest for those early years. In 1990, they had the lowest number of published articles, with only 6 articles, representing 0.071% of the total count. This data provides an overview of the research trends and interest in exoskeleton technology over the years, showcasing a notable increase in research activity in recent times.

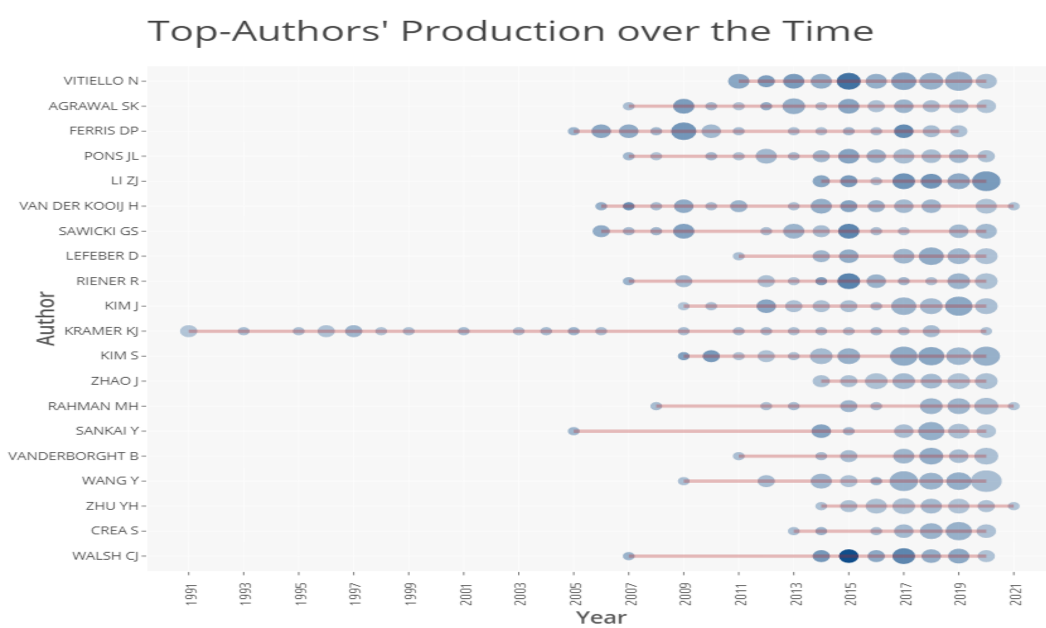

Figure 3.2. Bubble chart of top 20 authors by year. The size of the bubble represents the number of publications employing those authors.

Figure 3.2, provides a time-lapse analysis of the authors' work in exoskeleton research. Specifically, it focuses on the productivity and impact of the authors over time. The graph highlights the work of author Vitiello N. An explicitly. According to the analysis, it is claimed that the most productive period for exoskeleton authors spans from 1989 to 2022. During this time frame, author Vitiello N. has emerged as a prominent figure in the field. Although Vitiello N. began referencing articles only in 2011, the graph demonstrates their effectiveness in producing impactful publications rapidly increases. Vitiello N stands out in productivity and leads the list in metrics such as the H-index, G-index, and M-index. These indices are known for being more sensitive to highly cited articles with more citations, indicating that Vitiello N's work has significantly impacted the field. Considering the number of articles authored by Vitiello N. and the year when citations for their work started, the analysis suggests that the author's publications have effectively garnered citations and recognition from the research community. The data indicates a high possibility of Vitiello N. becoming more successful and influential over time.

Table 3.1 shows, the top 10 most productive countries in exoskeletons from 1989 to 2022. The table includes various metrics related to the research output of each country in this field. Rank: The ranking of the country based on its research output in exoskeletons. Country: The name of the country. Articles: The number of articles published by researchers from the country in the exoskeletons field during the specified period. Freq: The percentage of the total number of articles published by all countries represented in the data for the exoskeletons field. SCP: The number of articles published by researchers from the country in top-tier publications or prestigious venues in the exoskeletons field. MCP: The number of articles published by researchers from the country in mid-tier publications in the exoskeletons field. TC: The total count of articles published by researchers from the country in the exoskeletons field across all conferences or venues. AAC: The average number of authors per article for researchers from the country in the exoskeletons field. Based on the provided data, the rankings are as follows by USA: Ranked 1st with 2,158 articles, contributing 25.581% of the total articles in the exoskeletons field. China: Ranked 2nd with 1,614 articles, contributing 19.132% of the total articles. Italy: Ranked 3rd with 639 articles, contributing 7.575% of the total articles. Germany: Ranked 4th with 586 articles, contributing 6.946% of the total articles. Japan: Ranked 5th with 494 articles, contributing 5.856% of the total articles. United Kingdom: Ranked 6th with 484 articles, contributing 5.737% of the total articles. Canada: Ranked 7th with 470 articles, contributing 5.571% of the total articles. Korea: Ranked 8th with 395 articles, contributing 4.682% of the total articles. France: Ranked 9th with 326 articles, contributing 3.864% of the total articles. Australia: Ranked 10th with 297 articles, contributing 3.521% of the total articles.

Table 3.1. The top 10 most productive countries in exoskeletons field during 1990–2022

Rank	Countries	Publication	Freq	SCP	MCP	TC	AAC
1	USA	2158	25.581	1005	207	39991	33
2	China	1614	19.132	606	229	9533	11.42
3	Italy	639	7.575	185	78	4904	18.65
4	Germany	586	6.946	179	87	8978	33.75
5	Japan	494	5.856	236	45	5585	19.88
6	United Kingdom	484	5.737	129	92	5721	25.89
7	Canada	470	5.571	192	55	4983	20.17
8	Korea	395	4.682	205	41	3608	14.67
9	France	326	3.864	91	55	5053	34.61
10	Australia	297	3.521	87	65	3206	21.09

SCP- *Single Country Publications*; **MCP**- Multiple Country Publications; **TC**- Total Citations; **AAC**- Annual Average Citations

Figure 3.3 displays, the publications of the top 20 most productive affiliations during the specified period. The table provides information about the affiliations, their record count (the number of publications), and the percentage of their contribution to the total of 8,436 publications in the given field. The top 10 most productive affiliations based on their record count are as follows by Chinese Academy of Sciences: 222 publications, accounting for 2.632% ofhe total, University of California System: 173 publications, accounting for 2.051% of the total, Centre National de la Recherche Scientifique CNRS: 153 publications, accounting for 1.814% of the total, 4EU: 133 publications, accounting for 1.577% of the total, UDICE French Research Universities: 131 publications, accounting for 1.553%

of the total, Swiss Federal Institutes of Technology Domain: 130 publications, accounting for 1.541% of the total, Scuola Superiore Sant Anna: 125 publications, accounting for 1.482% of the total, Harvard University: 118 publications, accounting for 1.399% of the total, Consejo Superior de Investigaciones Cientificas CSIC: 111 publications, accounting for 1.316% of the total, CIVIS: 106 publications, accounting for 1.257% of the total. These affiliations have made significant contributions to the field in terms of research output and publication count during the specified period.

Figure 3.3. The Publications of Top 20 Most Productive Affiliations during the Period

Figure 3.4 illustrates a collaboration matrix map using a circular network layer, focusing on the top 50 countries with a minimum of 2 edges. Social Network Analysis (SNA) was employed to explore the interrelationships within the study subject. The nodes in the map represent the entities (writers, institutions, and nations) in the social network, while the linkages between these nodes indicate the network dynamics. The research investigated the distribution and participation of nations in 98-country collaboration networks related to exoskeletons. Geographically, the United States emerged as a dominant player in academic research and collaboration, working extensively with European nations and those developing exoskeleton technology. Cluster analysis was used to study the variety of knowledge bases in-depth. The identified clusters of strong working contacts with US researchers include countries such as China, Japan, Canada, the United Kingdom, Korea, Australia, Iran, Singapore, Israel, Turkey, New Zealand, Argentina, South Africa, Thailand, Pakistan, and Vietnam. The second cluster comprises nations like Germany, Spain, Brazil, Switzerland, the Netherlands, Belgium, Ireland, Portugal, Denmark, Austria, Norway, Romania, Slovenia, Greece, Hungary, and Croatia. The third cluster, led by France, includes Mexico, India, and Sweden, while a single nation, Venezuela, primarily represents the fourth cluster. Poland, Finland, and Indonesia head the fifth cluster. The figure provides valuable insights into the collaborative dynamics among the top 50 countries in the exoskeletons field and sheds light on the interactions and knowledge sharing within the research community.

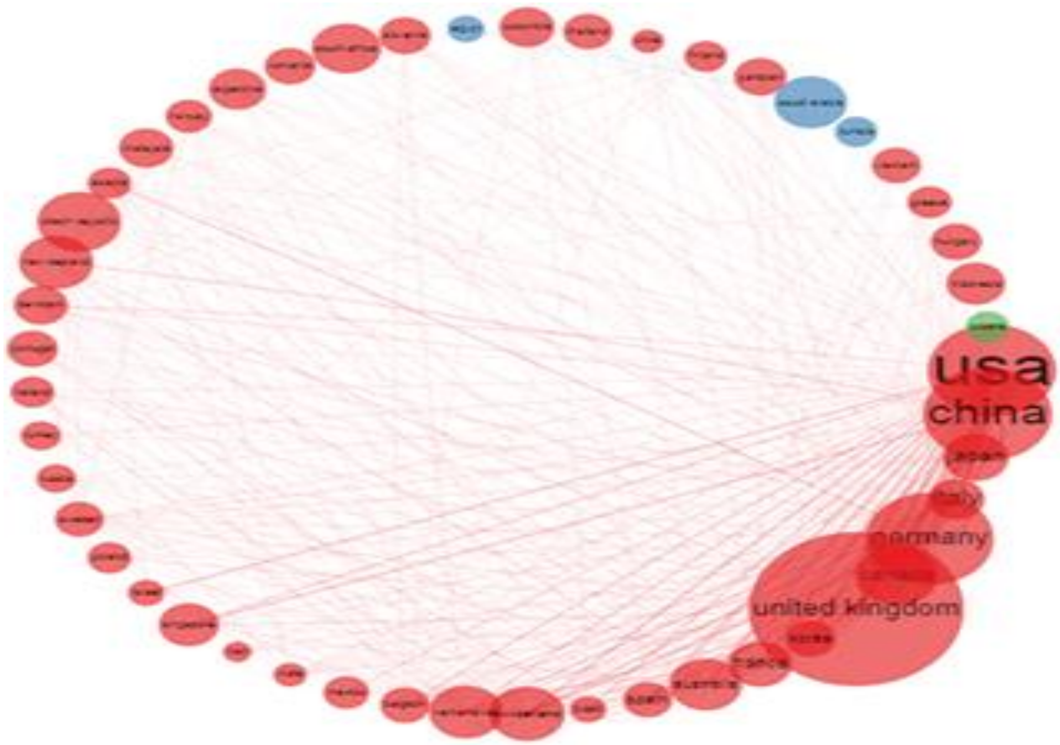

Figure 3.4. Collaboration matrix map by top 50 Country in a circle network layer with a minimum of 2 edges

Figure 3.5 presents a Sankey Plot that showcases the relationship between three fields related to exoskeletons: Affiliation, Sources, and Keyword Plus. The plot visualizes the flow of information and connections among these fields, where the size of each part corresponds to the node's value. On the left side of the Sankey Plot, the Affiliations of influential entities are displayed. These entities may include well-known institutions such as Northwestern University, the University of Tsukuba, The University of Twente, and Harvard University. In the center row, the Sources are shown, representing the sources of information or research related to exoskeletons. These sources may include academic journals, conferences, or other publications contributing to the field. On the right side of the plot, the Keyword Plus are depicted. Keyword Plus refers to specific keywords or terms associated with the research on exoskeletons. Some key sub-topics that emerged prominently from the influential research and Keyword Plus include "design," "exoskeleton," "rehabilitation," "walking," "stroke," "robot," and "recovery." The three-field plot helps visualize the interconnectedness and significance of various elements within the exoskeletons field, providing valuable insights into the relationships between affiliations, sources of information, and key sub-topics explored in research publications.

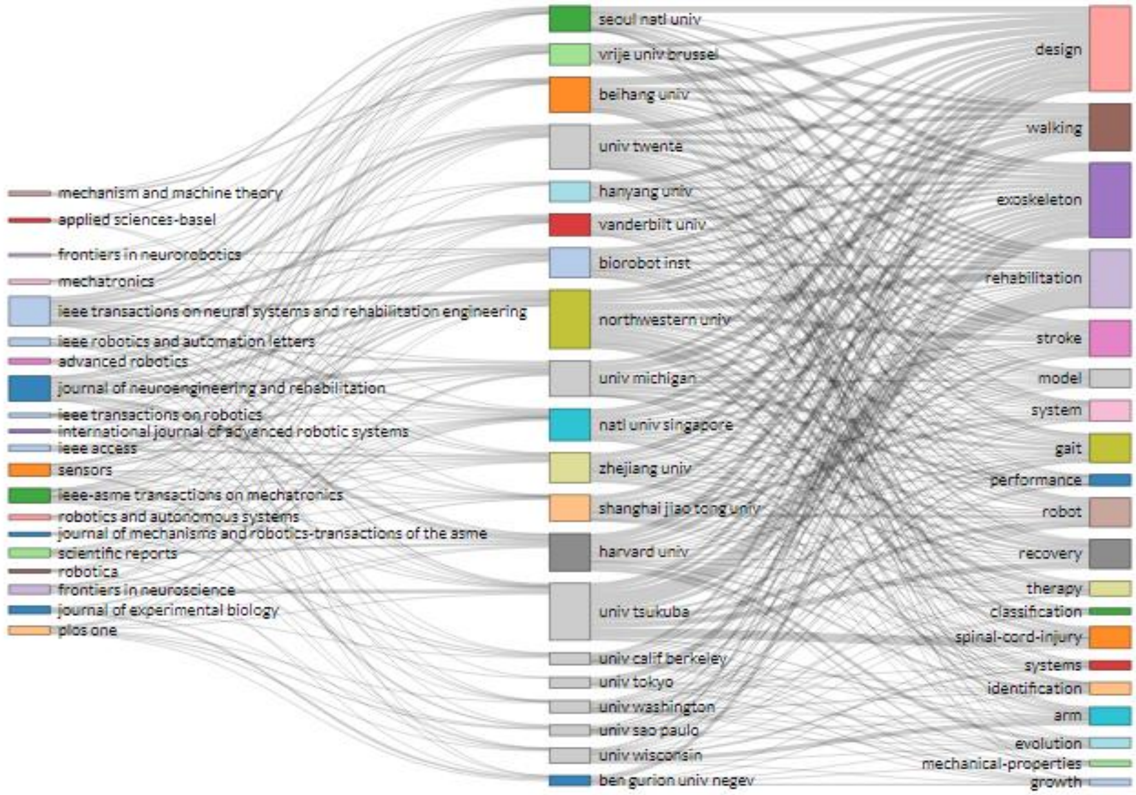

Figure 3.5. Three field plot Affiliation – Sources - Keyword Plus flow of exoskeletons.

Figure 3.6. WordCloud of Author’s Keywords on exoskeletons

Figure 3.6 presents a WordCloud that showcases the Author's Keywords related to exoskeletons based on their frequency in the publications. The size of each phrase in the WordCloud represents its frequency, indicating its literary value or prominence in the texts. The most frequently occurring keyword in the publications is "exoskeleton," which appeared 698 times. Following that, other prominent keywords include "rehabilitation," "exoskeletons," "stroke," "rehabilitation robotics," "chitin," and "robotics." The WordCloud also highlights other significant exoskeleton-related factors such as "lower limb," "prostheses," and "hand," indicating their importance in the research. Additionally, robotics-related variables like "over rehabilitation," "wearable," "neurorehabilitation," and "gait" are prominently featured. WordCloud suggests that the frequency of exoskeleton-related terms has significantly increased since 2010, indicating a growing interest and focus on exoskeleton research. The study seems to encompass various aspects of exoskeleton knowledge, including education and technology, and it covers a wide range of topics within the exoskeleton field.

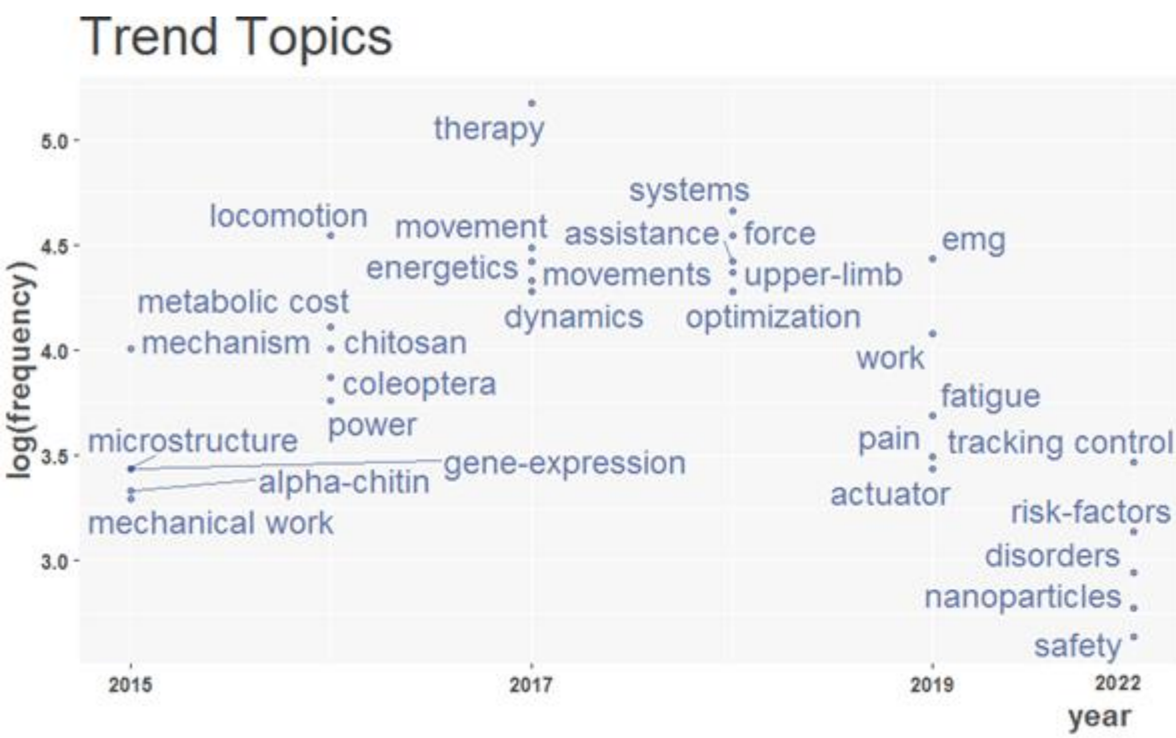

Figure 3.7. Trend topics of Keyword plus on exoskeletons.

Figure 3.7 presents the trend topics of Keyword Plus related to exoskeletons over the years. The two-dimensional scale shows logarithmic frequency values on the vertical axis and publication years on the horizontal axis. The analysis covers five years and reveals exciting trends in the research. In 2016, the significant concerns and trending topics in exoskeleton research were related to "power," "chitosan," "metabolic cost," and "locomotion." By 2018 and 2019, the focus shifted towards "optimization," "upper-limb," "force," "systems," "actuator," "pain," "work," and "EMG" (electromyography). In 2020 and 2022, new emerging subjects became prominent, including "safety," "nanoparticles," "diseases," "risk factors," and "tracking control," with a particular emphasis on the "gene-expression approach." The year 2017 showed a variety of themes, likely indicating a transitional period or diverse research interests during that time. The trend analysis provides valuable insights into the shifting research interests and areas of focus in exoskeleton research over the years.

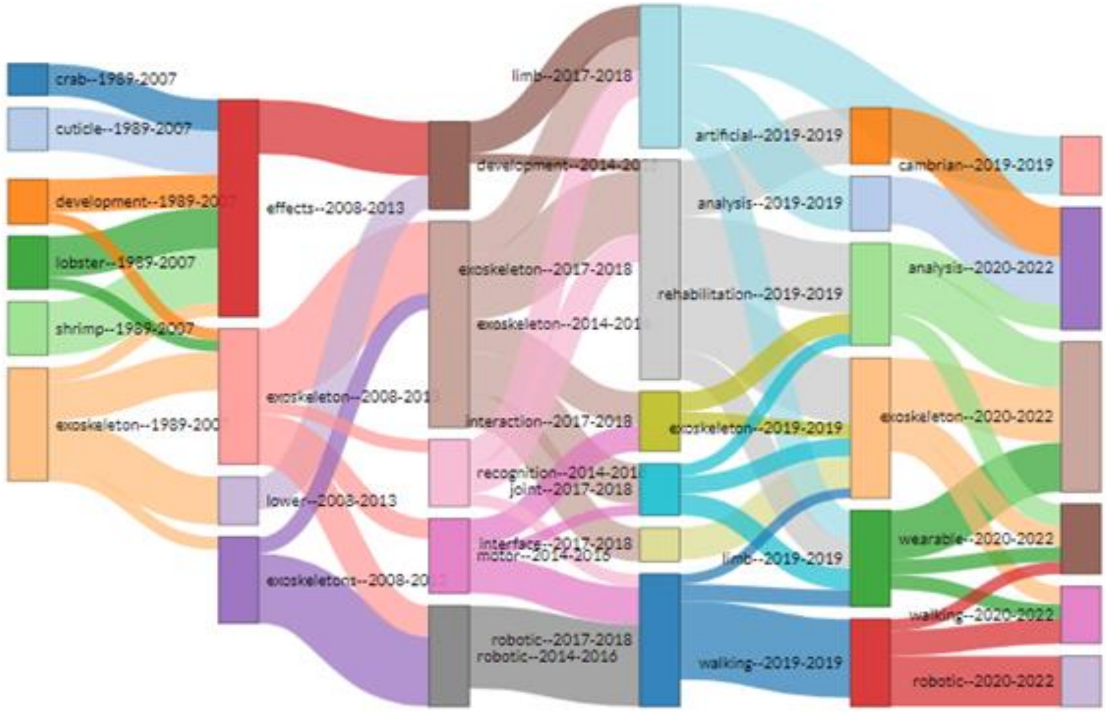

Figure 3.8. Thematic Evolution for title based **on exoskeletons.**

Figure 3.8 illustrates the thematic evolution of research article titles related to exoskeletons over different periods. The data shows five sub-themes that have been consistently used throughout the years. From 1989 to 2007, the left side of the graph represents the most popular topics. The initial theme was "exoskeleton," followed by related themes such as "shrimp," "lobster," and "development." Between 2008 and 2013, the second part of the graph shows four popular themes, some extensions of previous themes. For example, the topic "effects" emerged as a progression from themes like "shrimp," "lobster," "cuticle," "development," and "crab." The most frequently used themes during this period were "effects," "exoskeletons," and "exoskeleton." The third part of the graph displays themes commonly used between 2014 and 2016. Only one of the five declared themes, namely "robotic," "motor," and "recognition," is an extension of previous concepts, especially the theme "exoskeleton." The most common themes during this time were "effects" and "exoskeleton." The fourth segment focuses on the year's most popular topics. Six themes were identified, including "limb," "interaction," "joint," and "interface," two of which are evolutions of previous period themes, namely "exoskeleton" and "robotic." The most common themes in this section were "effects" and "exoskeleton." The fifth section lists the most commonly used themes between 2017 and 2016. Only one of the six indicated topics, "rehabilitation," "walking," "artificial," and "analysis," is an expansion of previous notions, particularly "exoskeleton" and "limb." The sixth and last part, on the right, depicts the most recently utilized themes between 2020 and 2022. Six themes were identified, three of which are evolutions of previous themes, notably "exoskeleton," "walking," and "analysis," which is an extension of several themes as seen by the colourful grooves. The thematic evolution highlights the changing trends and research interests in exoskeleton-related studies over time, providing valuable insights into the development of the field.

CONCLUSION

This paper presents a comprehensive analysis of exoskeleton research from 1989 to April 2022 using Scientometric methods. The study delves into various aspects of exoskeleton research, including common keywords for authors, study topics, contributions by nation, the most productive affiliations, collaboration patterns, and author keyword analysis. The findings reveal that exoskeleton research has a rich history spanning almost five decades. The Scientometric analysis provides valuable insights into the state of research frontiers and potential collaboration opportunities at both national and international levels. The collaboration matrix map showcases the relationships between countries, indicating strong working contacts between certain nations. While the Web of Science core databases was used for this study and yielded a considerable number of articles, the authors acknowledge that integrating papers from other databases, such as Scopus, IEEE, PubMed, JSTOR, ERIC, DOAJ, and Google Scholar, could further enhance the analysis by including additional relevant publications. This Scientometric approach provides substantial and critical information on robotic exoskeletons, shedding light on their evolution and progress. It is a valuable resource for researchers, policymakers, and stakeholders interested in the advancements and trends within the exoskeleton research domain.

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