Academic Review and Perspectives on Robotic Exoskeletons

Guanjun Bao, Lufeng Pan, Hui Fang, Xinyu Wu, Haoyong Yu, Shibo Cai, Bingqing Yu, and Yuehua Wan

***Abstract*—Since the first robotic exoskeleton was developed in 1960, this research field has attracted much interest from both the academic and industrial communities resulting in scientific publications, prototype developments and commercialized products. In this article, to document the progress in and current status of this field, we performed a bibliometric analysis. This analysis evaluated the publications in the field of robotic exoskeletons from 1990 to July 2019 that were retrieved from the Science Citation Index Expanded database. The bibliometric analyses were presented in terms of author keywords, year, country, institution, journal, author, and the citation. Results show that currently the United States has taken the leading position in this field and has built the largest collaborative network with other countries. The Massachusetts Institute of Technology (MIT) made the greatest contribution to the field of robotic exoskeleton investigations in terms of the number of publications, average citations per publication and the h-index. In addition, the Journal of NeuroEngineering and Rehabilitation ranks first among the top 20 academic journals in terms of the number of publications related to robotic exoskeletons during the period investigated. Author keyword analysis indicates that most research has focused on rehabilitation robotics. Biomedical engineering, rehabilitation and the neurosciences are the most common disciplines conducting research in this area according to the Web of Science (WoS). Our study comprehensively assesses the current research status and collaboration network of robotic exoskeletons, thus helping researchers steer their projects or locate potential collaborators.**

***Index Terms*—Exoskeletons, rehabilitation robotics, human-robot interaction, bibliometrics.**

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I. INTRODUCTION

ACCORDING to the survey of Downey [1] and Heuermann and Kurtz [2], the concept of "exoskeleton" was originally used as a biological term to describe the structure that provides support and protection for soft organs inside animal body. The first exoskeleton for humans was a passive device that assisted people to walk and jump [3], [4], developed by Nicholas Yagin in 1890. However, the term "exoskeleton" was not endowed with its current meaning in robotic field until 1960, when the US Armed Forces and General Electric invented the first powered exoskeleton, Hardiman, with a strength augmentation ratio of 25 for human limbs [5], [6]. As such, the term "exoskeleton" can be employed to describe wearable robotic devices that are active and powered. Thus, those non-robotic exoskeletons and passive devices [7], [8] will not be discussed in this paper. Exoskeletons are not only used to enhance the performance of an able-bodied wearer, but also act as assistive devices and prostheses. Currently, exoskeletons find their way into various fields including but not limited to medical applications [9]–[17], military equipment [5], [18] and industrial practices [7], [19], [20]. Moreover, multiple disciplines, such as mechanics, sensing, control, data science and mobile computing, have been integrated to develop robotic exoskeletons [21]. Based on supporting the different parts of the human body, exoskeletons can be further classified as the upper extremity exoskeleton [9]–[11], the lower extremity exoskeleton [22]–[25], the full body exoskeleton [5], [20], as well as the specific joints supporting exoskeleton [26]–[28].

Driven by the increasing social demand and attention to robotic exoskeletons, scientists and engineers have made great progress in the field. Indeed, a number of review articles summarizing recent progress have been published [11], [23], [24], [29], which highlighted the technical problems in mechanical design, control, and sensing [30]–[35], and discussed the challenges and potential future developments [4], [10], [21], [36], [37]. Yet, the retrieved review articles only focused on specific research branches, such as lower limb [4], [21]–[25], [30], [37], [38] and upper limb [10]–[13], [33]. In general, all the cited reviews were organized in terms of technical content [38]–[41]. According to our literature analysis, there was no paper covering the exoskeleton field in its entirety. Therefore, to fill this deficiency, we performed a bibliometric analysis.

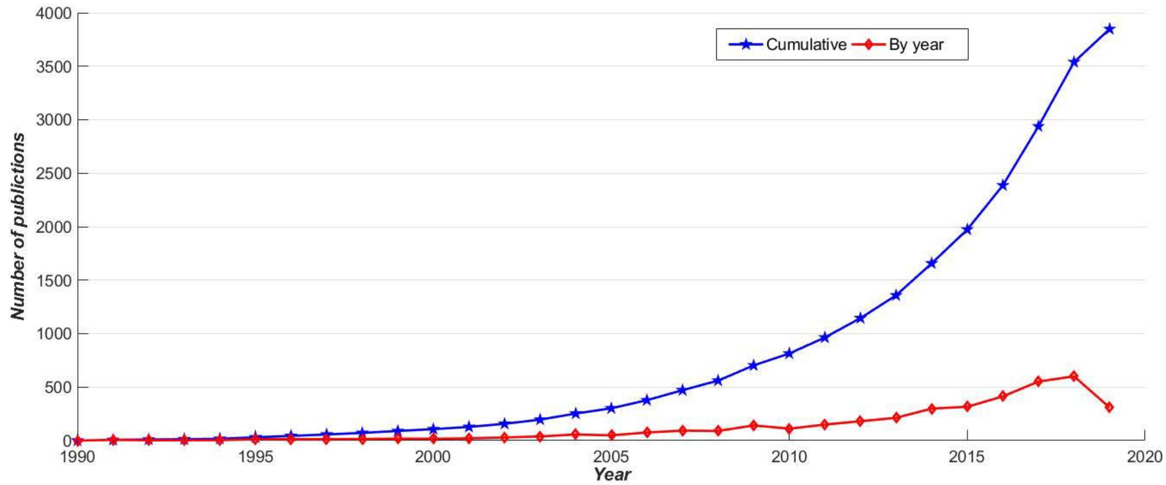

Fig. 1. Yearly and cumulative number of published articles related to robotic exoskeletons.

Bibliometric analysis is considered an effective method for analyzing scientific publications. Such analyses can document the developmental history of the target topic and find the hotspots in research; they can also highlight the distribution of active research countries, institutions, authors, collaborative relations, top journals for publications, leading influential articles and research trends. Bibliometric analysis has been adopted in a variety of disciplines, including chemistry [42], economics [43], computer science [44], management [45], [46], education [47], medicine [48], energy [49], [50] and robotics [51], [52]. However, to our knowledge, bibliometric analysis has not been performed on research involving robotic exoskeletons. Thus, our study represents the first analysis to assess this research field using this method. Our goal is to provide a general overview of this research area with respect to the following aspects: (1) an historical map of the topic; (2) the popular author keywords [53] and research areas; (3) the main contributors in terms of authors, institutes and countries; (4) collaboration patterns between countries and institutions; (5) the most influential journals; and, (6) the most highly cited articles.

II. Methodology and Data Source

In this paper, literature related to "robotic exoskeletons" published from 1990 to July 2019 was retrieved through the Science Citation Index-Expanded (SCI) and Social Science Citation Index (SSCI) on July 26, 2019 with three retrieval formulas: Formula 1: "exoskelet* robot*" or "robot* exoskelet*" or "rehabilitat* robot*" or "robot* rehabilitat*" or "exoskelet* rehabilitat* robot*" or "therapy robot*" or "robot* therapy*" or "mot* rehabilitat*" or "rehabilitat* mot*" or "hand exoskelet*" or "finger exoskelet*" or "robot* for therapy" or "train* robot*" or "mot* robot*" or "assistant robot*" or "wearable robot*" or "wearable exoskeleton robot*" or "exoskeleton suit" or "man machine integrat*" or "man comput* integrat*" or "wearable resistive robot*" or "robot* assistance"; Formula 2: (exoskeleton* or exoskeletal) and robot*; and Formula 3: (exoskeleton* or exoskeletal) not robot*. Searching the SCI and SSCI, the retrieval was performed with Formula 1 and Formula 2 in "or" relationship, defining the document type as an article or review in the field of topic; 19 medical research areas that have no obvious link to robotic exoskeletons were excluded, such as surgery, urology, nephrology, obstetrics, gynecology, cardiology, cardiovascular systems, peripheral vascular disease and oncology. Using this search, 3519 items were collected. Additionally, 346 items were added to the list with Formula 3, defining the document type as an article associated with or review of the topic, using the index SCI and SSCI, and refining the publications only in the research area of engineering biomedical, neurosciences and robotics.

As a result, after subtracting 7 double-counted publications, 3848 articles and reviews were collected from the InCites data set including WoS content indexed on July 26, 2019. The full records of the 3848 publications including title, abstract, author keywords, institutions, WoS research areas and authors were exported in text format and then imported into the Derwent Data Analyzer (DDA), an analytical tool for refining and reporting search results from scientific literature databases. All the data in the following tables were from the original records collected from WoS, whereas the bubble charts and collaboration maps were generated by DDA. The impact factor (IF) for each journal was derived from the 2018 Journal Citation Reports. Since the WoS "topic" searching was applied to the title, abstract, and keyword fields, and the document type was set as article and review, some other related publications may not have been detected.

III. Results and Discussions

A. Publication Numbers, Keyword Usage and Leading Countries

The emerging trend of publications on robotic exoskeletons is shown in Fig. 1. The red line, with points denoted by rhombi, shows the trend of annual number of publications from 1990 to July 2019, whereas the blue line, with points denoted by stars, indicates the cumulative number of publications, which increased exponentially. During the initial research period from 1990 to 2002, the total number of publications for each year was relatively stable and

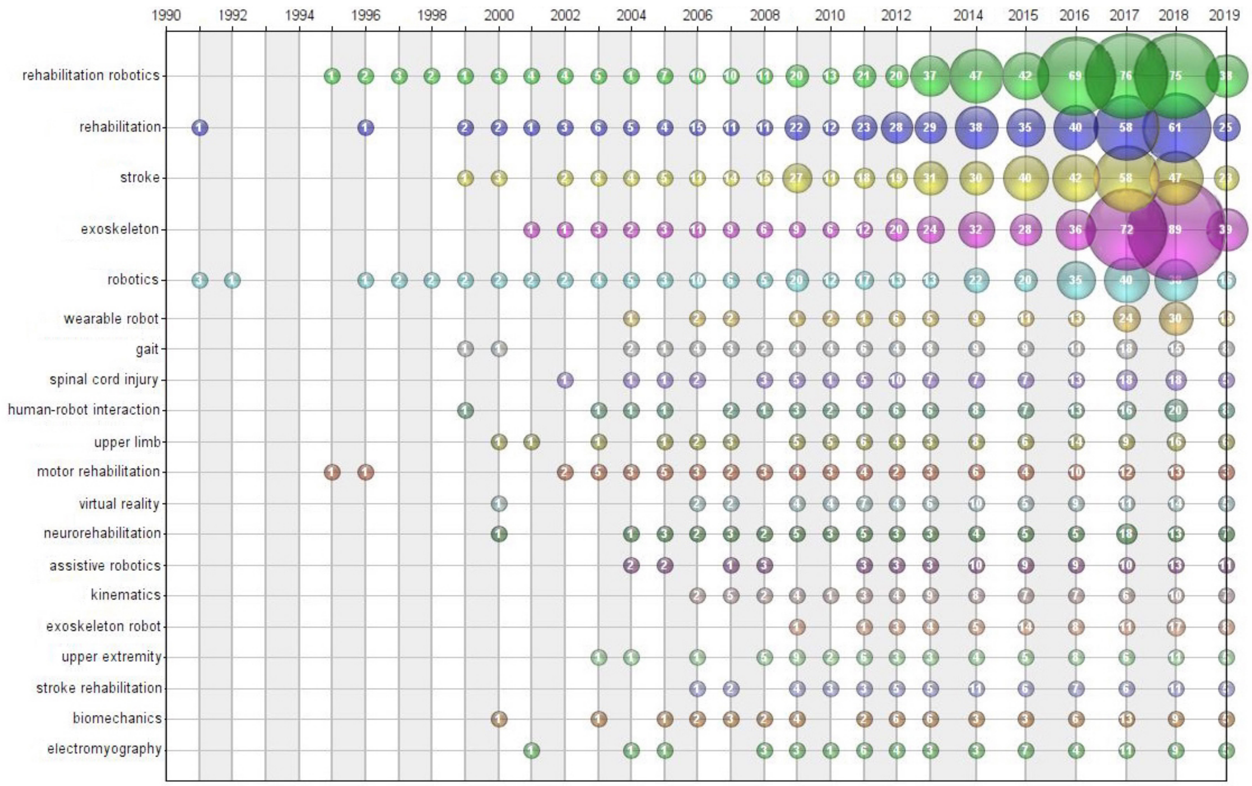

Fig. 2. Bubble chart of top 20 author keywords by year. The size of the bubble represents the number of publications employing that keyword.

was less than 30. This relatively "latent" period could be ascribed to the limitations of required technologies including sensing and control and materials. However, in the next decade, with demands both in the military [54] and in industry [55] as well as the development of supporting technologies [56]–[58], the average number of publications per year increased to 99, indicating that exoskeleton research had entered a stage of vigorous growth [59]. Because of the demand for better medical quality and assistive products, interest in exoskeletons for medical applications increased in 2013, resulting in a surge in publications. Since then, the average increasing rate of yearly publications has reached 22.83%, and the publications in the past seven years contributed over 70 % of the total. The sudden drop at the right end of red line is because the results only covered seven months of 2019.

In the initial research into exoskeletons, authors generally preferred the key words "robotics" [60] and "rehabilitation [61]. When the research on exoskeletons became more specialized, the new keywords "motor rehabilitation" [62] and "rehabilitation robotics" [63] gradually appeared. And, even more specialized keywords, such as "stroke" [64], "gait" [65], "human-robot interaction [66], [67]," "upper limb," "virtual reality" [68] and "neurorehabilitation" [64], appeared in publications. The keyword "exoskeleton" first appeared in 2001 after exoskeletons had been investigated for over half a century and was widely adopted in scientific papers in 2006 and thereafter, as shown in Fig. 2. It is notable that "rehabilitation robotics," "exoskeleton," "rehabilitation," "stroke" and "robotics" became the most popular five keywords in recent years. This trend shows that exoskeleton research is increasingly integrated in the health care field. Another interesting phenomenon is that in the past two years, the number of publications using the keywords "wearable robot [69], [70]," "gait [71]–[73]," "human-robot interaction [74], [75]," and "spinal cord injury [76]–[78]" increased dramatically. This usage could indicate emerging hot topics in this research area. To illustrate, wearable robots mainly emphasize comfort without causing any undesired pressure and pain to users. In order to overcome the intrinsic disadvantages of the traditional rigid materials, soft material technology led to the development of "soft" exoskeletons. Such a soft exoskeleton is lighter, safer and more compatible with the human body [79]–[82]. Neurologic injuries, such as spinal cord injury and stroke, increased the demand for rehabilitation exoskeletons, and gait detection can provide a continuous locomotion phase for the calibration of exoskeleton devices. Finally, human-robot interaction based on the technology of human motion and consciousness detection is a current research challenge [32].

The top 20 countries or regions in terms of the number of publications on robotic exoskeletons are listed in Table I. Articles originated from England, Scotland, Northern Ireland, and Wales were grouped under the United Kingdom heading. Although Taiwan is a part of China, it is listed separately. Data analysis shows that the United States is the most productive country with a total of 1112 publications since 1990, followed by China (564) and Italy (440). Although we cannot attribute this productivity to particular causes, these countries have launched several research initiatives or programs such as the

TABLE I
THE TOP 20 MOST PRODUCTIVE COUNTRIES OR REGIONS IN ROBOTIC EXOSKELETONS FIELD DURING 1990–2019

Rank	Country	TA	TC	ACPP	TPCP%
1	United States	1112	34117	30.68	31.56
2	China	564	4435	7.86	34.04
3	Italy	440	8884	20.19	43.86
4	Germany	278	7355	26.46	48.92
5	Japan	249	3838	15.41	32.53
6	Canada	242	3925	16.22	37.60
7	South Korea	220	2562	11.65	21.82
8	UK	219	4046	18.47	68.12
9	Spain	214	3073	14.36	45.33
10	Switzerland	172	5351	31.11	61.05
11	France	143	1968	13.76	45.45
12	Netherlands	115	3875	33.70	58.26
13	Australia	88	1467	16.67	65.91
14	Brazil	86	701	8.15	62.79
15	Singapore	79	1180	14.94s	68.35
16	Belgium	77	1529	19.86	49.35
17	New Zealand	64	1340	20.94	56.25
18	Taiwan	51	545	10.69	17.65
19	Turkey	51	522	10.24	27.45
20	Mexico	49	324	6.61	44.90

TA, total articles; TC, total citations; ACPP, average citations per publication; TPCP, the percentage of cooperative publication.

Exoskeleton for Human Performance Augmentation sponsored by DARPA.

It is worth noting that a significant proportion (>48%) of the publications from the top 20 countries or regions are internationally recognized papers, especially for the United Kingdom (68.12%) and Singapore (68.35%), implying that robotic exoskeleton research from these 20 countries has drawn global attention. Scientists and engineers from all over the world are exchanging experiences and collaborating. Surprisingly, although the United States plays a leading role, its international collaboration rate is relatively low. This is mainly attributed to the domestic collaboration among the large number of research institutes within the country, which may reduce international collaboration. In addition, despite the high number of publications from China (second with 564 papers), the average citations per publication (ACPP) is quite low, only 7.86. As the most populous country in the world, it is not surprising that China would have the highest number of total publications. However, high domestic cooperation also weakens international cooperation, consequently reducing the academic impact possibly resulting in a low citation rate. Other reasons such as language barriers, difficulty in accessing publications, as well as the scope and quality of the research, cannot be excluded as factors reducing the citation rate.

The collaboration map between the top 20 productive countries or regions is shown in Fig. 3. The sizes of nodes are proportional to the number of publications of each country or region. The lines represent the collaboration between the connected countries or regions, and the thickness indicates the intensity of cooperation. The United States is the most active country with many collaborations with China, Italy, UK, Germany, Canada and South Korea. This is likely because the United States is the leading country in the most cutting-edge technologies in this field, thus attracting global scholars to pursue investigations via cooperation. Italy ranks second, followed by the United Kingdom and Germany. The main reason for the latter two countries may be that the European visa policy facilitates research institutes in Europe to recruit researchers from other countries within the Europe Union. And, the European research council provides many cooperation opportunities for researchers from different countries within Europe.

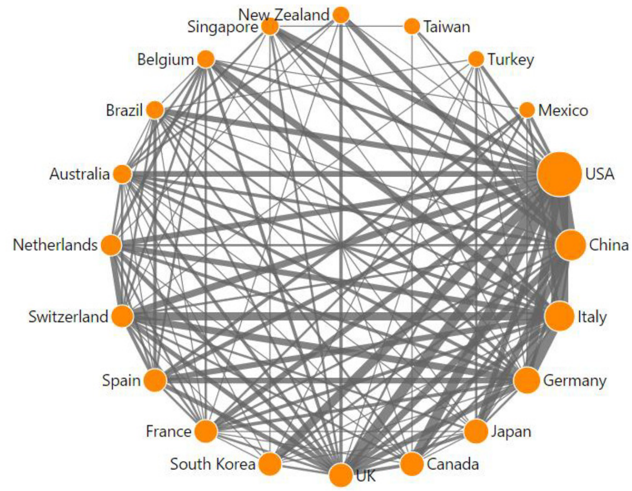

Fig. 3. Collaboration matrix map among the top 20 productive countries.

B. Contribution of Leading Institutions

The top 20 productive institutions in robotic exoskeleton research are listed in Table II, along with their total number of publications, citations, and h-index. All of them are from the top 10 most productive countries, and almost half are from the United States. The Massachusetts Institute of Technology (MIT) leads the group with the most publications, followed by Scuola Superiore Sant'Anna and Harvard University. Also, MIT has the highest h-index at 40. As for the ACPP, MIT and University of Twente lead the list with 62.77 and 57.09, respectively. These institutions have played a significant role in developing and promoting robotic exoskeletal research. By contrast, the four Chinese institutions in the top 20 have relatively low ACPP results. Notably, Harbin Institute of Technology in China ranked 6^{th} in total publications, while the ACPP is only 3.66. Compared with other productive counterparts, this indicates that Chinese institutions may need to improve the quality and/or accessibility of their research in order to enhance their global impact.

The collaboration network among the top 20 institutions is shown in Fig. 4 in the form of a DDA cluster map, which can help researchers find more opportunities to cooperate with other institutions. In this map, the number in parentheses next to each name represents the total number of publications from the corresponding institution. The numbers on the intersection nodes gives the numbers of collaborative publications with other institutions. Other data on the individual nodes gives the numbers of papers resulting from work within the institute or collaborating with other institutions outside the top 20.

TABLE II
THE PUBLICATIONS OF TOP 20 MOST PRODUCTIVE INSTITUTIONS DURING THE PERIOD 1990–2019

Rank	Institutions	TA	TC	ACPP	h-Index	Country
1	Massachusetts Institute of Technology	92	5775	62.77	40	United States
2	Scuola Superiore Sant'Anna	83	2387	28.76	24	Italy
3	Harvard University	71	3756	52.90	30	United States
4	Northwestern University	70	1723	24.64	23	United States
5	University of Auckland	53	1164	21.96	19	New Zealand
6	University of Michigan	48	2141	4460	23	United States
7	Harbin Institute of Technology	47	172	3.66	6	China
8	Rehabilitation Institute of Chicago	46	1605	34.89	20	United States
9	University of Twente	46	2626	57.09	22	Netherlands
10	University of Zurich	45	1716	38.13	20	Switzerland
11	Chinese Academy of Sciences	45	467	10.38	10	China
12	ETH Zurich	43	1789	41.60	20	Switzerland
13	Delft University of Technology	41	1388	33.85	18	Netherlands
14	Ecole Polytechnique Federale de Lausanne	38	1019	26.82	16	Switzerland
15	Huazhong University of Science & Technology	38	463	12.18	11	China
16	Korea Advanced Institute of Science & Technology	37	730	19.73	12	South Korea
17	Arizona State University	37	486	13.14	12	United States
18	Shanghai Jiao Tong University	36	381	10.58	9	China
19	Nanyang Technology University	36	348	9.67	11	Singapore
20	University System of Maryland	35	1380	39.43	17	United States

TA, total articles; TC, total citations; ACPP, average citations per publication.

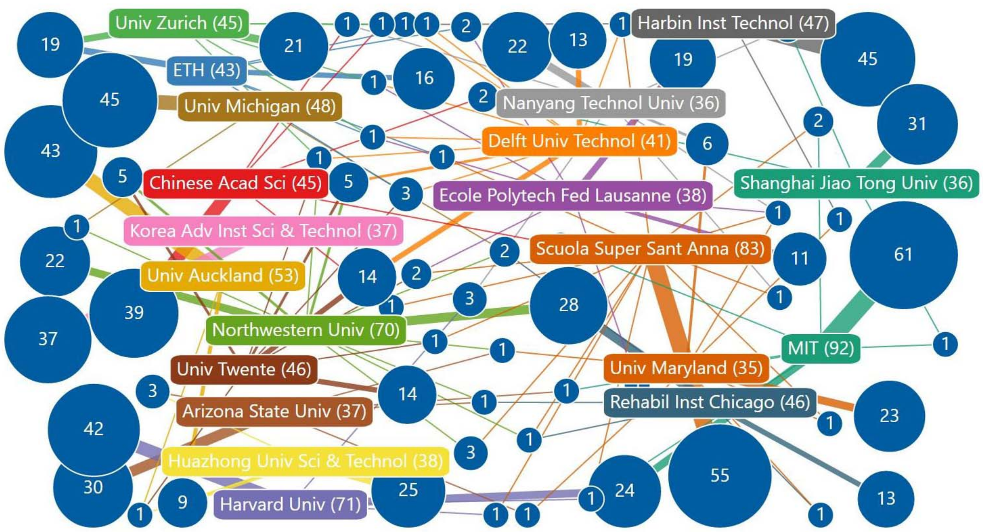

Fig. 4. DDA cluster map of collaborations between the top 20 institutions.

As shown in Fig. 4, MIT, Scuola Superiore Sant'Anna, and Northwestern University have a large collaborative network, whereas University of Michigan, Harbin Institute of Technology, and University of California Irvine work mostly independently within this field as seen from their weak exterior collaborative networks. Notably, institutions from Switzerland including Ecole Polytechnique Federale de Lausanne, ETH Zurich, and University of Zurich have strong domestic cooperation. Furthermore, consistent with the result in Fig. 3, the collaborative publications between European institutions are also numerous.

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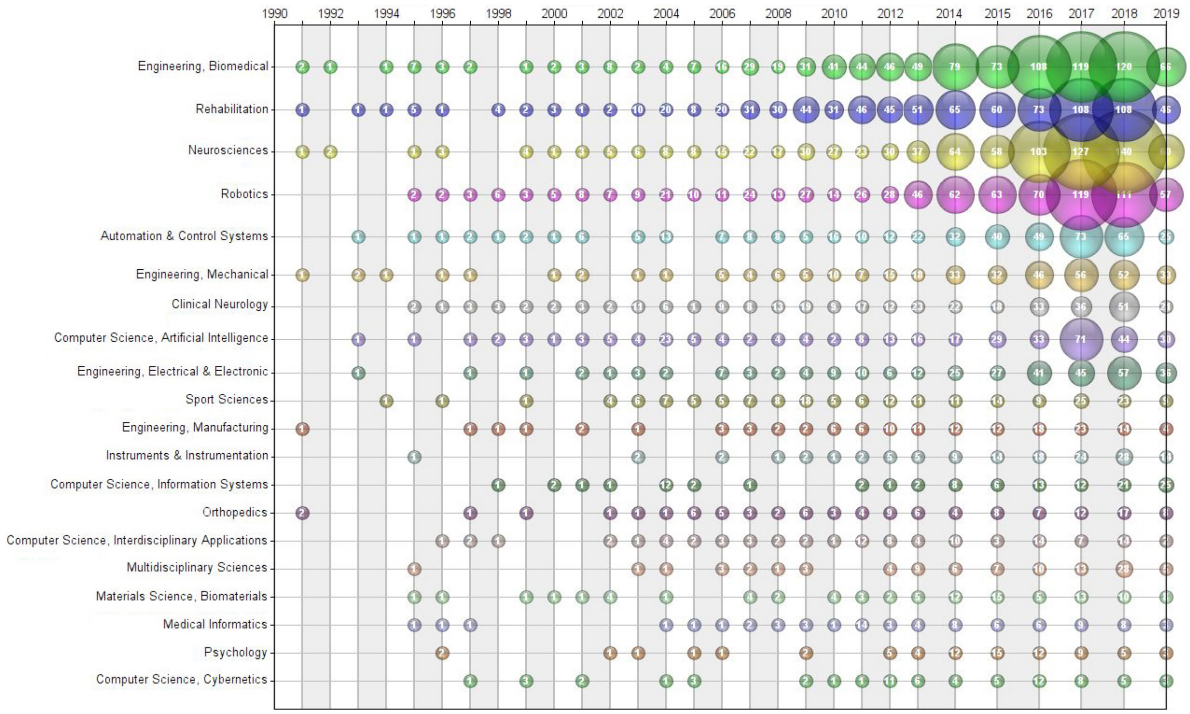

Fig. 5. Bubble chart of top 20 WoS research areas by year.

C. Contribution of Leading Research Areas

Exoskeletal research is a popular developing multidisciplinary field [33], [38]. This is supported by publications distributed in 81 WoS research areas. Table III illustrates the top 20 WoS research areas ranked by the number of publications related to robotic exoskeletons. The "Engineering, Biomedical" area dominates the research area rankings with 883 publications, followed by the "Rehabilitation," "Neurosciences," "Robotics" and "Automation & Control Systems" research areas; these are the main scientific areas that put special emphasis on robotic exoskeletal research. These top five research areas also rank highest in the h-index. The "Sport Sciences" and "Engineering, Manufacturing" have the highest ACPP, at 30.06 and 29.00, respectively. Thus, this literature analysis reveals that researchers from medical and engineering areas cooperated with each other in the course of exoskeletal research [83]–[87]. In addition, neuroscientists are also contributing to our understanding of human consciousness and motion, thus providing knowledge bases for engineers to develop the technology of human-machine integration [64], [88]–[91]. In addition, kinesiology reveals the relationship between physical exercise and the human organism [92]–[95], contributing to kinematic investigations and greatly promoting the development of exoskeletons.

The number of annual publications in the top 20 research areas are shown in Fig.5 in the form of a bubble chart. About ten years ago, the annual publication numbers in the research areas of "Engineering, Biomedical" and "Rehabilitation" grew significantly and this trend has been maintained. Since 2013, publications in "Neurosciences" and "Robotics" research areas have also grown rapidly. The research areas of "Automation & Control Systems," "Engineering, Mechanical," "Computer Science, Artificial Intelligence" and "Engineering, Electrical & Electronic" also experienced growth in the field of exoskeletal research in terms of the number of publications in recent years.

TABLE III
CONTRIBUTION OF THE TOP 20 RESEARCH AREAS IN ROBOTIC EXOSKELETONS FIELD

Rank	WoS research area	TA	TC	ACPP	h-index
1	Engineering, Biomedical	883	20171	22.84	70
2	Rehabilitation	820	23005	28.05	76
3	Neurosciences	795	16520	20.78	61
4	Robotics	748	13261	17.73	58
5	Automation & Control Systems	405	9208	22.74	50
6	Engineering, Mechanical	333	5292	15.89	35
7	Clinical Neurology	328	9037	27.55	48
8	Computer Science, Artificial Intelligence	326	5688	17.45	39
9	Engineering, Electrical & Electronic	295	6258	21.21	41
10	Sport Sciences	188	5651	30.06	37
11	Engineering, Manufacturing	133	3857	29.00	31
12	Instruments & Instrumentation	128	1432	11.19	20
13	Computer Science, Information Systems	110	672	6.11	13
14	Orthopedics	107	2466	23.05	27
15	Computer Science, Interdisciplinary Applications	98	1639	16.72	21
16	Multidisciplinary Science	94	1002	10.66	16
17	Materials Science, Biomaterials	93	2657	28.57	24
18	Medical Information	76	1597	21.01	20
19	Psychology	73	1027	14.07	18
20	Computer Science, Cybernetics	68	1859	27.34	21

TA, total articles; TC, total citations; ACPP, average citations per publication.

TABLE IV
THE TOP 20 JOURNALS PUBLISHING PAPER IN ROBOTIC EXOSKELETONS FIELD

Rank	Journal title	TA	TC	ACPP	ACP%	IF
1	*Journal of NeuroEngineering and Rehabilitation*	212	5121	24.16	83.96	3.582
2	*IEEE Transactions on Neural Systems and Rehabilitation Engineering*	194	6104	31.46	87.11	3.478
3	*IEEE-ASME Transactions on Mechatronics*	79	3265	41.33	91.14	4.943
4	*Advanced Robotics*	75	944	12.59	80.00	1.104
5	*International Journal of Advanced Robotic Systems*	67	302	4.51	70.15	1.223
6	*Frontiers in Neuroscience*	66	513	7.77	75.76	3.648
7	*IEEE Transactions on Robotics*	62	3083	49.73	93.55	6.483
8	*Robotics and Autonomous Systems*	62	1376	22.19	80.65	2.928
9	*Neurorehabilitation and Neural Repair*	53	2160	40.75	96.63	3.757
10	*Robotica*	53	530	10.00	86.80	1.184
11	*Sensors*	48	392	8.17	79.17	3.031
12	*Frontiers in NeuroRobotics*	46	345	7.50	71.74	3.000
13	*IEEE Transactions on Biomedical Engineering*	46	1572	34.17	93.48	4.491
14	*Mechatronics*	43	720	16.74	88.37	2.978
15	*Frontiers in Human Neuroscience*	41	577	14.07	92.68	2.870
16	*Neurorehabilitation*	39	421	10.79	76.92	1.197
17	*PloS One*	37	436	11.78	83.78	2.776
18	*Gait & Posture*	34	598	17.59	91.18	2.414
19	*Industrial Robot-An International Journal*	33	436	13.21	76.92	1.190
20	*Journal of Mechanisms and Robotics Transactions of the ASME*	33	171	5.18	73.33	2.377

ACP, article cited percentage.

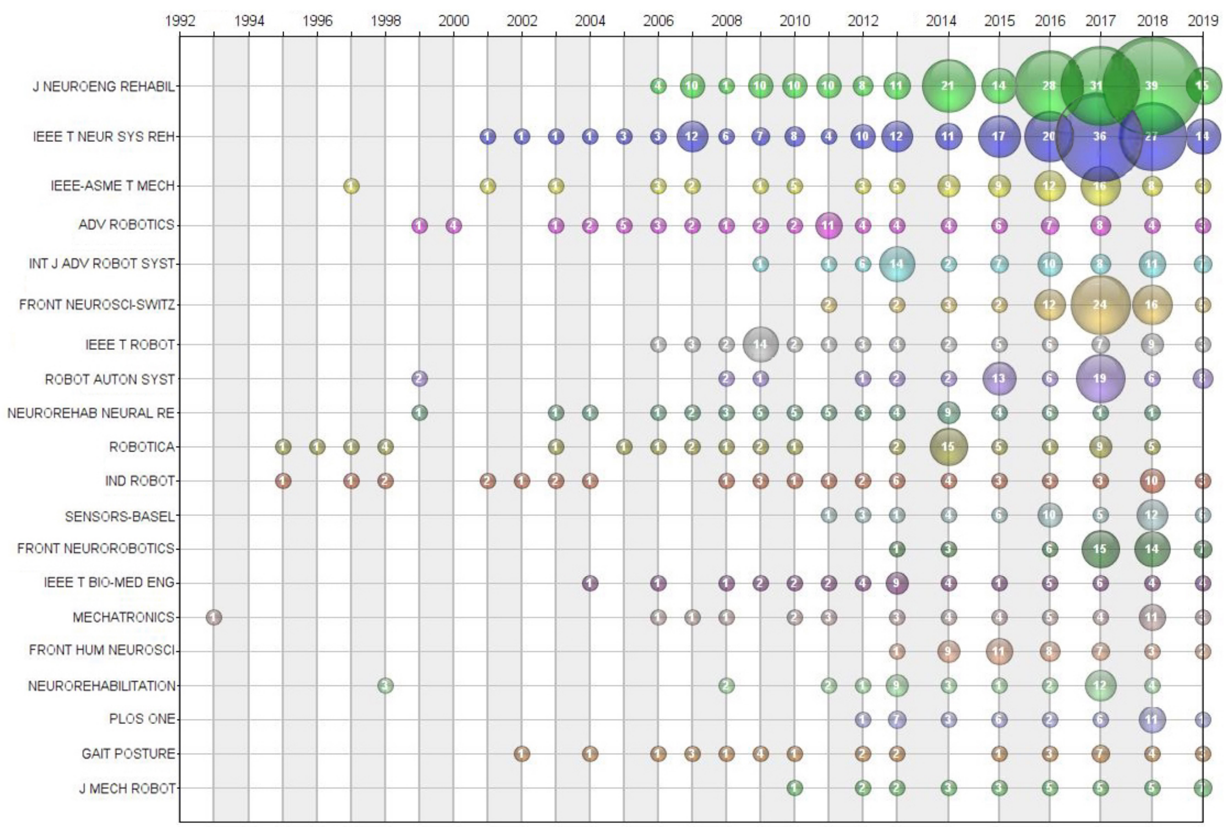

Fig. 6. Bubble chart of top 20 productivity journals by year.

D. Leading Journals in Terms of Publication Number

The 3848 papers related to robotic exoskeletons during 1990-2019 were published in 545 journals, but 350 of these journals contributed less than a 1% share. Since the robotic exoskeletons is a multidisciplinary subject, the research is published in a variety of journals. As listed in Table IV, *Journal of NeuroEngineering and Rehabilitation* leads with 212 publications, followed by *IEEE Transactions on Neural Systems and Rehabilitation Engineering* with 194. Both of these journals publish papers focusing on biomedical engineering and rehabilitation. This result agrees with the pattern revealed in Table III. These two journals contributed a 10.6% share (406) of the total publications (3848) in this field; and, the top 20 journals listed in Table IV published 34.4% (1323)

TABLE V
CONTRIBUTION OF THE TOP 10 AUTHORS IN ROBOTIC EXOSKELETONS RESEARCH

Rank	Author	TA	TC	ACPP	h-Index	Institution
1	Krebs, Hermano Igo	48	3668	76.41	28	Massachusetts Institute of Technology
2	Vitiello, Nicola	45	1190	26.44	16	University of Twente
3	Riener, Robert	44	1717	39.02	20	Scuola Superiore Sant'Anna
4	Xie, Shengquan	36	947	26.31	16	University of Auckland
5	Pons, Jose L.	32	686	21.44	14	Consejo Superior de Investigaciones Cientificas (CSIC)
6	Hogan, Neville	30	3308	110.27	24	Massachusetts Institute of Technology
7	Reinkensmeyer, David J.	28	1923	68.68	20	University of California Irvine
8	van der Kooij, Herman	28	1823	65.11	19	University of Twente
9	Ferris, Daniel P.	27	1586	58.74	19	University of Michigan
10	Agrawal, Sunil K.	27	1031	38.19	13	Columbia University

TA, total articles; TC, total citations; ACPP, average citations per publication.

TABLE VI
TOP 10 MOST CITED PUBLICATIONS DURING THE PERIOD OF 1990–2019

No.	Author	Title	TC	TCY	Source	Year
1	Gery Colombo, *et al.*	Treadmill training of paraplegic patients using a robotic orthosis	687	34.4	*Journal of Rehabilitation Research and Development*	2000
2	Peter S. Lum, *et al.*	Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke	642	35.7	*Archives of Physical Medicine and Rehabilitation*	2002
3	Jan F. Veneman, *et al.*	Design and Evaluation of the LOPES Exoskeleton Robot for Interactive Gait Rehabilitation	581	44.7	*IEEE Transactions on Neural Systems and Rehabilitation Engineering*	2007
4	Aaron M. Dollar,*et al.*	Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art	572	47.7	*IEEE Transactions on Robotics*	2008
5	Gerdienke B. Prange, *et al.*	Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke	543	38.8	*Journal of Rehabilitation Research and Development*	2006
6	Maureen K. Holden, *et al.*	Virtual Environments for Motor Rehabilitation: Review	538	35.9	*Cyberpsychology & behavior*	2005
7	CathrinBütefisch, *et al.*	Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand	512	20.5	*Journal of the Neurological Sciences*	1995
8	Laura Marchal-Cr espo, *et al.*	Review of control strategies for robotic movement training after neurologic injury	483	43.9	*Journal of NeuroEngineering and Rehabilitation*	2009
9	Zoss, AB, *et al.*	Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX)	454	28.4	*IEEE Transactions on Biomedical Engineering*	2004
10	Latash, Mark L, *et al.*	Motor Control Strategies Revealed in the Structure of Motor Variability	426	23.7	*Exercise and Sport Sciences Reviews*	2002

TC, total citations; AAC, average annual citations.

of the total number of papers. In terms of impact factor (IF), *IEEE Transactions on Robotics* has the highest value of 6.483.

To show the historical map of robotic exoskeletons-related publications in the various journals, we produced a bubble chart of the top 20 productive journals by year, shown in Fig. 6. It can be seen that there were a few publications sparsely distributed in the top 20 journals from 1990 to 2006. After a smooth increase in the succeeding seven years, the robotic exoskeleton field has witnessed an explosive growth in publications since 2013. The number of papers in journals focusing on biomedical engineering and rehabilitation grew rapidly in recent years, including the *Journal of NeuroEngineering and Rehabilitation*, the *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, and *Frontiers in Neuroscience*.

E. Contribution of Leading Authors

The top 10 productive authors are listed in Table V. The Krebs-Hermano-Igo group leads the list with 48 total publications, followed by Vitiello-Nicola group with 45. As for the ACPP, the Hogan-Neville group ranks the first with a value of 110.27. The Krebs-Hermano-Igo group has the highest h-index of 28. Most of the top 10 authors are from the top 10 productive institutions in 4 different countries, suggesting there is potential for more international cooperation in this field. Nevertheless, the top 10 authors were involved in only 9% of the total publications indicating that a large number of researchers are contributing to the total publication number. It is highly likely that the large community in this research field will lead to important progress in the near future.

F. Analysis of the Most Cited Articles

Although citation of an article can be influenced by several of factors [96], [97], it is still a widely accepted measure for evaluating scientific papers. We list the top 10 most cited publications in Table VI. The article "Treadmill training of paraplegic patients using a robotic orthosis" published in the *Journal of Rehabilitation Research and Development* by Colombo *et al.* in 2000 is the most highly cited (687). This paper introduced a driven gait orthosis that could apply automated loco-motor training to immobile patients. With respect to the average annual citation rate (AAC), the article, "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art" published in *IEEE Transactions on Robotics* by Aaron M. Dollar, *et al.* in 2008, ranks first (47.7), followed by (44.7), "Design and Evaluation of the LOPES Exoskeleton Robot for Interactive Gait Rehabilitation" published in *IEEE Transactions on Neural Systems and Rehabilitation Engineering* by Jan F. Veneman, *et al.* in 2007. The former reviewed the history of lower limb exoskeletons and active orthoses, while the later proposed a gait rehabilitation device that could enforce a gait pattern when configured and also allowed the wearer to walk unhindered. Another recent paper, "Review of control strategies for robotic movement training after neurologic injury" published in *Journal of NeuroEngineering and Rehabilitation* by Laura Marchal-Crespo, *et al.* in 2009, reviewed the control strategies for robotic therapy devices, including assistive, haptic simulation, and coaching; it, too, had a high AAC (43.9).

Among the top 10 articles, seven focused on rehabilitation exoskeletons, five investigated lower limb exoskeletons, and two studied control strategies. This reveals that rehabilitation exoskeletal research is active and that the lower limbs attracted the most attention in this research area. Furthermore, control strategies have become an active research topic and a major challenge in exoskeleton research field.

IV. Conclusion

Research on robotic exoskeletons has been on-going for more than a half a century. In this paper, the overall profile of published literature from 1990 to July 2019, retrieved from the WoS database, was analyzed and hot topics were determined using bibliometric analysis. Our work also provides popular author keywords, research areas, as well as the contributions by country, institution and author. This allows readers to quickly assess current status of research frontiers, and locate potential national and international collaborators.

The bibliometric technique provides extensive, important information on robotic exoskeleton research, yet, some method inherent limitations exist. Although a great number of publications are covered by the WoS database, those from other databases such as Scopus and Google Scholar are not included in our study and the perfect search formula has yet to be designed. Thus, some relevant publications may be omitted.

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