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Robotics and artificial intelligence applications in neurorehabilitation: a bibliometric analysis (2003–2025)

Burhan Taşkaya^{1*} and Cengiz Taşkaya¹

Abstract

Background Robotic and artificial intelligence (AI)-assisted neurorehabilitation has emerged as a rapidly growing interdisciplinary field, integrating engineering innovations with clinical practice to enhance motor and cognitive recovery in neurological disorders. While research in this domain has expanded substantially over the last two decades, only a few bibliometric studies have examined related topics (e.g., new technologies in neurorehabilitation, rehabilitation robotics after stroke, AI in stroke care), and, to our knowledge, no study has provided a comprehensive bibliometric mapping specifically focused on robotics and artificial intelligence applications in neurorehabilitation. This study aimed to analyse the global trends, influential contributors, thematic evolution, and collaborative networks in robotic and AI-assisted neurorehabilitation.

Methods A bibliometric analysis was conducted using the Web of Science Core Collection. A comprehensive search covering 2003–2025 identified relevant articles using controlled terms for neurorehabilitation, robotics, and AI. Data were exported as plain text files (savedrecs.txt) from the Web of Science Core Collection and processed using the Bibliometrix R package via the Biblioshiny interface. Analyses included annual growth, citation performance, authorship patterns, journal impact, keyword co-occurrence, thematic mapping, and international collaboration networks.

Results A total of 468 articles were retrieved from 191 sources, showing a rapid annual growth rate of 19.57%. The average citation per article was 24.22, with 17,792 references cited overall. Authorship analysis revealed contributions from 1,972 authors, with an average of 5.49 co-authors per paper and 32.05% international collaboration. The *Journal of NeuroEngineering and Rehabilitation* (h-index = 15, 1,740 citations) and *Sensors* (m-index = 1.714) were identified as the leading journals. The most prolific authors included Aiguo Song (8 publications) and Robert Riener (6 publications), while Marchal-Crespo L. and Reinkensmeyer D.J. were the most locally cited. Keyword analysis highlighted “stroke” ($n = 93$), “rehabilitation” ($n = 82$), “design” ($n = 58$), “recovery” ($n = 53$), and “exoskeleton” ($n = 49$) as dominant themes, with stroke rehabilitation and robotic exoskeletons representing core research foci. China ($n = 697$) and the USA ($n = 251$) emerged as the most productive countries, with strong collaborative ties.

Conclusion Robotic and AI-assisted neurorehabilitation has demonstrated exponential growth, reflecting both technological innovation and clinical translation. Stroke rehabilitation and gait training remain central themes,

*Correspondence:

Burhan Taşkaya
b.taskaya@alparslan.edu.tr

Full list of author information is available at the end of the article



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while emerging areas such as AI-based assessment systems, wearable sensors, and tele-rehabilitation suggest future directions. To our knowledge, this study provides a comprehensive bibliometric overview specifically centred on robotics and artificial intelligence applications in neurorehabilitation, offering strategic insights for guiding future research and clinical integration.

Keywords Neurorehabilitation, Robotics, Artificial intelligence, Stroke rehabilitation, Exoskeleton, Gait training, Bibliometric analysis, Scientific mapping

Introduction

Neurorehabilitation is a multifaceted, patient-centred medical process aimed at facilitating recovery in individuals with injuries or disorders of the nervous system, such as stroke, traumatic brain injury, multiple sclerosis, and Parkinson's disease. Its primary objectives are to minimise or compensate for functional impairments and assist patients in adapting to new ways of living [1, 2]. This approach is fundamentally interdisciplinary, involving physicians, therapists, psychologists, nurses, and the patient's social network to address physical, cognitive, emotional, and social challenges [3]. Neurorehabilitation is based on neuroplasticity, which is the brain's ability to reorganise and form new connections in response to injury and training. Interventions are tailored to individual needs and may include physical, occupational, and speech therapy, psychological support, and advanced technologies such as robotics, virtual reality, and non-invasive brain stimulation [4, 5]. Within this broad technological landscape, the present study specifically focuses on robotics and artificial intelligence applications in neurorehabilitation, as reflected in the keyword-based search strategy described in the Methods section.

Robotic and AI-assisted neurorehabilitation refers to the integration of robotic devices with data-driven, adaptive artificial intelligence (AI) methods to support assessment and training in individuals with neurological disorders. In this context, robotics primarily provides precise, repetitive and task-specific movements or haptic interactions, whereas AI encompasses computational techniques such as machine learning, deep learning, neural networks and decision-support algorithms that learn from patient data over time to adjust assistance, personalise therapy parameters and optimise progression [1, 2, 6]. These combined systems have been used to support motor function recovery, gait training, upper-limb rehabilitation, cognitive tasks and sensory stimulation, and can deliver more intensive and engaging therapy than conventional methods alone [6–8]. Importantly, in the present article the term AI does not refer to simple pre-programmed, non-learning control routines or to fully autonomous clinical decision-making or “general” artificial intelligence, but rather to narrowly focused algorithms that support and augment, rather than replace, the clinical judgement of rehabilitation professionals [1, 9].

Bibliometric analysis offers a systematic and quantitative approach to evaluate scientific literature and research trends in a particular field. This method involves examining various publication aspects, such as citations, authors, institutions, countries, and keywords, to describe the current state of the subject and identify research gaps and trends. Advanced tools, such as Bibliometrix and VOSviewer, are frequently used to conduct comprehensive analyses [10, 11]. As the volume of scientific literature continues to expand, bibliometric analysis remains a critical method for navigating and understanding the evolving landscape of academic research. Based on the comprehensive and standardised data provided by scientific databases, bibliometric analyses enhance the reliability and generalisability of the research findings [12]. Both studies guide researchers and offer a wide range of data by contributing to a better understanding of interdisciplinary work.

A review of the literature revealed that, although several bibliometric analyses have addressed related themes such as new technologies in neurorehabilitation, rehabilitation robotics after stroke and AI in stroke care, there is still no comprehensive bibliometric analysis that jointly maps robotics and artificial intelligence applications across neurorehabilitation conditions within a single analytical framework [13–16]. In the present study, the term “robotics and artificial intelligence applications in neurorehabilitation” is used in an operational sense to denote the use of rehabilitation robots, exoskeletons, robotic upper- and lower-limb devices, sensor-based intelligent systems, and AI/machine learning algorithms for the assessment, training or treatment of individuals with neurological disorders in a neurorehabilitation context. In this definition, AI-based assessment or prediction tools (for example, outcome prediction, automated gait analysis or decision support) are considered part of the field when they are explicitly linked to rehabilitation planning, personalisation or monitoring, rather than to diagnosis alone. In this context, this study aimed to conduct a bibliometric analysis of academic articles published on robotics and artificial intelligence-supported neurorehabilitation using the R-based Bibliometrix program.

Method

Study design

This study was designed using bibliometric analysis.

Data source and search strategy

Bibliometric analyses can be conducted using databases such as the Web of Science (WoS), Scopus, and PubMed [17, 18]. The extensive datasets provided by WoS enable researchers to measure scientific productivity, map collaboration networks, and assess academic impact [19–21]. Among these options, we selected the Web of Science (WoS) Core Collection as the sole data source for the present analysis because it offers broad coverage of high-impact journals, standardized citation and bibliographic information, and full compatibility with the Bibliometrix R package and Biblioshiny interface used in this study. Because there is currently no universally accepted formal definition of ‘robotics and artificial intelligence applications in neurorehabilitation’, we operationalized this concept through a transparent keyword-based search strategy.

In bibliometric analyses, large datasets are generally used [22, 23]. As there is a continuous scientific flow into the WoS database, it is important to complete the search in a single session. In this context, the data for this study were obtained using the WoS database on 18 August 2025. All studies published before the search date were included in the initial screening without applying any time restrictions. Concepts and synonyms were first explored using MeSH (Medical Subject Headings) in PubMed, and these MeSH-informed terms were then translated into a Web of Science Topic (TS) free-text search string to conduct a thorough analysis. The search was performed as follows: (TS=(“neurorehabilitation” OR “neurological rehabilitation” OR “stroke rehabilitation” OR “CNS rehabilitation” OR “motor rehabilitation” OR “brain injury rehabilitation” OR “spinal cord injury rehabilitation” OR “Parkinson rehabilitation” OR “upper limb rehabilitation” OR “gait training” OR “locomotor training”)) AND (TS=(“robot*” OR “robotic device*” OR “exoskeleton” OR “rehabilitation robot*” OR “robot-assisted therapy” OR “robotic rehabilitation” OR “assistive robot*” OR “wearable robot*” OR “intelligent assistive device*” OR “powered orthosis”)) AND (TS=(“artificial intelligence” OR “AI” OR “machine learning” OR “deep learning” OR “neural network*” OR “intelligent system*” OR “decision support system*” OR “algorithm*” OR “smart rehabilitation” OR “cognitive computing”)). These keywords were used to define the scope of the research and select relevant studies from the literature. Operationally, records were eligible for inclusion if at least one neurorehabilitation-related term (e.g. “neurorehabilitation”, “stroke rehabilitation”, “motor rehabilitation”) and at least one robotics/AI-related term (e.g. “robot*”, “exoskeleton”, “artificial intelligence”, “machine learning”) appeared in the title, abstract or author keywords. Within this retrieved set, “robotics and artificial intelligence applications in neurorehabilitation” were operationally defined

as studies in which robotics and/or AI systems were used for neurorehabilitation assessment, training, treatment or decision-support in individuals with neurological disorders. This includes, for example, machine learning or deep learning models used to predict rehabilitation outcomes or to provide automated performance analysis when these functions are explicitly framed as part of the rehabilitation process. By contrast, AI-only diagnostic or imaging tools without a rehabilitation implication, as well as robotic systems applied exclusively to neurosurgical procedures or non-neurological populations, were considered outside the conceptual scope of the field. Given the bibliometric design of the study, however, inclusion was determined primarily by the above search string and document-type filters, and no additional manual reclassification by specific algorithm type or intervention modality was undertaken.

Selection and extraction of work

The following inclusion criteria were determined: [1] studies that contained search terms in the title, keywords, or abstract, and [2] only studies in the form of articles. English was selected as the language of the study. Within the Web of Science Index, the Science Citation Index Expanded (SCI-EXPANDED), Emerging Sources Citation Index (ESCI), and Social Sciences Citation Index (SSCI) were selected. The Conference Proceedings Citation Index (CPCI) was deliberately not included, as the present bibliometric analysis focused on peer-reviewed journal articles with more stable citation patterns and more standardized bibliographic information, whereas conference proceedings often report preliminary prototype work with heterogeneous formats and limited clinical evaluation. As a result of the search, 468 articles of the “article” type were identified. All bibliographic data were obtained from the WoS database to create bibliometric maps. The study selection process is summarised in a PRISMA-style flow diagram (Fig. 1). In total, 762 records were initially retrieved from the WoS Core Collection; after applying language and document-type filters (English, article) and removing records that did not match the neurorehabilitation–robotics–AI focus based on titles and abstracts, 468 articles were retained for the final analysis. Each record set was exported as a plain text file in the “savedrecs.txt” format, including titles, abstracts, author keywords, Keywords Plus and reference information, and then imported into the RStudio environment for analysis.

Data analysis

Biblioshiny is a web interface used for bibliometric analysis and scientific mapping as part of the Bibliometrix R package. It allows users to perform annual growth rate calculations, publication and citation relationship

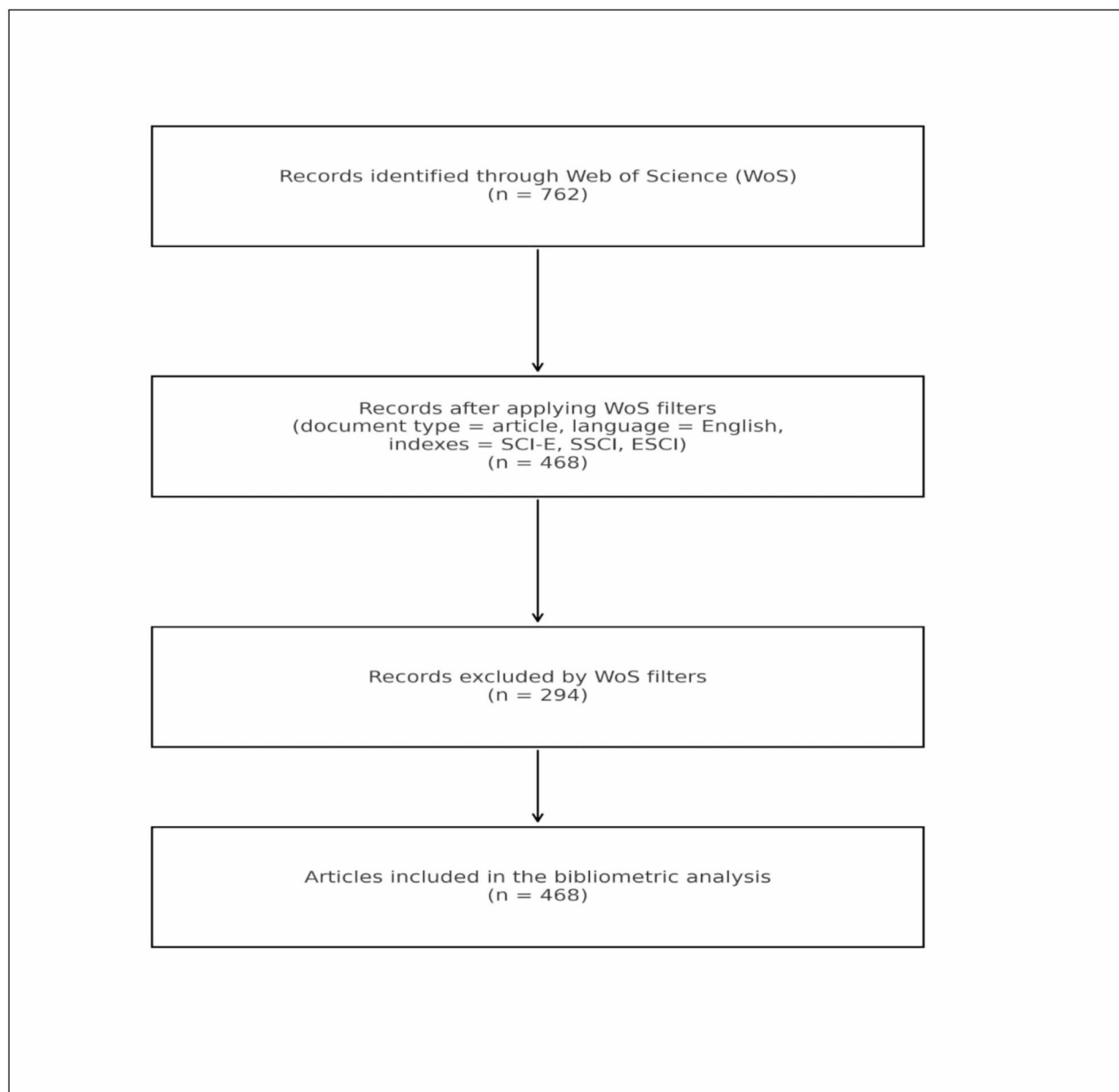


Fig. 1 PRISMA flow diagram of study selection

analyses, identify productive authors and institutions, and conduct keyword analyses without requiring any coding knowledge. These analyses are used to identify trends in the literature and guide future research areas [12, 24, 25]. In this study, the “Biblioshiny” application provided by the Bibliometrix R package was used. During the processing and analysis of the data, various aspects of the literature were examined using this app. All statistical and science-mapping analyses were carried out in R (version 4.5.0; R Foundation for Statistical Computing, Vienna, Austria) using the bibliometrix package (version 4.3.3) and its Biblioshiny web interface. Web of Science “savedrecs.txt” files were converted into a bibliographic

data frame with the function ``convert2df()``. Descriptive indicators (e.g. annual scientific production, most productive sources, authors, and countries) were obtained with ``biblioAnalysis()`` and summarised with ``summary()``. Co-authorship, co-citation and keyword co-occurrence networks were generated with ``biblioNetwork()`` and visualised using ``networkPlot()``, whereas thematic structures were explored with ``thematicMap()``. For all collaboration and co-occurrence networks we applied a **full counting** scheme, whereby each multi-country or multi-author publication was counted once for every country or author listed; therefore, aggregated country and author counts can exceed the total number

of documents in the dataset. Networks were normalised using the association strength index and clustered with the default walktrap community detection algorithm implemented in Biblioshiny. For co-word and co-citation analyses, items were included if they appeared at least five times in the dataset and, unless otherwise stated, up to the top 250 items were retained. For impact indicators we considered both total global citations and citations per year (citations divided by the number of years since publication) as provided by bibliometrix. Self-citations were not excluded, because the aim was to map the overall structure and dynamics of the field rather than to evaluate individual performance. All Web of Science searches were completed on 18 August 2025; consequently, records from 2025 represent a partial year and trends for 2025 are interpreted descriptively.

Ethical considerations

This study did not require ethical committee approval, as it only included data obtained from publicly available databases and was not conducted on human or animal subjects. This study was conducted entirely in accordance with ethical principles and was based solely on a literature analysis.

Results

Main data statistics

A total of 468 articles addressing robotics, artificial intelligence, and neurorehabilitation were found to have been published between 2003 and the screening date of 18 August 2025. An average annual growth rate of 19.57% indicates rapid development. The average number of citations for the publications included in the analysis was 24.22, revealing that the topic has attracted academic

interest. When examined at the author level, it was observed that a total of 1,972 researchers contributed to the field. There is an average of 5.49 co-authors per article, and only six publications are identified as single authors. The rate of international collaboration is 32.05%, reflecting the field’s openness to interdisciplinary studies at the global level. In terms of reference diversity, the works were published in 191 different sources and contained 17,792 distinct references. This demonstrates that the topic is based on a solid scientific foundation. Additionally, 1,642 author keywords and 846 Keywords Plus tags were identified in the data analysed. These findings support the strong thematic diversity and technological orientation of the literature. (Table 1) Unless otherwise specified, all citation counts reported in the Results section include self-citations, because the aim of this analysis was to describe the overall citation structure of the field rather than to evaluate individual author or institutional performance.

Publication output and growth trend

When the number of publications between 2003 and 2025 was examined, a distinct upward trend was observed in the field of robotics and artificial intelligence-assisted neuro-rehabilitation. In particular, there was a noticeable and consistent increase in the number of publications after 2010. The annual number of publications fluctuated between 0 and 3 between 2003 and 2010, rose to 9 in 2011, reached 13 in 2015, and accelerated to 20 in 2018. This increase became more pronounced after 2020. The number of publications reached 35 in 2020, 51 in 2021, 58 in 2022, 66 in 2023, and achieved the highest value of 69 in 2024. Although data for 2025 are incomplete because the search was closed on 18 August 2025, the number of publications has already reached 51 and is likely to increase further by the end of the year (Fig. 2).

Journals publishing articles

When examining the annual scientific output of studies conducted in the field of robotics and artificial intelligence-assisted neurorehabilitation, the journals producing the most publications were the Journal of Neuroengineering and Rehabilitation ($N=28$), Sensors ($N=28$), IEEE Transactions on Neural Systems and Rehabilitation Engineering ($N=23$), IEEE Robotics and Automation Letters ($N=13$), and Robotica ($n=12$) (Fig. 1). According to analyses based on Bradford’s law, among the 191 journals publishing on the subject, 11 journals were identified in the first zone, 44 in the second zone, and 136 in the third zone. Within this scope, the journals that produced the most publications and are in the first zone are listed below. (Table 2; Figs. 3 and 4)

Table 1 Key statistics on robotics and artificial intelligence-assisted neurorehabilitation

Description		Results
Main information about data	Timespan	2003:2025
	Sources (Journals, Books, etc.)	191
	Documents	468
	Annual Growth Rate %	19,57
	Document Average Age	4,48
	Average citations per doc	24,22
	References	17,792
Document contents	Keywords Plus (ID)	846
	Author’s Keywords (DE)	1642
Authors	Authors	1972
	Authors of single-authored docs	6
Authors collaboration	Single-authored docs	6
	Co-Authors per Doc	5,49
	International co-authorships %	32,05

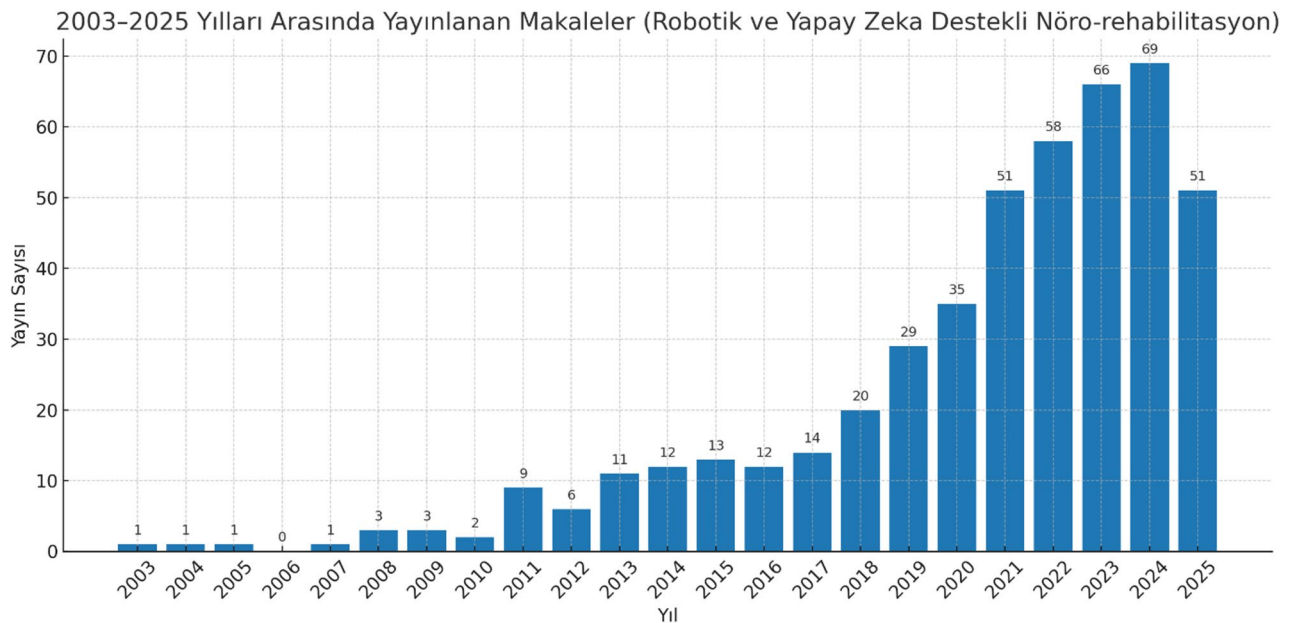


Fig. 2 Number of articles produced by year (Data for 2025 are partial and refer to records indexed up to 18 August 2025.)

Table 2 Journals located in zone 1 according to bradford's law and their publication frequencies

Order	So	Frequency	Cumulative frequency
1	Journal of Neuroengineering and Rehabilitation	28	28
2	Sensors	28	56
3	IEEE Transactions on Neural Systems and Rehabilitation Engineering	23	79
4	IEEE Robotics and Automation Letters	13	92
5	Robotica	12	104
6	Frontiers in Neuroscience	11	115
7	Frontiers in Neurorobotics	10	125
8	IEEE Access	10	135
9	Applied Sciences-Basel	8	143
10	IEEE Transactions on Biomedical Engineering	8	151
11	Robotics and Autonomous systems	7	158

Frequency (freq) The number of publications within that interval, *Cumulative frequency*: The total number of all broadcasts up to that interval

Sources' local impact

According to the analysis results, the Journal of Neuroengineering and Rehabilitation and Sensors emerged as the sources with the most publications on the subject. Both journals feature a total of 28 publications, with the Journal of Neuroengineering and Rehabilitation also having the highest h-index [15] and being the most cited source overall, with 1,740 citations. This journal has contributed to the field since 2009. IEEE Transactions on Neural Systems and Rehabilitation Engineering is also among the influential sources, with 23 publications and an h-index

of 11 and published its first work in this area in 2007. Frontiers in Neuroscience (11 publications, 895 citations) and IEEE Robotics and Automation Letters (13 publications, 297 citations) are also notable for their high number of publications and citations. When examining the m-index values, which measure annual publication performance, Sensors stands out with an m-index of 1.714, whereas IEEE Robotics and Automation Letters follows with an m-index of 1.143, indicating exceptional annual productivity. These journals, in particular, have drawn attention with their rapidly increasing publication volume after 2019. Other journals, such as Frontiers in Neurorobotics, IEEE Access, Robotica, and Applied Bionics and Biomechanics, also contribute to the field to a certain extent. IEEE Access and Frontiers in Neurorobotics, with m-index values of 0.857 and 1.000, respectively, can be considered new yet impactful journals (Table 3) (Fig. 5). Where 2025 values appear in source-level trends, they also reflect only the partial citation window up to 18 August 2025.

Authors and collaboration

Based on the analysed data, the author with the highest number of publications in the field of robotics and artificial intelligence-assisted neuro-rehabilitation was Aiguo Song ($n=8$). He is followed by Sheng Quan Xie, Robert Riener and Guozheng Xu (with 6 publications each). In addition, researchers such as Hongliu Yu, Nicolas Garcia-Aracil, and Shahid Hussain also stand out with five publications each. These findings reveal that certain researchers in this field demonstrate high productivity and play a central role in shaping the literature (Fig. 6).

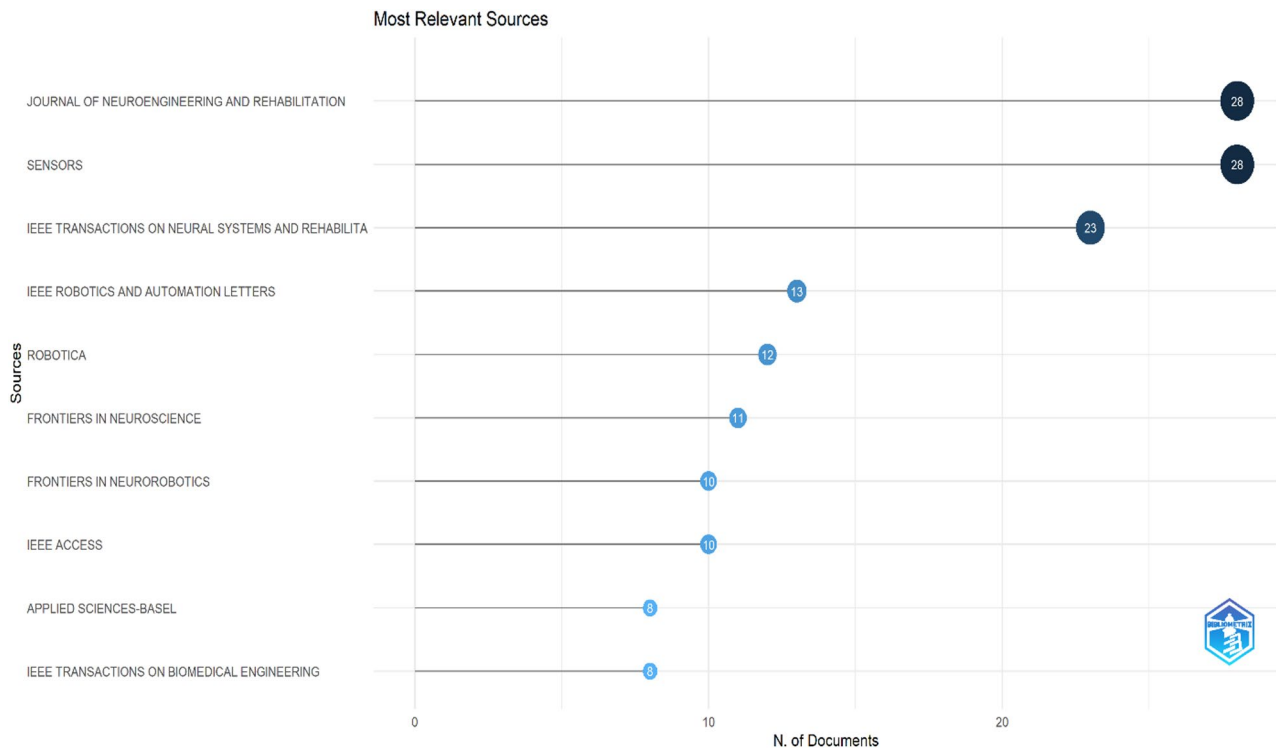


Fig. 3 The top 10 journals with the highest number of publications on robotic and artificial intelligence-assisted neurorehabilitation studies

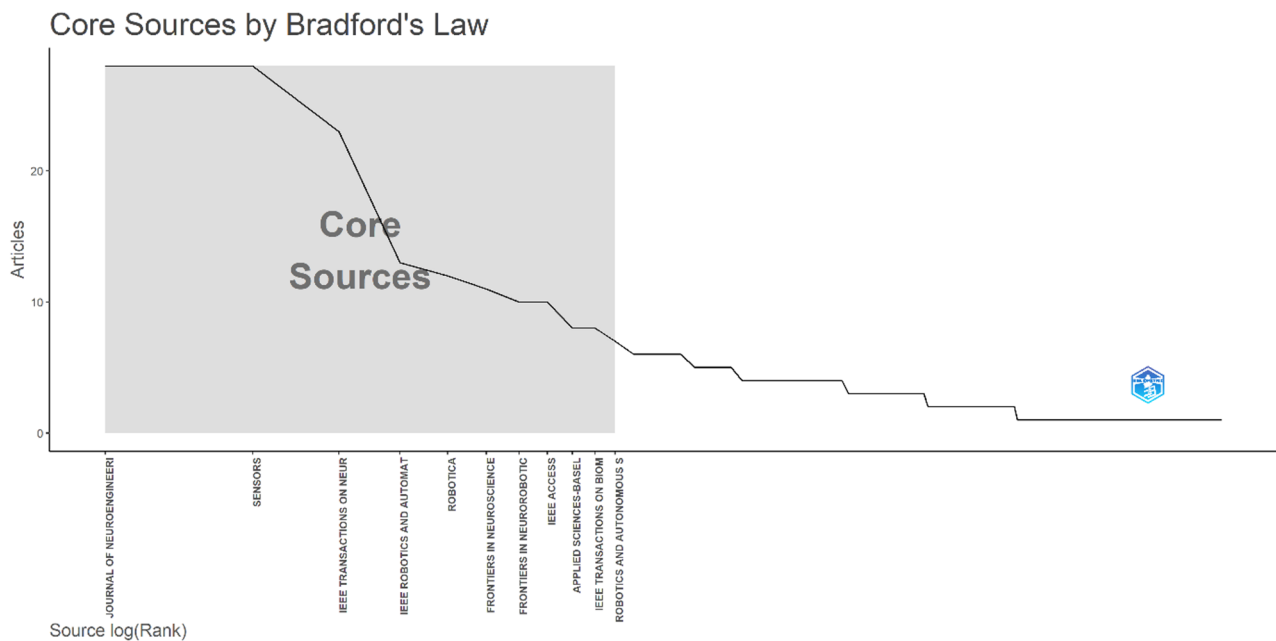


Fig. 4 Core sources identified according to Bradford's law

Among the authors with the most local citations, Marchal-Crespo L. (47) and Reinkensmeyer D.J. (46) were the most prominent. They are followed by names such as Krebs H.I., Dipietro L., Hogan N., Palazzolo J.J., and Volpe B.T. (in the 33–34 citation range) (Fig. 7).

When author productivity in the field of robotics and artificial intelligence-assisted neurorehabilitation was evaluated within the framework of Lotka's Law, the following pattern emerged: approximately 82% of the total number of authors produced only one publication. Of these, 10% produced two publications, 4% produced

Table 3 Top sources by citation impact indicators (h, g and m indices)

Source	h_index	g_index	m_index (h index / publication duration (years))	Total citations	Number of publications	The first publication year related to the subject
Journal of Neuroengineering and Rehabilitation	15	28	0.882	1740	28	2009
Sensors	12	21	1.714	462	28	2019
IEEE Transactions On Neural Systems and Rehabilitation Engineering	11	23	0.579	573	23	2007
Frontiers in Neuroscience	8	11	0.500	895	11	2010
IEEE Robotics and Automation Letters	8	13	1.143	297	13	2019
IEEE Transactions on Biomedical Engineering	8	8	0.364	655	8	2004
Frontiers in Neurorobotics	7	10	1.000	183	10	2019
IEEE Access	6	10	0.857	180	10	2019
Robotica	6	11	0.400	138	12	2011
Applied Bionics and Biomechanics	4	5	0.500	98	5	2018

h, g and m indices are citation impact indicators calculated from the Web of Science dataset and do not correspond to Journal Citation Reports impact factors

Sources' Production over Time

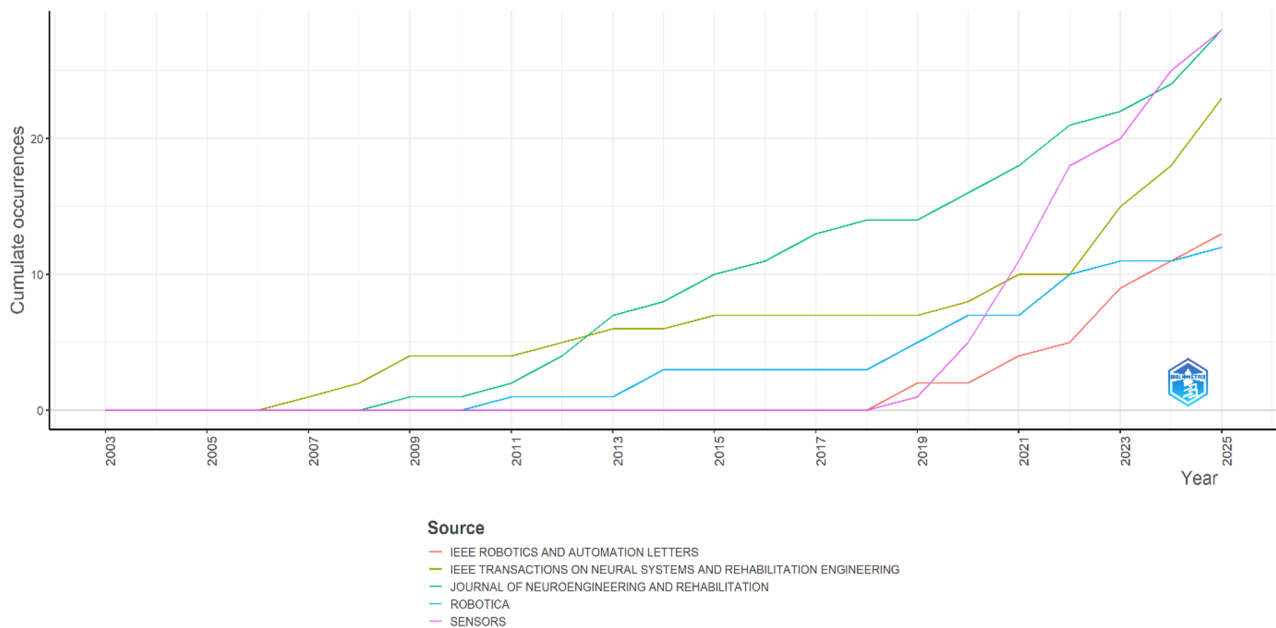


Fig. 5 Trend of citation impact indicators over the years for the top five journals with the highest citation impact (based on h, g and m indices) (Data for 2025 are partial and refer to records indexed up to 18 August 2025.)

three publications, 2% produced four publications, and less than 1% produced five or more (Fig. 8). The goodness-of-fit of author productivity to Lotka's law was assessed using a chi-square test, assuming the classical Lotka exponent $\alpha=2$. The observed author distribution significantly deviated from the theoretical Lotka distribution ($\chi^2 = 350.84$, $p < 0.001$), indicating that author productivity in this field does not strictly follow Lotka's law.

Most cited works

Among the analyzed documents, it was determined that the most cited study in the global context (across the entire database) is the article published in 2009 by

Marchal-Crespo L and colleagues, and this study has received a total of 841 citations [26]. In the local context (within the analysed document set), the most cited study is once again this same article, which received 46 citations. Furthermore, an examination of the cited references shows that this study ranks first, having been cited 46 times.

Reference publication year spectroscopy (RPYS)

When examining the citation distribution in the graph, it is evident that a significant portion of the sources used in robotics and AI-assisted neurorehabilitation belong to the post-2000 period. In particular, there has been a

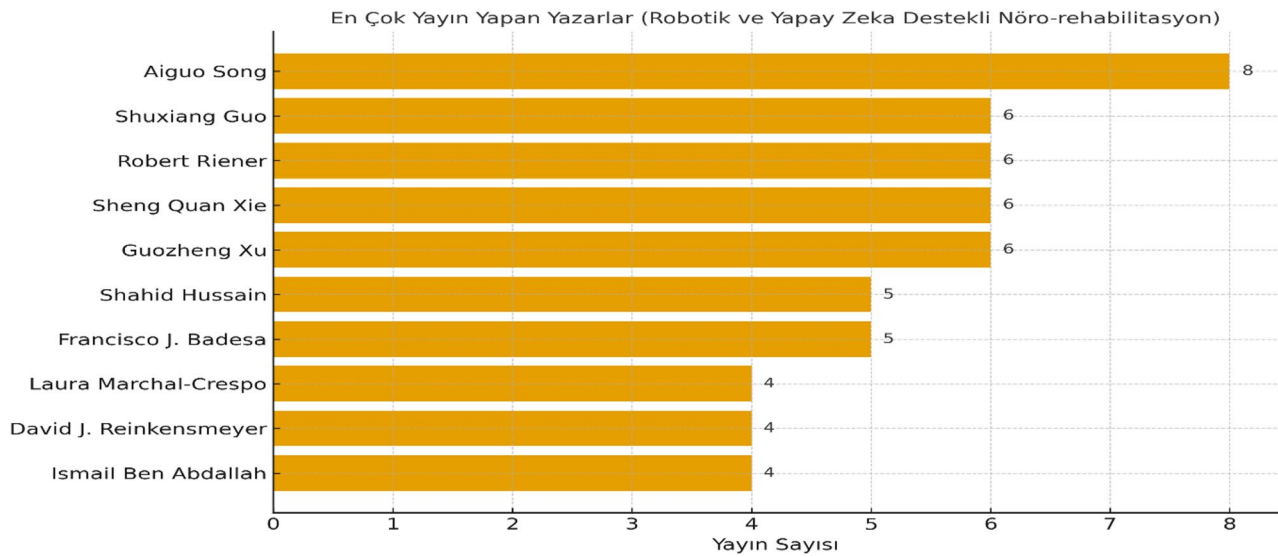


Fig. 6 Authors with the Most Publications and Their Number of Publications

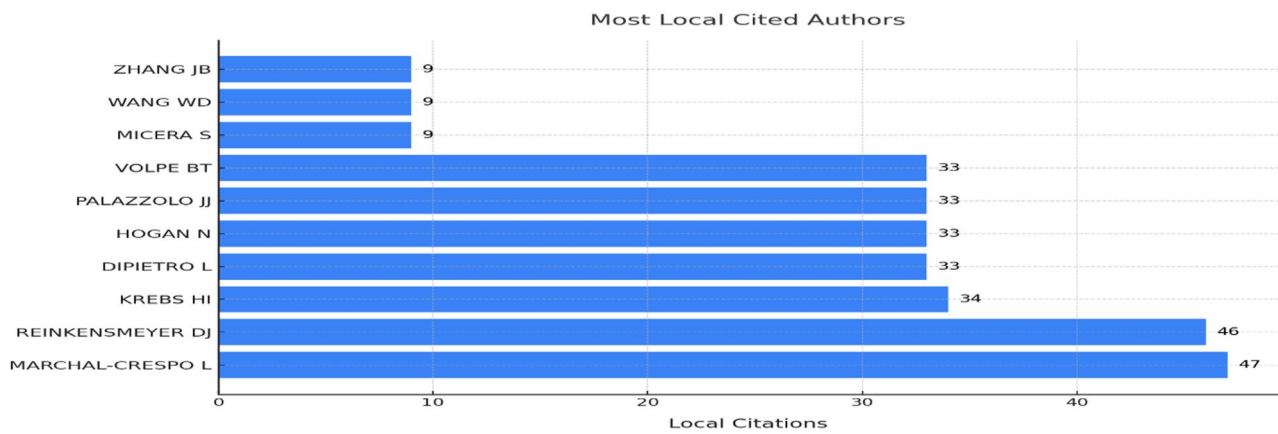


Fig. 7 Authors with the most citations and their citation counts

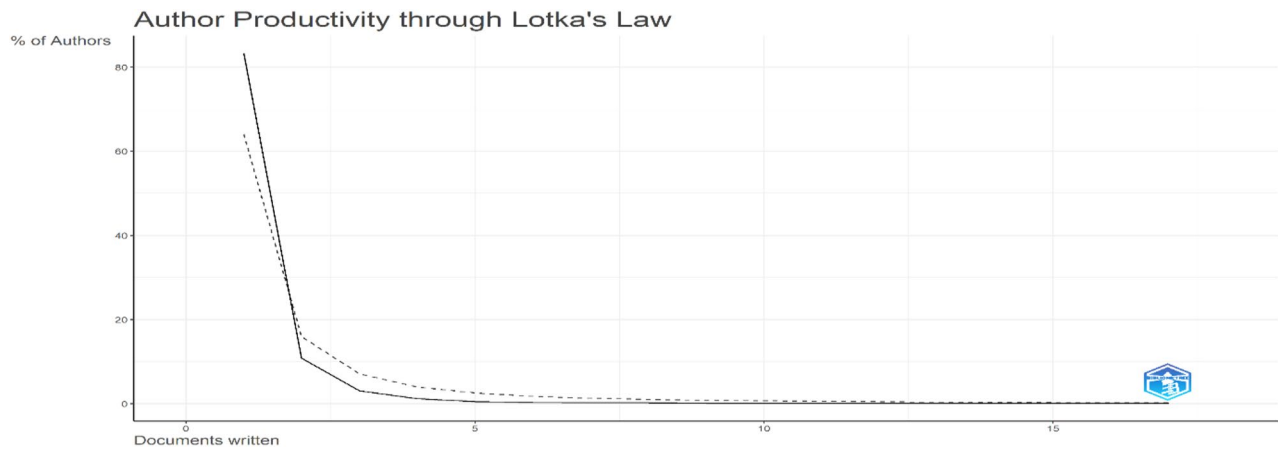


Fig. 8 Author productivity through Lotka's Law

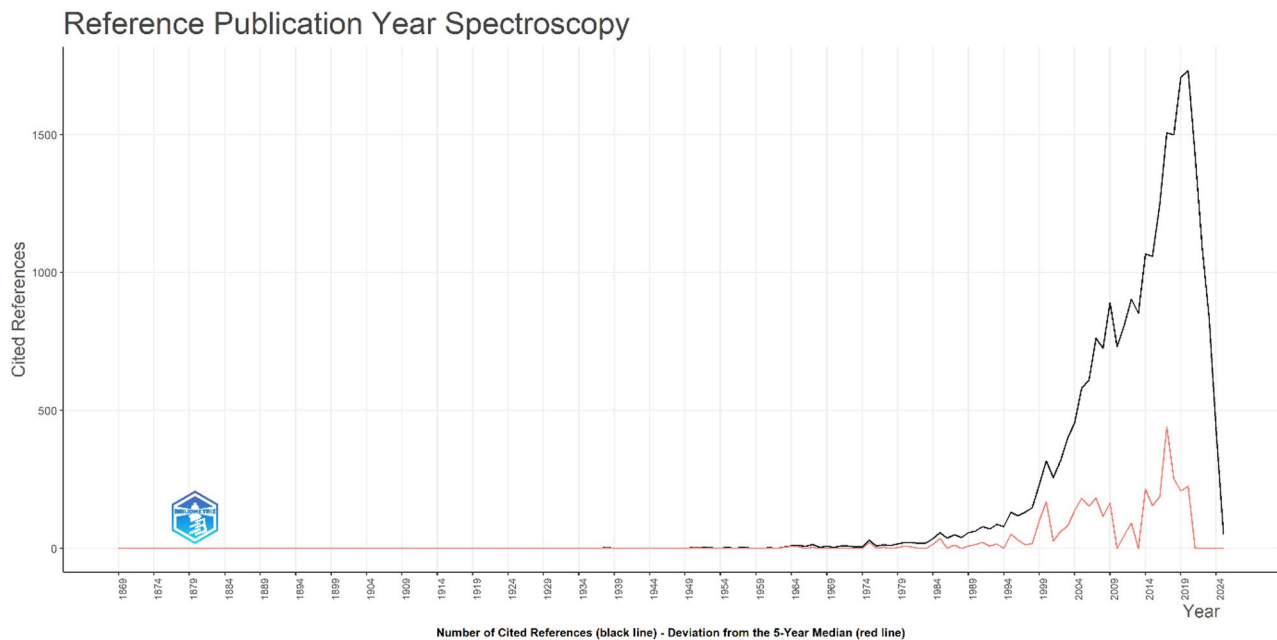


Fig. 9 Distribution of total citations by year (Data for 2025 are partial and refer to records indexed up to 18 August 2025.)

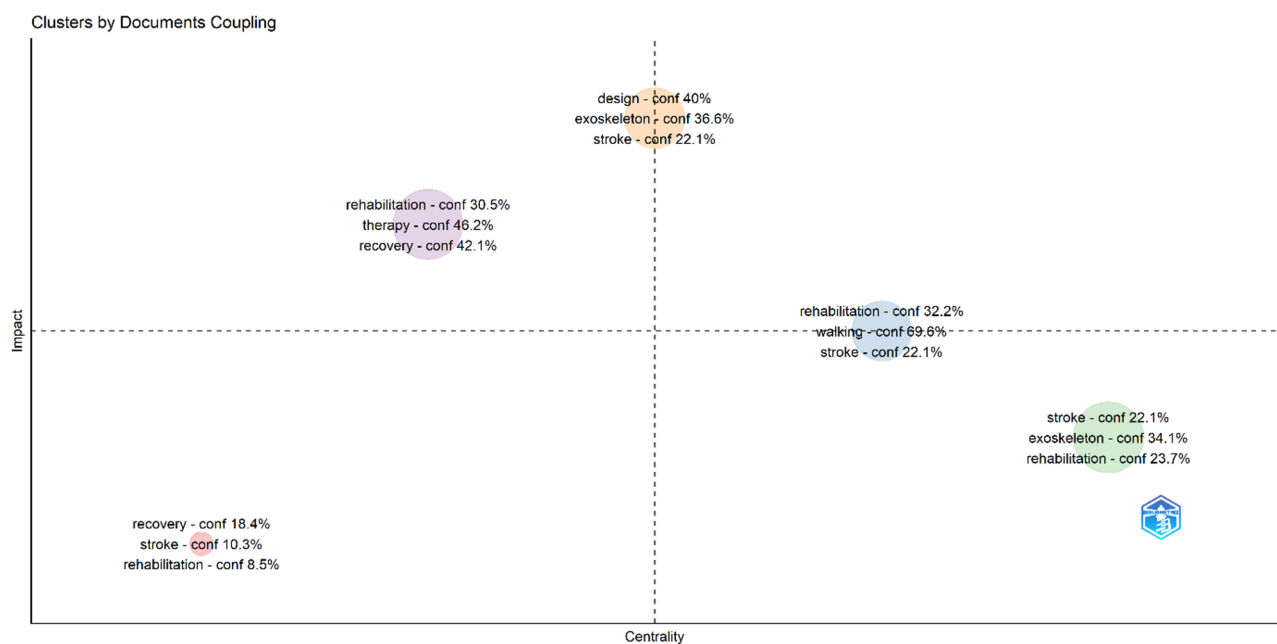


Fig. 10 Impact levels by reference clustering and subject headings

marked increase in the number of publications cited since 2010. The highest number of citations was for studies published in 2018, which can be considered a turning point in terms of the knowledge base of the field (Fig. 9). Because the WoS search was closed on 18 August 2025, the citation data for 2025 represent a partial year and should be interpreted with caution in longitudinal comparisons.

Clustering references

The graphic below visualises the clusters obtained by document coupling, which helps to elucidate the thematic structure of the literature (Fig. 10). For each cluster, we calculated the percentage of documents associated with the most frequent keywords, defined as: $(\text{number of documents in the cluster linked to a given keyword} / \text{total number of documents in that cluster}) \times 100$. In the first cluster, the dominant themes were rehabilitation,

Table 4 The 10 most frequently used keywords

Order	Words	Number	Appearance rate in publications (%)
1	Stroke	93	9
2	Rehabilitation	82	8
3	Design	58	6
4	Recovery	53	5
5	Exoskeleton	49	5
6	Therapy	46	4
7	Robot	38	4
8	System	37	4
9	Walking	36	4
10	Arm	29	3

therapy, and recovery, which were associated with 30.5%, 46.2%, and 42.1% of the documents in this cluster, respectively. The second cluster was characterised by design, exoskeleton, and stroke (40.0%, 36.6%, and 22.1% of documents in the cluster, respectively). In the third cluster, rehabilitation, walking, and stroke were the most salient topics (32.2%, 69.6%, and 22.1% of documents). In smaller clusters, recovery, stroke, and rehabilitation again appeared as relevant themes (18.4%, 10.3%, and 8.5% of documents, respectively), while in another minor group, stroke, exoskeleton, and rehabilitation were connected (22.1%, 34.1%, and 23.7% of documents).

Keywords plus analysis

WoS records contain two types of keywords: those provided by the author and Keywords +. Keywords Plus are generated by automatic algorithms from phrases found in

references but not in the titles or abstracts of the articles. In this study, analyses were conducted using Keywords Plus software.

According to the analysis results, the most frequently used keywords included “stroke” ($n=93$), “rehabilitation” ($n=82$), “design” ($n=58$), “recovery” ($n=53$), “exoskeleton” ($n=49$), and “therapy” ($n=46$). These keywords reflect the fundamental topics and multidisciplinary approaches that are frequently emphasised in the literature. The top 10 most frequently used keywords and word clouds are presented in a table and figure (Table 4; Fig. 11).

Thematic map analysis shows the distribution of research themes in the literature according to their centrality (relevance) and density (development) levels. Motor Themes (Core Research Areas): This cluster includes the concepts of stroke, rehabilitation, design, recovery, and exoskeleton. On the map, this cluster has a high centrality value, indicating that it plays a defining role in the general research structure of the field. The density levels were moderate, indicating that these themes are constantly developing and being supported by current studies. Niche Themes (Specialised and Narrow Areas): The themes of acquisition, Down syndrome, and infants emerged with relatively high-density values. This suggests that research in these areas is conducted in depth; however, because their centrality values are low, they have a limited connection to the broader field. Emerging or Declining Themes: The concepts of Kinect and health appeared with low centrality and low-density values. These indicators suggest that these areas either have emerging potential or are gradually losing their



Fig. 11 The most frequently used keyword cloud (with frequency of use decreasing from highest to lowest)

importance in literature (Fig. 12). It should be noted that pediatric-related terms such as “Down syndrome” and “infants” emerged as small, high-density but low-centrality clusters within the retrieved dataset and were not specified as a priori targets of the search strategy.

Geographical, institutional distribution and collaboration

Figure 12 shows that this topic is addressed at different levels across countries. Dark blue tones indicate countries where comprehensive studies have been conducted in this area, whereas light blue tones indicate countries with more limited research. Countries marked in gray indicate that there have not yet been any studies on the topic. The top ten countries in terms of country-level contributions were identified as follows: China (697 country-level contributions), USA (251), Italy (173), South Korea (97), Switzerland (74), Canada (59), India (59), Japan (56), the UK (54), and Spain (52) (Fig. 13). These values are based on a full counting approach, whereby each multi-country publication is counted once for every country listed in the authors’ affiliations; therefore, the sum of country counts exceeds the total number of documents Fig. 14.

The data in Table 5 show the network of international collaboration between countries. According to the findings, China is the main hub where international partnerships are concentrated. China has 11 joint publications with the United Kingdom, nine with Japan, nine with the USA, five with Australia, four with Canada, and four with Singapore. The USA is also a significant actor. It has

established partnerships with Italy [5], Canada [4], South Korea [4], Singapore [4] and Switzerland [4].

Discussion

Bibliometric analyses are an important research method that systematically reveals trends, collaborations, productivity, and the scientific impact level of academic literature in a particular field. A review of the literature shows that various bibliometric analysis studies have focused on neurorehabilitation. For example, a bibliometric analysis study was conducted on the use of new technologies in neurorehabilitation [13]. There is also a bibliometric analysis study on biomechanical research in stroke neurorehabilitation and post-stroke rehabilitation robotics in the literature [14, 15]. In addition, some bibliometric studies have been published in the field of robotics and artificial intelligence. For example, a study titled Robotic and Artificial Intelligence in Minimally Invasive Spine Surgery was conducted [16]. However, despite these related efforts, we did not identify any bibliometric analysis specifically designed to provide an integrated overview of robotics and artificial intelligence applications across multiple neurorehabilitation conditions within a single framework. This indicates that, although neighbouring areas have been examined, the joint robotics + AI, multi-condition landscape of neurorehabilitation has not yet been systematically evaluated.

The significant increase in publications in the field of robotics and artificial intelligence-assisted

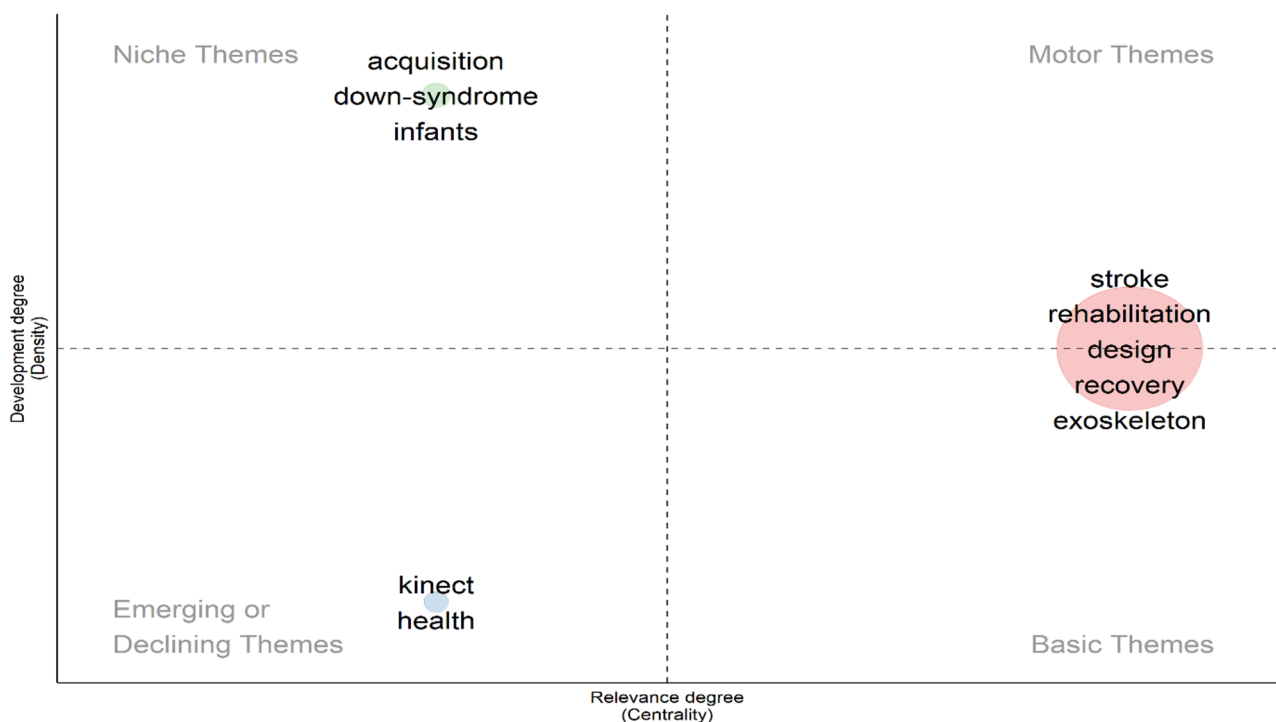


Fig. 12 Thematic map

Country Scientific Production

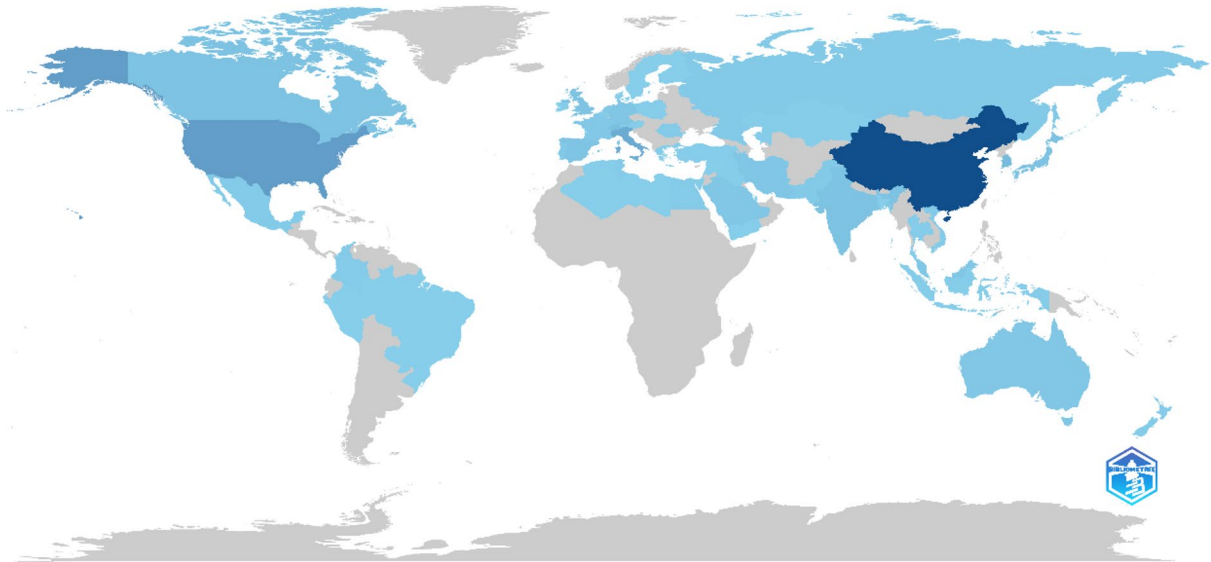


Fig. 13 Scientific production by country

Country Collaboration Map

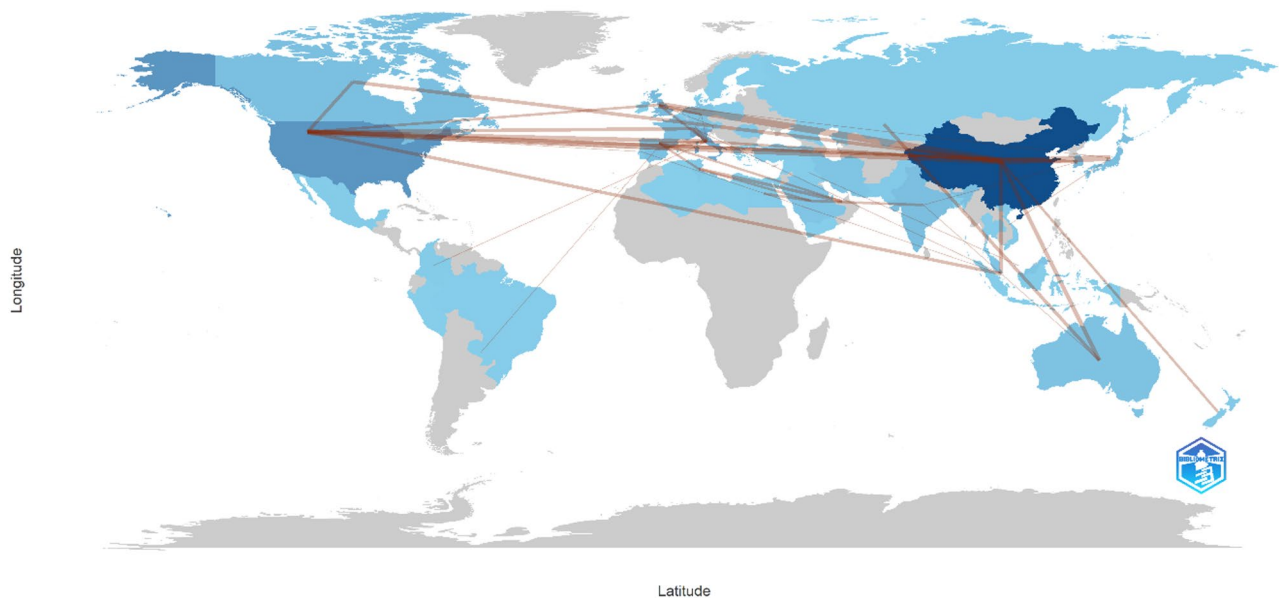


Fig. 14 Publication production by country and international cooperation map

neurorehabilitation between 2003 and 2025 (with an annual growth rate of 19.57%) indicates that clinical and technological developments are progressing in parallel. This rapid growth is not merely academic; it reflects a concerted effort to translate engineering breakthroughs into tangible clinical solutions for patients with neurological deficits. In particular, the surge in the number of publications after 2020 suggests that robotic exoskeletons

and AI-based algorithms are increasingly being applied in clinical rehabilitation. The bibliometric growth observed in this study reflects increasing scientific attention to robotic and AI-assisted neurorehabilitation; however, any inference regarding clinical effectiveness must be derived from disease- or device-specific clinical trials and systematic reviews rather than publication counts alone [27]. Additionally, the high average number of

Table 5 Number of co-publications between countries

Country	With	Frequency
China	United Kingdom	11
China	Japan	9
China	USA	9
Italy	Switzerland	6
China	Australia	5
USA	Italy	5
Australia	Kazakhstan	4
China	Canada	4
China	Singapore	4
Tunisia	U Arab Emirates	4
USA	Canada	4
USA	Korea	4
USA	Singapore	4
USA	Switzerland	4

citations in the studies (24.22) reveals that this research area has been strongly accepted by the scientific community and that the evidence generated is considered robust enough to inform and justify further clinical research and application. However, the high rate of author collaboration (32.05% international partnerships) indicates that an interdisciplinary approach is critical for the sustainability of future research [28]. In this context, the development of personalised rehabilitation protocols in clinical practice and the integration of artificial intelligence-assisted assessment systems should be the primary directions for future research.

This bibliometric analysis revealed that publications in the field of robotics and artificial intelligence-supported neurorehabilitation are concentrated in certain journals, and that the scientific impact of these journals varies. The *Journal of Neuroengineering and Rehabilitation*, which has the highest number of publications ($n=28$), stands out as one of the leading journals in the field, with a high h-index [15] and a total of 1,740 citations. Similarly, although the journal *Sensors* has the same number of publications ($n=28$), it has shown a rapid increase in impact in recent years, as indicated by its relatively high m-index (1.714), despite having a lower total number of citations ($n=462$). This demonstrates that the journal has recently become a preferred platform, particularly for integrating technological innovations and artificial intelligence-based applications in clinical neurorehabilitation. Additionally, *IEEE Transactions on Neural Systems and Rehabilitation Engineering* ($n=23$, 573 citations) maintained a strong position at the intersection of engineering and clinical sciences, while *Frontiers in Neuroscience* (895 citations, $n=11$) stood out with its high citation impact despite having fewer publications. Moreover, the increasing number of publications in journals such as *IEEE Robotics and Automation Letters* and *Frontiers in Neurorobotics* in recent years indicates that the field will

continue to focus on engineering innovations and the role of robotic systems in clinical applications. These findings demonstrate that multidisciplinary publication venues rapidly convey developments in the field to the scientific community, contributing to both clinical practice and new research directions. The leading journals' focus reveals the field's clinical ambitions. The prominence of *Journal of Neuroengineering and Rehabilitation* and *IEEE TNSRE* highlights the vital engineer-clinician collaboration, while the rise of *Sensors* underscores a shift towards data-driven, objective therapy assessment. This reflects a push to transform advanced technological concepts like exoskeletons into clinically viable, user-friendly tools for daily practice.

There is a distinct concentration of author productivity and impact distribution. In terms of the number of publications, Aiguo Song (8 publications), Guozheng Xu, Shuxiang Guo, and Robert Riener (6 publications) stand out; while in terms of local citation impact, names such as Marchal-Crespo L (47 citations) and Reinkensmeyer DJ (46 citations) are noteworthy. However, in line with Lotka's Law, it is revealed that the vast majority of authors have produced only 1–2 publications and that there are only a limited number of highly productive researchers. This shows that the development of the field is driven by a few pioneering researchers, while a broad group of researchers also contributes to it. In particular, the intense productivity and high citation numbers of leading figures reveal their critical role in shaping the scientific direction of robotics and AI-supported neuro-rehabilitation research.

The analysis results indicate that research in the field of robotic and artificial intelligence-assisted neurorehabilitation is concentrated around certain themes. In the word frequency analysis, stroke ($n=93$, 9%), rehabilitation ($n=82$, 8%), design ($n=58$, 6%), recovery ($n=53$, 5%), and exoskeleton ($n=49$, 5%) emerged as the most frequently used terms. This finding shows that the literature still focuses on stroke rehabilitation and developing exoskeleton-based devices. This clinical focus is logical given the high prevalence of stroke and the clear functional gains achievable with repetitive, task-specific training facilitated by robots. While this is consistent with the high prevalence of stroke in clinical practice, it also suggests that there is a research gap in areas such as Parkinson's disease, spinal cord injuries, and paediatric neurodevelopmental disorders. For instance, patients with spinal cord injuries could greatly benefit from AI-powered exoskeletons for gait training, but the complexity of their injury requires more personalized and adaptive algorithms, an area that needs expansion.

The results of document clustering indicate that clinically focused themes such as “rehabilitation–therapy–recovery” (46.2%; 42.1%) are strongly connected to

technology development-centered fields like “design–exoskeleton–stroke” (40%; 36.6%; 22.1%). This synergy is crucial for developing interventions that are not only technologically sophisticated but also grounded in the principles of motor learning and neuroplasticity, which are familiar to clinicians. This relationship reflects the increasing multidisciplinary collaboration between engineering and clinical sciences. However, the limited number of clinical validation studies raises questions about the applicability of newly developed devices in real-world settings. This gap represents a significant challenge for therapists seeking to adopt these technologies, as they require clear evidence of efficacy and practical implementation guidelines. In the future, randomised controlled trials and long-term follow-up data are expected to fill this gap.

Thematic analysis reveals that “stroke,” “rehabilitation,” “design,” “recovery,” and “exoskeleton” form the foundational core of the field, reflecting their enduring scientific and clinical relevance. In contrast, niche themes such as “acquisition,” “Down syndrome,” and “infants” appear as small and dense clusters; however, their emergence should be interpreted with caution, as they may reflect query sensitivity, over-inclusive search tokens, or keyword preprocessing effects rather than true thematic prominence. The decline of themes such as “Kinect” and “health” underscores the rapid evolution of technology, where older platforms give way to emerging innovations like AI-enhanced virtual reality, sensor integration, and telerehabilitation.

Beyond mapping the intellectual landscape, the thematic analysis offers strategic guidance for future work. Core themes should be strengthened through high-quality clinical trials to establish evidence-based protocols. Meanwhile, niche themes invite targeted research and funding to benefit underserved groups.

Keyword frequency further reinforces these insights: the dominance of “stroke” and “rehabilitation” confirms the central role of robotic and AI-assisted interventions in post-stroke care. Emphasis on “exoskeleton” and “walking” highlights a focus on lower-limb recovery and gait training, while terms like “arm” and “therapy” reflect strong research interest in upper-limb rehabilitation. Thus, while current applications are most advanced in stroke rehabilitation for both gait and upper-limb function, important gaps remain—particularly in pediatric and other niche neurological populations.

Country production rankings (China: 697; USA: 251; Italy: 173, etc.) clearly demonstrate that China showed the highest number of country-level contributions based on full counting methodology. This finding is consistent with Xu et al.’s 2024 study; in their analysis, China also ranked first with 688 articles, while the USA stood out with strong collaborative ties [29]. This demonstrates that

China’s high productivity is supported by its increasing effectiveness in both numerical volume and technological innovation. Furthermore, international collaboration data (for example, China–United Kingdom: 11, China–USA: 9) indicate that China is a key player in production and global scientific networks. Previous analyses of international scientific collaboration (for instance, Wang and Xu, 2014) also suggest that China’s scientific partnerships are largely established with major power centres, such as the USA, and that these collaborations have enhanced China’s international visibility [30]. This high contribution can be evaluated in connection with the strength of the technological infrastructure, rapid increase in research investments, and links with international academic networks [31]. From a futuristic perspective, if China continues this strategy, it could lead to rapid advances in next-generation robotic devices and artificial intelligence-based treatment protocols. This is also expected to contribute to technology transfer through collaborations with the United States, raise clinical standards to an international level, and increase interdisciplinary projects.

This study provides a comprehensive overview of scientific production trends in robotic and AI-assisted neurorehabilitation; however, several limitations should be noted. First, the analysis was restricted to specific databases (e.g., Web of Science) and English-language publications. As a result, potentially valuable studies published in other languages or indexed in different databases may have been excluded. In addition, since the study focused solely on bibliometric indicators, methodological quality, research designs, commonly used AI algorithms, robotic device types, and reported clinical outcomes were not examined in detail. While bibliometric analyses are powerful in reflecting trends and collaborations within the field, complementary approaches such as content analysis, systematic reviews, or meta-analyses are needed to generate stronger conclusions regarding clinical effectiveness and applicability. Finally, as the dataset covers the period up to 2025, it should be acknowledged that future publications may further update and expand the findings in this rapidly evolving field.

Limitations

First, the bibliometric dataset was extracted only from the WoS Core Collection. Therefore, relevant articles indexed exclusively in other databases such as Scopus or PubMed may not have been captured. Future bibliometric studies could expand the search to multiple databases and perform a harmonised de-duplication procedure to increase coverage. Moreover, as there is no universally accepted formal definition of robotics and AI applications in neurorehabilitation, our delineation of the field relied on the selected keyword strategy, which may not

fully capture all possible conceptualizations. In addition, because the search strategy was specifically centred on robotics- and AI-related terms, other emerging neuro-rehabilitation technologies (e.g., virtual reality, serious games, tele-rehabilitation) and certain clinical subpopulations (such as pediatric neurorehabilitation) may be underrepresented in the present dataset. Furthermore, the Conference Proceedings Citation Index (CPCI) and conference proceedings were not included in the search; given that robotics research is often first disseminated in conference venues, this journal-only strategy may underrepresent some emerging engineering-driven developments in robotics and AI for neurorehabilitation.

Conclusion

This bibliometric analysis reveals marked growth and transformation in the field of robotics- and artificial intelligence-assisted neurorehabilitation over the past 20 years. The annual increase in publications and robust international collaborations indicate that this subject is becoming an increasingly strategic area at both the scientific and clinical levels. Research has largely focused on stroke rehabilitation and robotic exoskeletons; however, there remain research gaps in clinical groups, such as those with Parkinson's disease, spinal cord injuries, and paediatric neurodevelopmental disorders. These trends, reflected in clinical practice, highlight the importance of individualised rehabilitation protocols and suggest that wearable sensors coupled with AI-based algorithms could play a significant role in real-time patient monitoring, providing therapists with objective data on home exercise compliance and functional recovery outside the clinic. In the future, hybrid approaches (for example, robotic systems supported by virtual reality, sensor integration, and brain-computer interfaces) will not only enhance clinical efficacy but also boost patient motivation. Future projections indicate that the field will evolve toward more standardised clinical protocols that are readily adoptable by rehabilitation centers, long-term randomised controlled trials that measure quality-of-life outcomes in addition to functional gains, and tele-rehabilitation solutions that bridge the gap between hospital and home, ensuring continuity of care. Moreover, the development of cost-effective technologies for low- and middle-income countries presents a critical opportunity to expand research on a global scale. In conclusion, robotics- and artificial intelligence-assisted neurorehabilitation is expected to gain a stronger scientific backbone through multidisciplinary collaborations and be integrated into clinical practice more rapidly in the coming years. Future research should aim to integrate bibliometric analyses with content analysis, systematic reviews, and meta-analyses. Such an approach would move beyond quantifying publication trends to also identify which algorithms, devices, and

clinical outcomes are most effective, thereby offering a more comprehensive and clinically meaningful understanding of the field.

Abbreviations

AI	Artificial Intelligence
WoS	Web of Science
m-index	h-index per year (publication duration adjusted)
h-index	Hirsch index
g-index	Egghe's g-index

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B.T.: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization. C.T.: Conceptualization, Methodology, Software, Investigation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization, Supervision.

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Author details

¹Vocational School of Health Services, Muş Alparslan University, Muş 49250, Turkey

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