IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Journal Européen des Systèmes Automatisés
Vol. 57, No. 4, August, 2024, pp. 935-943
Journal homepage: http://iieta.org/journals/jesa

Human-Hand Inspired Elastomeric Soft Pneumatic Actuators: Mapping the Research Landscape and Prospects

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https://doi.org/10.18280/jesa.570401

Received: 21 March 2024
Revised: 15 May 2024
Accepted: 4 June 2024
Available online: 27 August 2024

Keywords:
soft actuators, PneuNet, elastomers, soft robotics, hand

ABSTRACT

This article presents a bibliometric analysis of the current research landscape and future prospects in the field of elastomeric soft pneumatic actuators (ESPAs) inspired by the human hand. Drawing inspiration from the intricate mechanisms of the human hand, the study maps out the research landscape in the field of ESPAs, highlighting recent advancements and emerging trends. By analyzing the leading countries, institutions, authors, journals, funding bodies, citation patterns and intellectual structures, the article identifies emerging themes and research directions, shedding light on the evolution of human hand inspired ESPAs. Finally, the literature analysis is synthesized in the form of a list of research topics which could further extend the horizons of research on ESPAs. The findings of this bibliometric analysis offer valuable guidance for researchers, practitioners, and policymakers in understanding the current state of ESPA research and charting future research agendas. By synthesizing and visualizing the research landscape, the article aims to foster collaboration, innovation, and interdisciplinary exchange in the field of soft robotics and human-machine interaction.

1. INTRODUCTION

Soft robotics has emerged as a dynamic and interdisciplinary field, harnessing the principles of soft materials and novel actuation mechanisms for the development of versatile and adaptive robotic systems. Within this domain, elastomeric soft pneumatic actuators (SPAs) stand out as promising components due to their intrinsic compliance and adaptability. While soft actuators have been developed based on several bio-inspired designs, the human-hand is one of the most versatile systems which has inspired researchers to develop numerous types of SPAs. This bibliometric review delves into the landscape of research on human-hand inspired elastomeric SPAs, aiming to provide a comprehensive understanding of the field's evolution, key contributors, and emerging trends. This may assist in revealing potential avenues for future exploration in the realm of elastomeric SPAs.

The exploration of elastomeric SPAs is crucial for advancing soft robotics applications, spanning from medical devices to human-machine interaction. Our bibliometric analysis draws on a diverse range of research articles, reviews, and contributions from notable researchers and journals. Notably, Rusu et al. [1] work on soft pneumatic actuators based on a novel casting method has garnered significant attention, underscoring the impact of manufacturing methods on SPA capabilities. Furthermore, Bao et al. [2] academic insights and perspectives through bibliometric analysis provide a valuable framework for evaluating the scientific publications in soft robotics, including SPAs. Pagoli et al. [3] review on soft fluidic actuators provides a valuable reference for the classification and materials used in modeling SPAs, offering a comprehensive overview of analytical, numerical, and model-free methods employed in SPA research. Furthermore, the work of Herianto et al. [4] introduces a novel design optimization method for SPAs, utilizing computer simulation and finite element analysis to enhance SPA performance. These contributions exemplify the multidisciplinary nature of elastomeric SPA research, integrating engineering, materials science, and biomechanics.

Delving into the bibliometric analysis, the goal of this article is to not only present a snapshot of the current state of elastomeric SPA research but also to identify emerging prospects and potential avenues for future exploration. By synthesizing information from a myriad of sources, we aim to provide researchers, practitioners, and enthusiasts with a roadmap for navigating the evolving landscape of soft robotics. The research questions of the present work include – analysis

of global research trends on SPAs inspired by human hand's dexterity, the top research funders, and scope for collaborations. The exploration of these research questions can help upcoming researchers in this field to take up suitable themes/collaborators to flourish and achieve success.

In summary, this bibliometric review article serves as a comprehensive resource for those engaged in or interested in elastomeric SPAs and soft robotics, particularly on human-hand inspired SPAs. By amalgamating insights from influential works and mapping the scholarly landscape, we aim to contribute to the ongoing discourse surrounding the development, challenges, and prospects of elastomeric soft pneumatic actuators. In the following sections, we delve into the methodology and results of our bibliometric analysis, shedding light on the current state of elastomeric SPAs research and outlining potential directions for future exploration. Finally, a survey of the findings and limitations of the top 40 highly cited articles in this area is presented which would be helpful to pave the way for identifying avenues of future research.

2. SEARCH STRATEGY AND STUDY SELECTION

To comprehensively capture the evolving landscape of research trends in Elastomeric Soft Pneumatic Actuators (SPAs), a systematic search strategy was devised to retrieve relevant articles from the Scopus database. This methodology aimed to refine the search for articles specifically addressing elastomeric SPAs while excluding irrelevant content associated with the broader field of soft robotics.

Table 1. Search and exclusion keywords used for bibliometric analysis

Scopus Query String
((TITLE-ABS-KEY (soft AND robotics OR soft AND actuator) AND TITLE-ABS-KEY ((pneunet OR pneumatic) AND (elastomer OR rubber)))) AND (hand) AND (EXCLUDE (EXACTKEYWORD, "Electromyography") OR EXCLUDE (EXACTKEYWORD, "Hydrogels") OR EXCLUDE (EXACTKEYWORD, "Dielectric Elastomer Actuators") OR EXCLUDE (EXACTKEYWORD, "Dielectric Elastomers") OR EXCLUDE (EXACTKEYWORD, "Electrodes") OR EXCLUDE (EXACTKEYWORD, "Self-healing Materials") OR EXCLUDE (EXACTKEYWORD "Magnetism"))

The search strategy involved the use of Boolean operators and relevant keywords to narrow down the results to those directly related to elastomeric SPAs. The following search strings were employed across the title, abstract and keywords section of the research articles (refer Table 1 for the full query string):

1. *soft AND robotics OR soft AND actuator*: This string ensured the inclusion of articles related to soft robotics and soft actuators, refining the focus to elastomeric SPAs within these broader categories.
2. *pneunet OR pneumatic*: The inclusion of terms related to pneumatic systems helped capture articles specific to the pneumatic actuation of elastomeric structures, further narrowing down the search.
3. *elastomer OR rubber*: Incorporating materials-related keywords such as elastomer and rubber aimed to identify articles focusing on the unique properties and applications of these materials in soft pneumatic actuation.
4. *hand*: This keyword enabled the selection of articles involved in the development of human hand inspired SPAs.

To eliminate irrelevant articles and maintain the specificity of the search, certain exclusion criteria were applied. Terms like "Electromyography", "Dielectric Elastomer Actuators", "Dielectric Elastomers", "Electrodes", "Self-healing Materials" and "Magnetism" were excluded to ensure a focus on articles discussing elastomeric materials in soft pneumatic actuation. The search was conducted on Scopus, a comprehensive scholarly database, ensuring coverage of a diverse range of journals and conference proceedings in the field of engineering and robotics [5]. The inclusion and exclusion criteria were implemented to obtain a dataset that specifically reflects research trends in elastomeric SPAs.

3. RESULTS AND DISCUSSION

3.1 Global research output, leading countries, and application areas

The Scopus search resulted in a total of 161 articles obtained from the Scopus database covering the period between 2000 to 2023. Figure 1 presents the number of publications on human-hand inspired SPAs over the years. The volume of publications during the first decade of 2000s was ≤ 5/year, except the year 2005. The emergence of human-hand inspired SPAs is seen prominently after the year 2014, wherein a rapid increase in the number of publications is observed. While it is not possible to pinpoint a specific cause for this, certain research initiatives in the surrounding years had an important role to play. For instance, the Defense Advanced Research Projects Agency (DARPA) ChemBots program in the USA launched in 2008, the Chinese national research funding initiative Tri-Co Robot in 2016, Coordination Action for Soft Robotics funded by the European Commission under the Future and Emerging Technologies (FET) – Open Scheme in 2013, the Japanese government support to innovative projects related to "Science of Soft Robots: Interdisciplinary integration of mechatronics, material science, and bio-computing" since 2018 [6-8], etc. The rapid growth after 2014 can be assessed as a total culmination of these various initiatives.

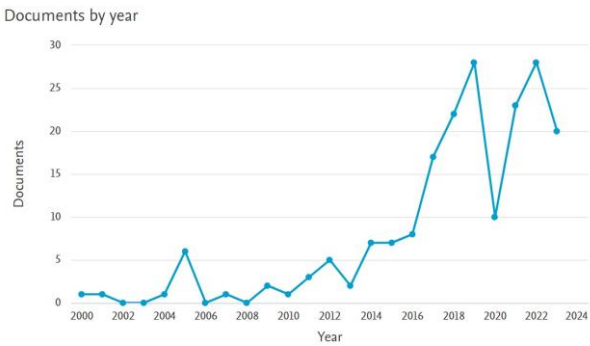

Figure 1. Number of publications on elastomeric soft pneumatic actuators by year

It is noteworthy that Japanese investigators spearheaded the early developments of human-hand inspired SPAs during the first decade of 2000. The group led by Noritsugu made

pioneering contributions by developing rotary bending type SPAs made of silicone rubber with the goal of assisting elderly people and those undergoing hand motor skills rehabilitation [9-11]. The studies [12-15] designed and implemented soft robotic systems in conjunction with conventional joint-based hard robotic apparatus to mimic the human hand muscles and tendons. Japan's focus on biomimicry, creating robots emulating the flexibility and adaptability of natural organisms, has inspired numerous international research projects. These bio-inspired approaches have led to breakthroughs in medical robotics and wearable technologies [1, 2]. Besides, the innovations in development of novel materials have set benchmarks for the development of flexible and adaptive robotic systems worldwide [9].

Over the course of the years, researchers from other countries have also contributed to develop technologies and solutions in this direction. China and USA stand at the second and third place based on the number of publications in this area between 2000 to 2023, see Figure 2. Naturally, this is reflected in the number of citations garnered by the publications. Japan [10-35] China [36-56], and USA [57-63] take the top three positions in terms of the citations received by the publications of researchers affiliated with their institutions, see Figure 3.

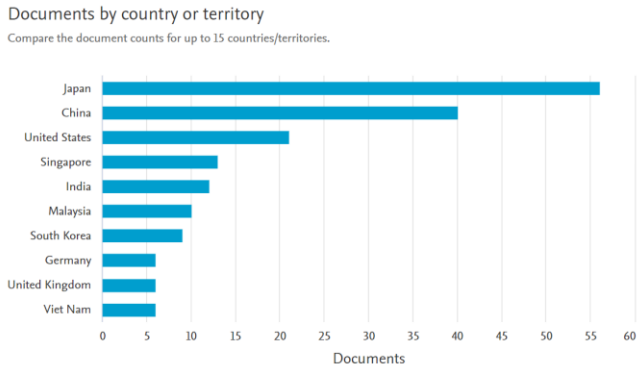

Figure 2. Top 10 countries by research output

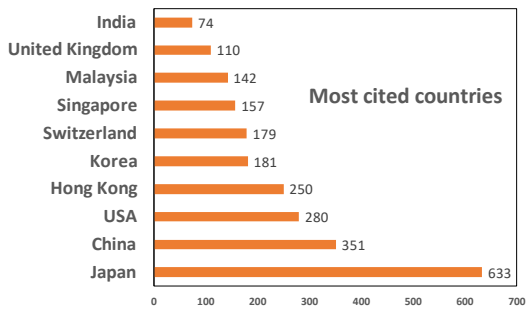

Figure 3. Leading countries based on the number of citations to the articles published by affiliated researchers

The distribution of articles based on the type of publications is shown in Figure 4. While close to 94% of the articles are either journal articles or conference publications, only 2.6% are review articles and, remaining being book chapters and conference reviews. The multi-faceted and multidisciplinary nature of this area of research is apparent by the distribution of subject areas in which published articles on human-hand inspired SPAs have been categorized, see Figure 5. It is therefore evident that there is a scope for revisiting, summarizing, and synthesizing the works conducted in this area through review articles keeping different perspectives and applications in mind.

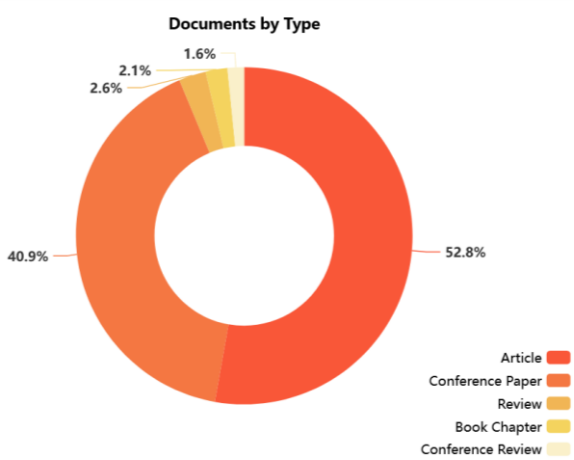

Figure 4. Distribution of types of research publications

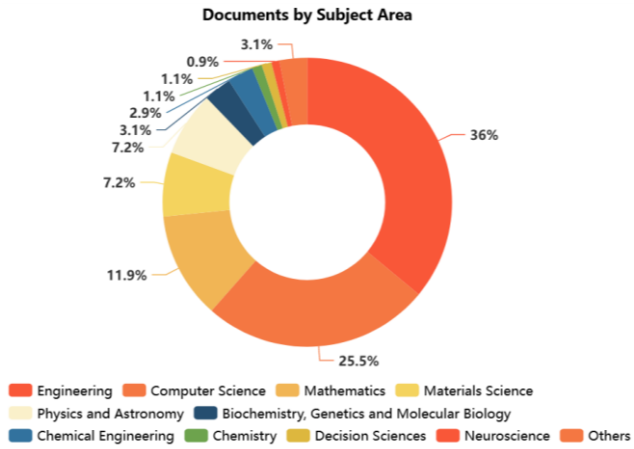

Figure 5. Distribution of subject areas of research output

3.2 Top institutions by research output and funding

The leading institutions conducting research in this area and their top sponsoring and funding agencies are summarized here. As observed in case of the country-wise distribution of research output, 6 out of the top 10 institutions based on the volume of the research output are Japanese and Chinese, with 4 and 6 institutions, respectively to their credit, see Figure 6. Okayama university has the most contributions with 27 articles. National University of Singapore stands at the close second position with 25 articles to its credit, followed by Universiti Teknologi Malaysia with 21 articles. Apart from these, Seoul National University of South Korea and Le Quy Don Technical University of Vietnam also have produced considerable output over the years with over 10 articles published with their affiliation.

Publications are results of systematic research work which requires the funding to sustain the manpower and technical and non-technical infrastructure to support them. Hence, funding agencies play a major role in sustaining the research culture in any academic institution. It is observed that among the top 10 funding agencies according to number of publications, 4 belong to China, see Figure 7. The National Natural Science Foundation of China stands at the first position with 20 articles supported by their funding. Notably, only one Japanese funding agency, i.e., Japan Society for the Promotion of

Science (JSPS) features in the top 10, at a close second position with 17 articles. Apart from this, agencies from South Korea and USA also find their place among the top 10 sponsors funding research on elastomeric SPAs.

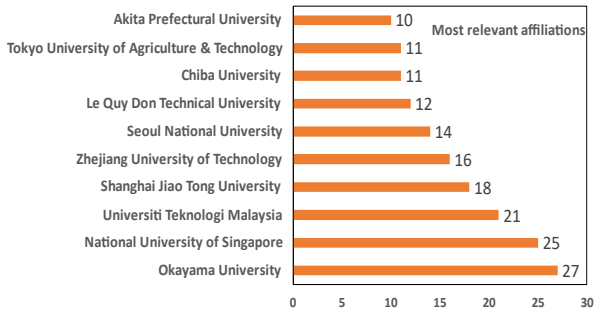

Figure 6. Top institutions by research output

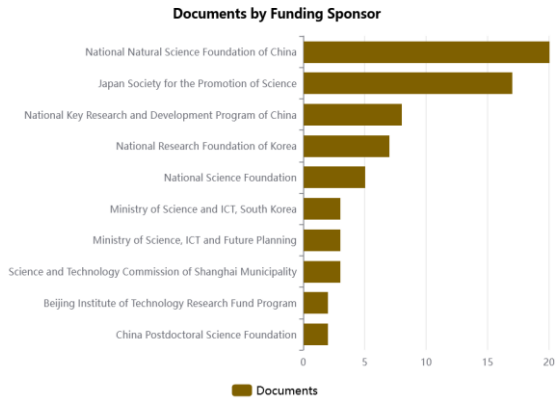

Figure 7. Top 10 sponsors funding research on SPAs

3.3 Principal research themes and their trends

Soft robotics is a multi-disciplinary area of research encompassing different actuation methods, materials, and control systems. When it comes to SPAs, the top theme of research can be summarized by means of the most relevant keywords used in their publications. The actuation method, viz., "pneumatic actuators" and "pneumatics" are found to be comparatively the most prominent keywords, being used in 119 and 92 articles, respectively, see Figure 8. Silicone-rubbers seems to be the typically used materials for fabrication of these SPAs. The word growth pattern shown in Figure 9 highlights the rapid rise in the research in the topics related to "pneumatic actuators", "pneumatics", and "rubber" based materials.

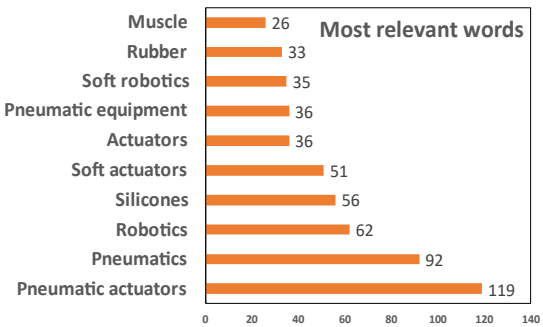

Figure 8. Distribution of associated keywords

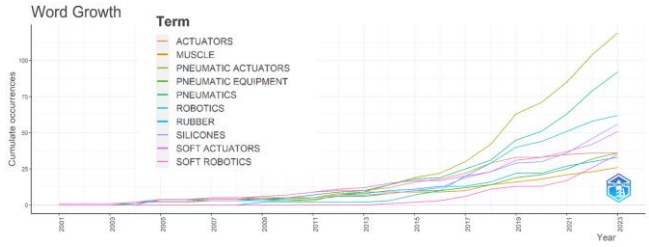

Figure 9. Trends in research themes over the years in terms of the growth of keywords

3.4 Leading journals by research publications and impact

The analysis of leading journals in this area of research shows that, "Actuators", "IEEE Robotics and Automation Letters", "Soft Robotics", "IEEE International Conference on Intelligent Robots and Systems (IROS)", and "Journal of Robotics and Mechatronics", form the top 5 influential publications with respect to the quantity of the articles published, as shown in Figure 10. These same journals have a sway over most citations as well, as indicated by the superior H-index of the articles published in them (refer Figure 11).

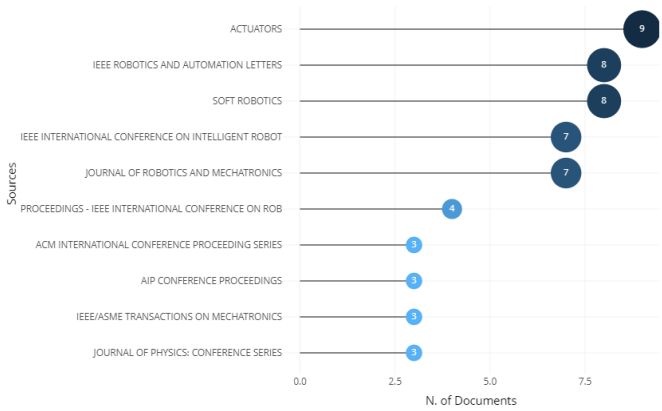

Figure 10. Top 10 leading journals based on number of publications

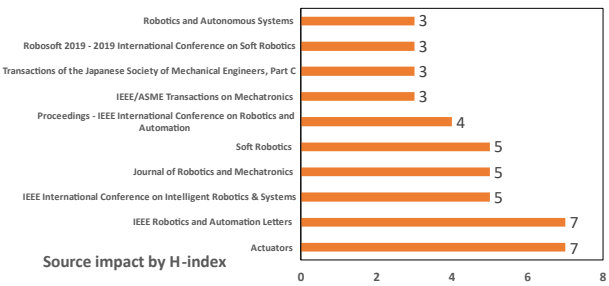

Figure 11. Top 10 leading journals based on their H-index

Bradford's law, proposed by Samuel C. Bradford in 1934, is a bibliometric principle that describes the distribution of scientific literature across journals. It suggests that the number of articles on a particular subject is distributed in a series of concentric zones, with a small core of journals containing most relevant articles, followed by a zone with a greater number of journals containing fewer articles each, and finally, a large number of journals with only occasional articles on the subject [64-66]. This law helps researchers identify core journals where a significant portion of relevant literature is published, allowing for more efficient literature searches and resource

allocation. Figure 12 shows the Bradford's law's perspective on articles published in the present topic. It is observed that distribution of articles in the different journals, with the influential journals, as shown in Figure 10 and Figure 11, being the most frequent publishers, is in accordance with Bradford's law.

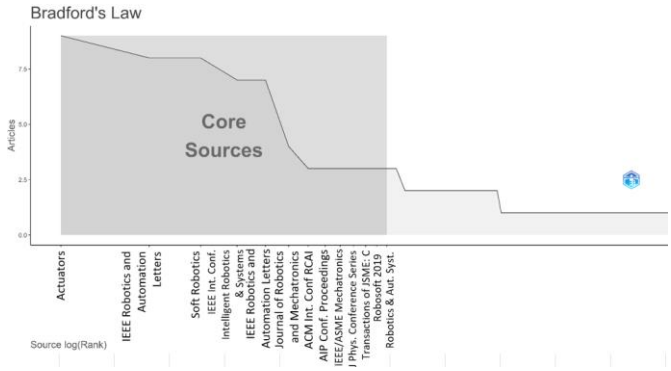

Figure 12. Distribution of articles in view of Bradford's law

Bradford's law helps identify the core journals that are most productive and influential in a particular field. These journals are crucial as they publish the highest concentration of significant research, guiding researchers on where to focus their literature searches and where to publish their work for maximum impact. Libraries and institutions can use this information to prioritize subscriptions to these core journals, optimizing their resources effectively. Furthermore, by examining changes in the distribution of articles over time, one can identify emerging research areas. If new journals start moving into the core zone, it signals a growing interest and significant developments in those areas. Conversely, if a topic shows a steady number of publications in core journals without expansion, it might indicate a mature or saturated research area. Funding bodies can use insights from Bradford's law to make informed decisions about where to allocate resources, focusing on high-impact areas and emerging fields with significant potential. Policymakers can leverage this analysis to support fields that are critical for societal advancement, ensuring that vital areas are well-supported and developed. This deeper understanding helps researchers, librarians, policymakers, and funding bodies make more informed decisions, ultimately advancing the progress and impact of scientific research.

3.5 Leading authors by research output, impact, and country of affiliation

The leading authors by research output and their H-index are listed in Figure 13 and Figure 14, respectively. "Wakimoto, S.", "Suzumori, K.", and "Deng, M." are found to be the top three most influential researchers in this area, both according to the number of research articles published and their H-index. Notably, "Wakimoto, S." has established collaborative partnerships with both "Suzumori, K." [17, 18, 67, 68] and "Deng, M." [20, 25, 31, 69, 70], as evidenced by the frequent research publications. This has undoubtedly augmented their research output.

Figure 15 shows the countries to which the corresponding authors are affiliated with. China and Japan have a predominant influence because of the significantly higher number of research articles published by their researchers compared to other countries. Notably, more than 80% of these are single country publications (SCP) wherein all the authors belong to the same country. This indicates a scope for improved collaboration which other countries can explore with the leading countries to enhance their research output. Malaysia and India stand at third and fourth positions with almost 1/3rd the number of articles as China and Japan.

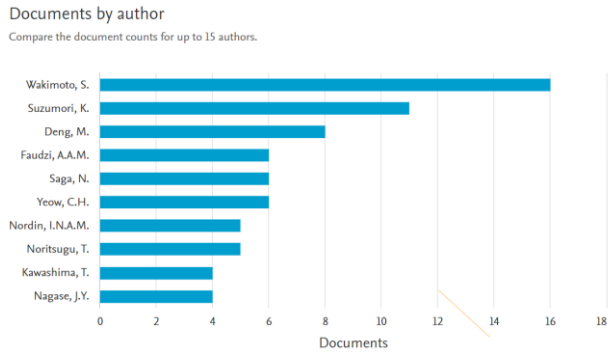

Figure 13. Leading authors based on the quantum of research output

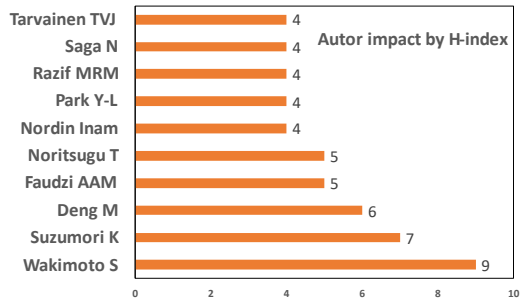

Figure 14. Impact on the research field by the leading authors based on their H-index

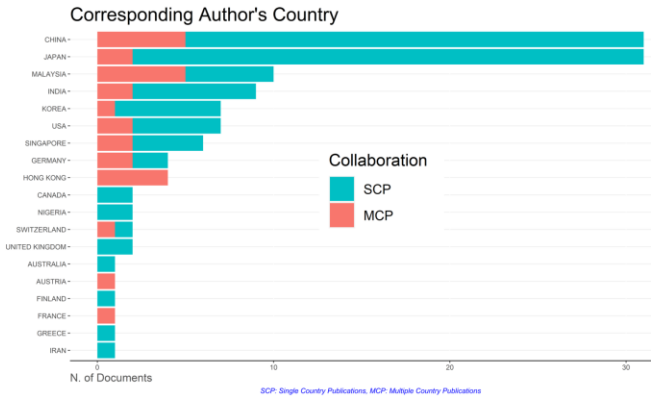

Figure 15. Affiliated countries of the leading researchers

3.6 Research prospects

Based on the review of the research landscape on human hand inspired SMA actuators, some prospective topics of research are listed below:

- **Enhancing Dexterous Manipulation**: Investigating ways to improve the dexterity and manipulation capabilities of soft pneumatic hands, such as enhancing finger coordination and precision [71-74].
- **Sensing and Feedback Systems**: Developing

advanced sensing and feedback systems to provide real-time information about the hand's interactions with objects, enabling better control and adaptability [71].

- **Material Optimization**: Researching novel materials and fabrication techniques to improve the performance, durability, and compliance of soft pneumatic actuators, enhancing their biomimicry and functionality [75].
- **Integration with Wearable Robotics**: Exploring the integration of soft pneumatic actuators into wearable robotic systems for applications such as prosthetics, exoskeletons, and rehabilitation devices [76].
- **Adaptive Grasping and Object Recognition**: Researching adaptive grasping algorithms and object recognition techniques to enable soft pneumatic hands to autonomously adapt their grip and manipulation strategy based on object properties and environmental conditions [77-80].
- **Energy Efficiency and Power Supply**: Investigating methods to improve the energy efficiency of soft pneumatic actuators and exploring alternative power supply solutions, such as self-sustaining energy harvesting systems [81, 82].

These topics can help advance the capabilities, versatility, and practical applications of soft pneumatic actuators in mimicking the dexterity and functionality of the human hand.

4. CONCLUSIONS

The bibliometric review threw light on the developments and the rapid progress being made on human hand inspired ESPAs. Japan, China, and USA have emerged as the leading contributors of knowledge consolidating the technical research. Regarding the journals, 'Actuators', 'IEEE Robotics and Automation Letters', 'Soft Actuators', 'IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)', and 'Journal of Robotics and Mechatronics' are positioned occupy the top 5 positions with consistent publications over the last 24 years. 'Wakimoto, S.', 'Suzumori, K.', and 'Deng, M.' are the top 3 researchers based on their quantitative contributions and impact on the field. The survey also revealed that ESPAs involve multiple domain knowledge requirements such as materials development and improvisation, computational sciences, fabrication and manufacturing techniques, control-automation theory, etc. Although there exist certain constraints for commercialization of this technology for mass production, there is a strong potential and ample opportunities for practical implementation to address issues related to precise control and automation, wearable robotics, adaptive grasping and object detection, and sustainable energy-harvesting systems.

ACKNOWLEDGMENT

The authors express their gratitude to Manipal Institute of Technology, Manipal Academy of Higher Education, for the infrastructural support and encouragement provided to carry out this study.

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