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REVIEW

Research Trends on Astronaut Physical Training as Countermeasures: A Bibliometric Analysis from Past 30 Years

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Abstract

Astronauts are exposed to microgravity-induced health problems in spaceflight missions. Countermeasures and physical exercises have received increasing attention and its current research trends and landscapes warranted investigation. We conducted a comprehensive bibliometric analysis on astronaut training/countermeasures using the available data from the Web of Science Core Collection database from 1992 to 2022 to summarize the research trends and identify future directions. A total of 1,520 relevant articles were identified. Annual publications of the field have been increased over the years with the emergence of new and effective countermeasures. 'Microgravity' was the centered hotspot surrounded by the topics included 'spaceflight', 'hind leg hanging', 'simulated microgravity', and 'simulated weightlessness'. The top countries that produced the most publications included United States (726 articles), Germany (129 articles), and France (84 articles). The United States played a dominant role in the collaboration network with other countries. Meanwhile, NASA from the United States led the global collaborations and dominated the literature. Future research trend might lie on the design of physical training exercises to tackle the potential health problems on osteoporosis, muscle atrophy, and abnormality on the nervous and cardiovascular system; and artificial/simulated gravity with interdisciplinary sports countermeasure research on physiology, brain science, biomechanics, and aerospace medicine.

Keywords Space Exercises · Physical Training · Network Analysis · Citations · Outputs

Introduction

Astronauts are exposed to zero to low gravity environment during long spaceflight missions that can induce significant physiological threats included muscle atrophy, decreased bone density, orthostatic intolerance, cardiovascular disorders, visual impairment, and physical fatigue (Sawin et al. 2007). Physical training is considered as a key and effective countermeasure to minimize the negative health effects due to microgravity environments, which aim at preserving muscular strength, endurance, and bone mineral density (Kozlovskaya and Grigoriev 2004; O'Conor et al.

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2020). Previous studies have simulated microgravity environments through centrifuge chamber or negative-inclined bed rest approach to examine the physiological effectiveness of these exercise-based countermeasures (Clément 2017; Linnarsson et al. 2015; Vernikos 1997). There were mixed findings on whether countermeasure training under microgravity environment could improve muscle and bone health (De Martino et al. 2021; Tran et al. 2021; Yang et al. 2007; Zwart et al. 2009).

Minimizing the loss in bone mineral density is one of the major goals for astronaut countermeasures (O'Conor et al. 2020). X-ray absorptiometry and quantitative computed tomography (QCT) are commonly applied to measure the bone density in body regions and biomarkers of bone metabolism, respectively. It is showed that physical training (e.g., running, cycling and resistance exercises) combined with bisphosphonic acid supplement was effective to improve bone health (Leblanc et al. 2013). In addition, as indicated by the human negative-inclined (i.e. head-down tilt) bed rest and animal test (i.e., mouse tail hanging model), low-frequency vibration exercises can be a plausible strategy to prevent bone loss due to the adverse effects of microgravity on bone marrow and intervertebral disc (Holguin et al. 2011). Vibration training can promote the bone metabolism and increase osteoclast activity for bone mass growth (Baecker et al. 2012). On the other hand, some advance resistance exercise devices combined with bisphosphonate acid intake was also effective in minimizing the loss of bone mineral density during long-duration spaceflight, but only use of this intervention was reported to be insufficient to maintain muscle function and mass (Comfort et al. 2021). Mulavara et al. (2018) showed that resistance exercises and aerobic exercises would play an important role in maintaining neuromuscular and cardiovascular functions in space flight, while high-power endurance exercises could reduce fatigue during space flight (Abitante et al. 2022). Most of these studies have been conducted in either international space station or simulated microgravity environments to examine how space environment might affect human body system for more comprehensive understanding of countermeasures in astronauts (Ferranti et al. 2020; Williams et al. 2009).

Over the past decades, clinical and innovative research on astronaut countermeasures has significantly evolved. However, the discrete information obtained from publications make it increasingly difficult for the researchers and scientists to keep use of the latest advances and identify the current trend in this area. Bibliometric analysis is an advanced technology in computer engineering, database management and statistics for assessing the available research areas (Ninkov et al. 2022). This can assess various levels of information included journals, institutions, countries and authors, providing a qualitative description of trends in the literature (Belter 2018). Bibliometric analysis is considered to be more objective and can also manage large amounts of data and generate insightful information of current trends, key articles and future directions (Bhandari 2022; Donthu et al. 2021). By understanding the current trend and key contributors in the field, it can promote the international scientific collaborations amongst contributors and develop a comprehensive and in-depth research.

While astronaut countermeasures including physical training, nutrition, drugs and protective gear have been a growing topic in space sciences, physical training or exercise is particularly important to maintain the general fitness and strength during the fight missions. Furthermore, the bibliometric analysis is rarely reported in the scientific community. To review the landscape of astronaut countermeasures research, a comprehensive bibliometric review was performed on all related studies published in the *Web of Science Core Collection* from 1992 to 2022. The results from this study can facilitate better understanding on the publication profiles at the global level, provide an accurate overview of the scientific output over time and predict future strategies for research in this area.

Methods

Literature Search

The articles related to countermeasures in astronauts were retrieved from the *Web of Science (WOS) Core Collection* database. The algorithm of the search terms on the topic field was ((‘astronaut*’ OR ‘spaceflight*’ OR ‘space flight*’ OR ‘aerospace’ OR ‘astronavigation’ OR ‘space navigation’ OR ‘microgravity’ OR ‘weightlessness’ OR ‘artificial-gravity’ OR ‘weightless’) AND (‘physical training’ OR ‘exercise’)). The search was limited to English articles published from 1 January 1992 to 31 December 2022. A total of 1520 articles, including original peer-reviewed articles ($n=1218$), and proceeding abstracts and full papers ($n=302$) was identified. The sources of data are provided in Table 1.

We standardized the data extract format and merged the data records to reduce data noise for this study: 1) standardization and merging of author information and affiliations. For example, authors who may appear to have different name spellings/initials in accordance with different journals should be merged into a single author entity. For institutions with different abbreviations, a mapping table should be established to standardize and unify these abbreviations across the dataset. Furthermore, different sub-institutions of the same parent institution should be merged under the parent institution to reduce duplication; 2) Merging of renamed

Table 1 Data Sources

Project	Contents
Database	*Web of Science (WOS) Core Collection* database
Research Topic	('astronaut*' OR 'spaceflight*' OR 'space flight*' OR 'aerospace' OR 'astronavigation' OR 'space navigation' OR 'microgravity' OR 'weightlessness' OR 'artificial-gravity' OR 'weightless') AND ('physical training' OR 'exercise')
Publication data	1 January 1992 to 31 December 2022
Document Types	Articles and Proceeding Paper
Total number of Documents	1520

journals. For example, if the names of source journals or cited journals have changed, the records should be merged under their original names (e.g., 'AVIATION SPACE AND ENVIRONMENTAL MEDICINE ' was renamed 'AEROSPACE MEDICINE AND HUMAN PERFORMANCE ') to achieve the accurate source journal and co-citation analysis; 3) Processing and merging of keywords. We firstly removed any unnecessary special characters or spaces from keywords. The keywords with the same or similar meanings should then be merged, such as merging 'bed-rest', 'bed-rest', and 'bed rest', merging 'space flight', 'space-flight', 'space flights', and 'spaceflight', or merging 'international space station', 'international-space-station', and 'ISS'.

Bibliometric Analysis

The data management and bibliometric analyses were conducted using R statistical packages (R Foundation, Vienna, Austria), online bibliometric analysis platform (http://bibliometric.com/, last access on 21 Apr 2023), and *VOSviewer* (ver. 1.6.18, Centre for Science and Technology Studies, Leiden University, Leiden, Netherlands). Data import, transformation, analysis, and visualization were performed using the *Bibliometric* toolkit of the R statistical package. Online bibliometric analysis platform and *VOSviewer* were used to analyze the distributions of institutions, authors, co-cited authors, countries, citation counts, keyword of high frequency, and collaboration analysis among institution and research groups. In addition, the network visualization maps, overlay visualization maps and density visualization maps on trends and hotspots were created in the *VOSviewer*. In the analysis, the publishing countries/regions were defined as the primary affiliations of the corresponding authors. International collaboration was the ratio of multiple country publications (MCP), which is defined as the ratio of articles with coauthors of different countries/regions to the total number of included articles. If an article is co-authored by multiple institutions, the count was given for each participating institution.

Additionally, this study focused more on analyzing China because of its economic status and recent advancements in space technology, including space flights and the construction of space stations, which may alter the landscape of international research and collaborations.

Results

Publication Characteristics

A total of 1520 articles were retrieved from 61 different countries or regions and 1931 different institutions in the past three decades (i.e. from 1992 to 2022). The number of articles presented an overall increasing trend, from six articles in 1992 to 62 articles in 2022 (Fig. 1), with an average annual growth rate of 8.15%. The average citation rate of each paper was 23.54 times, and the average annual citation frequency of each article also showed a gradual increasing trend (Fig. 1). The average number of collaborators in each article was 5.46, and the proportion of international collaboration was 26.32%, indicating more local than international collaboration.

The *Web of Science core collection* provided a standard classification of research field across the journals, and each article was belonged to at least one of these research fields. Table 2 shows the top 10 key research fields, which included "sports science", "physiology", "engineering, aerospace", "public environmental & occupational health", "medicine, general internal", "neurosciences & neurology", "science technology-other topics", "biophysics", "endocrinology & metabolism", and "medicine research & experimental". The field of "sports science" accounted for the greatest number of publications (460 papers), accounting for 30.26% of the total article number. This indicates that physical exercise is the key research field for astronaut countermeasures. While there was limited publications identified before year of 2002, the rank change curves of all key research fields from 2002 to 2022 are provided in Fig. 2. The results (Fig. 2) indicated "Physiology" and "Engineering" dominated astronaut countermeasure research in the past 20 years. In 2014 and 2015, it seems there was a major reshuffle of ranks. Research related to "Science Technology" became an emerging topic in the field, whilst those related to "Medicine, General Internal", has been gradually desending the leaderboard.

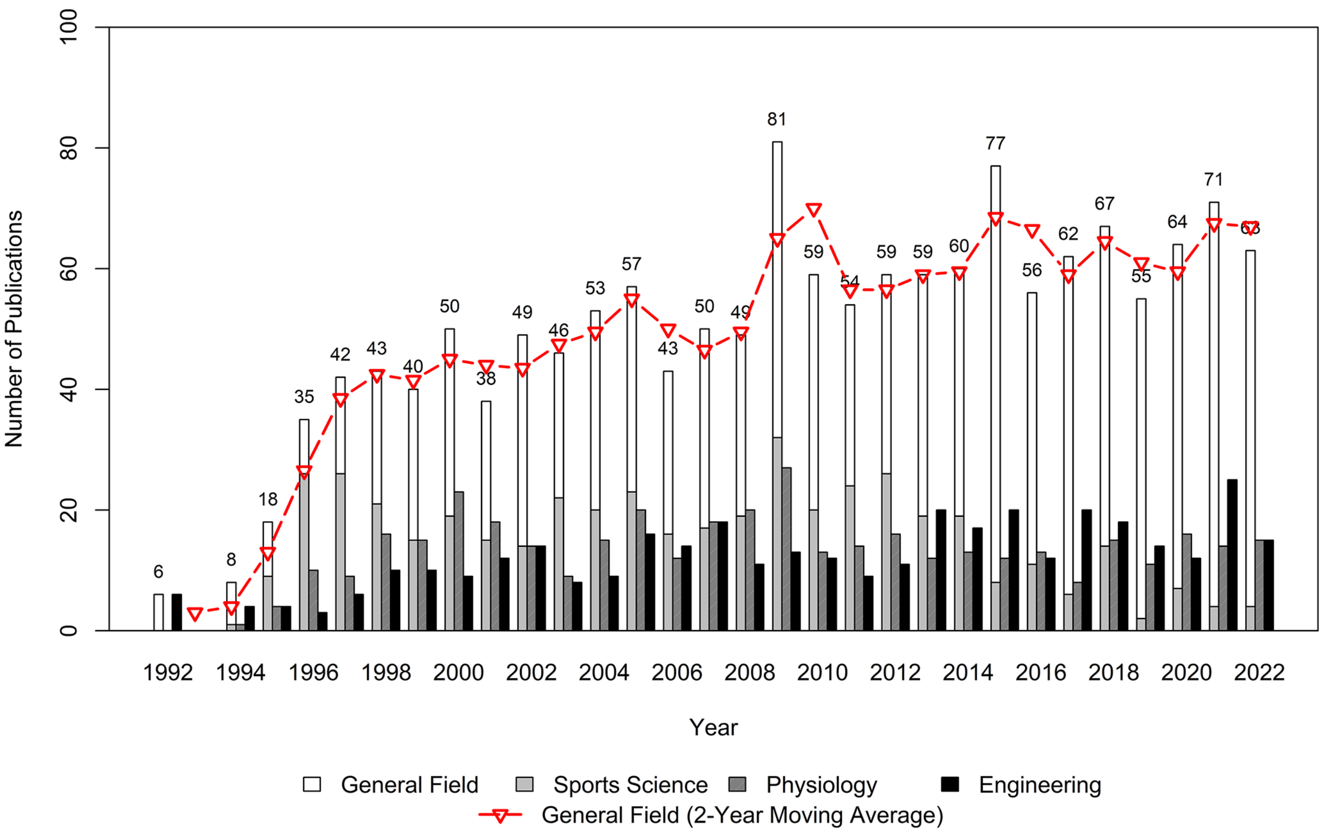

Fig. 1 Annual publications in various scientific fields and average annual citations per article from 1992 to 2022

Table 2 Top ten research scopes on space countermeasures

Rank	Research Scope	No. of Published Articles	Proportion (%)
1	Sports sciences	460	30.26
2	Physiology	403	26.51
3	Engineering, aerospace	375	24.67
4	Public environmental & occupational health	183	12.04
5	Medicine, general internal	148	9.74
6	Neurosciences & neurology	100	6.58
7	Science technology-other topics	79	5.2
8	Biophysics	73	4.80
9	Endocrinology & metabolism	68	4.47
10	Medicine research & experimental	62	4.08

International Publication Characteristics and Visualization Analysis

As shown in Fig. 3; Table 3, the top six countries that published most were the United States (726 articles), Germany (129 articles), France (84 articles), Japan (75 articles), UK (72 articles) and China (71 articles). Of the six countries, the United States (12.7%) and China (14.1%) had a lower proportion of international collaboration compared with Germany (57.4%). It shall also be noted that the number of articles published (47.76%) and the number of total citations (19,180 times) from the United States greatly surpassed other countries/regions. It could be related to the larger financial support and influence from NASA on space technology in earlier decades than other countries. As shown in Fig. 3, the annual output was led by the United States, while China published its first paper in 2006 and caught up progressively. In 2011, the annual research output by China began to outperform France, the United Kingdom and Japan (4 articles in China; 3 in France; 2 in UK; 2 in Britain; 3 in Japan).

The types of scientific collaboration network can be divided into national, institutional and author collaboration networks. In the scientific collaboration network, the importance of the topic and the strength of its connection are predetermined by the collaboration direction and tasks between collaborators. The meaning of nodes (circles) in the network is set as point degree centrality, and the size of nodes represents the number of publications of the institution (or author or country). The thicker the link, the closer the institutions (or authors or countries) at both ends of the line are to each other. Figure 4 shows the mapping of the 17-nation collaboration network among all the ISS member states and China. In terms of international collaboration, the United States of American have played a dominant role in the collaboration

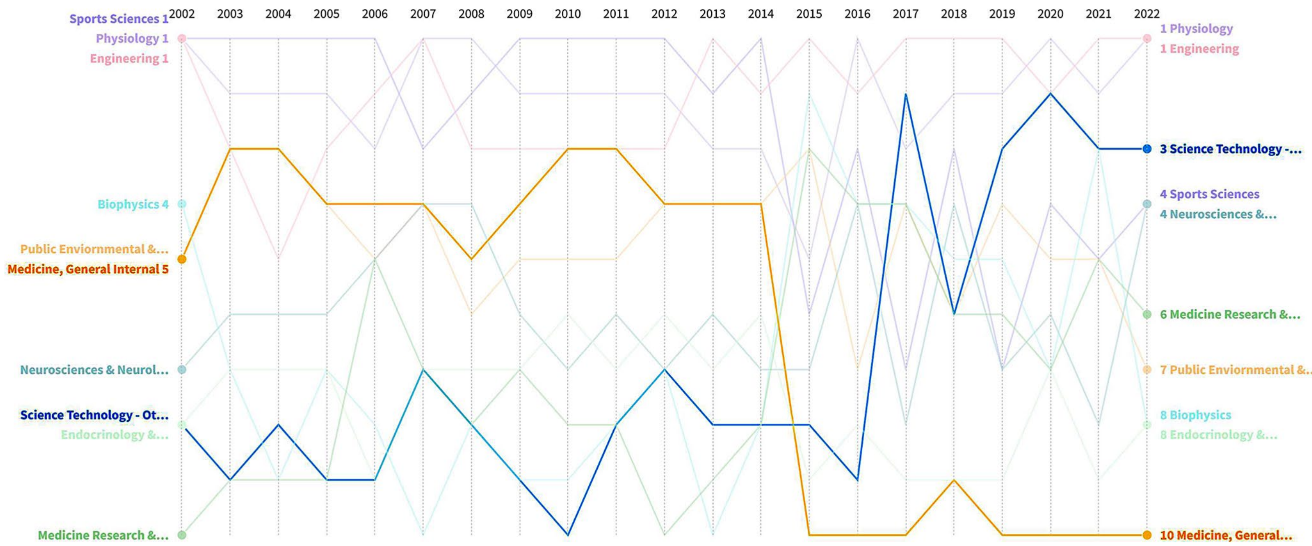

Fig. 2 Rank change of research fields from 2002 to 2022

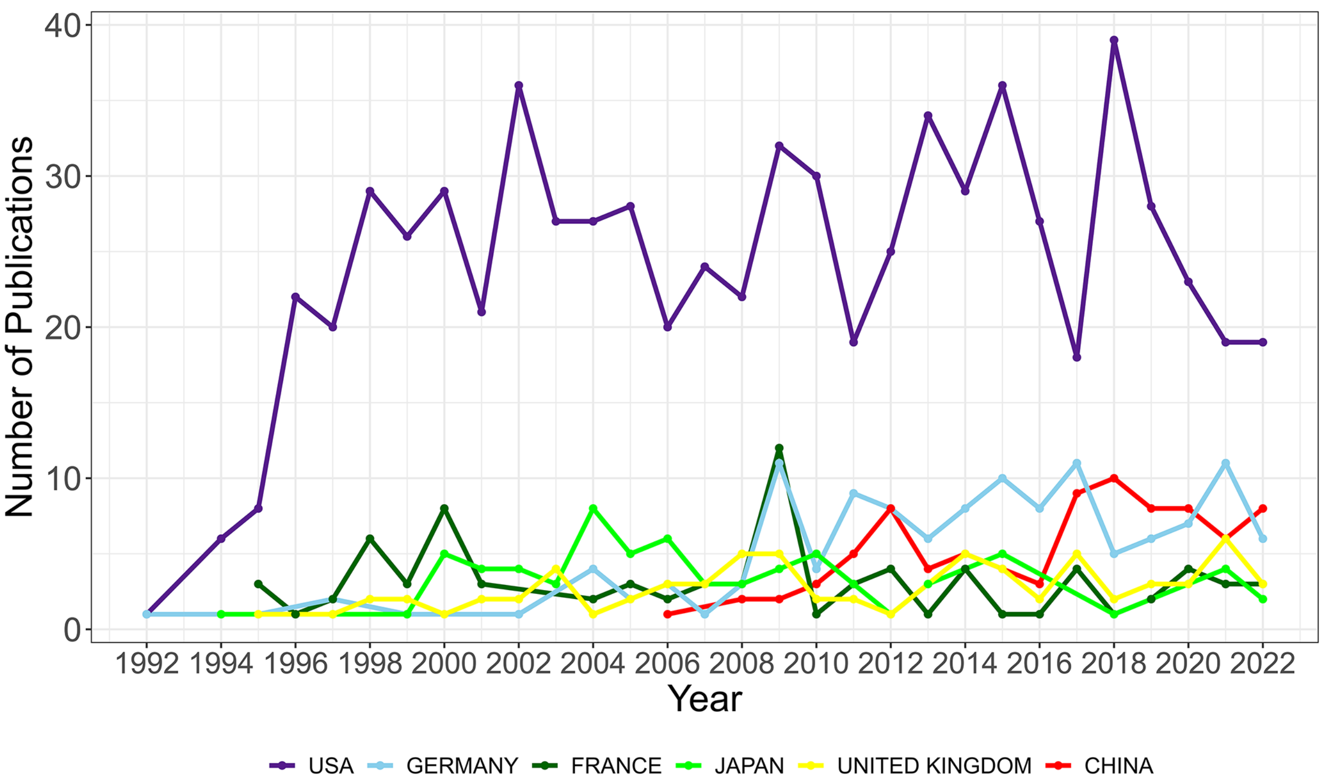

Fig. 3 The annual trend of publication counts on the five countries/regions with the most publications

network with other countries. The research collaboration among the United States, Germany and the United Kingdom was the most comprehensive and in-depth. There were two clusters of extensive collaborations, including USA, Germany, Italy, and the United Kingdom, as well as the those among USA, Canada, France and Germany.

Distribution Characteristic of Research Institutions and Visualization Analysis

Table 4 shows the 28 institutions that have published at least 18 articles and 15 of them were from the United States. With 229 publications and 7,113 citations, NASA was far ahead than all other institutions. As the pioneer of aeronautics, NASA set solid foundation in the research of astronaut

Table 3 Top ten countries/region contributes included articles

Rank	Country	No. of Published Articles	Proportion	MCP ratio (%)	Total Citation
1	USA	726	47.76	12.70	19,180
2	Germany	129	8.49	57.40	2586
3	France	84	5.53	47.60	2485
4	Japan	75	4.93	22.70	1635
5	UK	72	4.74	43.10	1733
6	China	71	4.67	14.10	506
7	Italy	62	4.08	41.90	1235
8	Sweden	38	2.50	47.40	1333
9	Canada	32	2.11	46.90	505
10	Russia	24	1.58	4.20	280

MCP: multiple country publication

countermeasures (Ruyters et al. 2021). NASA and German Aerospace Center were ranked the first and third in the list of national-level institutions, respectively. In contrast, university-level institutions had relatively fewer publications, as aerospace or aeronautics research was generally dominated by countries' military units (especially air force). Academic institutions that played as affiliating or supporting roles could not have full access to necessary knowledge and technology base or professional astronauts because of possible national security concerns.

The visualization map of the collaboration network of the top 37 institutions in the number of published articles is shown in Fig. 5. In terms of collaboration, NASA had the largest number of publications and highest influential collaboration network. A total of the 229 articles was published by NASA, which has linked to eight different affiliated institutions included NASA headquarters, Ames Research Center, Langley Research Center, Glenn Research Center, Goddard Space Flight Center, Marshall Space Flight Center, Johnson Space Center Center, Stennis Space Center. NASA has also worked closely with local universities such as the University Space Research Association (USRA), the University of Houston, the University of Michigan, the University of Texas, the University of California, San Diego, and Ball State University. NASA has provided space life science training and/or internship programs to attract top graduates from the universities across the country and these universities provided the bachelor and master degrees to support the careers in space and life sciences. Moreover, NASA has close collaborations between the Wyle Laboratory, Baylor College of Medicine and the University of Texas Medical Branch. Wyle Laboratory is a key collaborator of NASA in the field of environmental simulation and experimental technology. The laboratory has provided engineering and experimental services for the USA government and industry. While Baylor College of Medicine is one of the most distinguished medical schools and a world leader in biomedical research, the University of Texas Medical Branch has a long history and track record in health sciences.

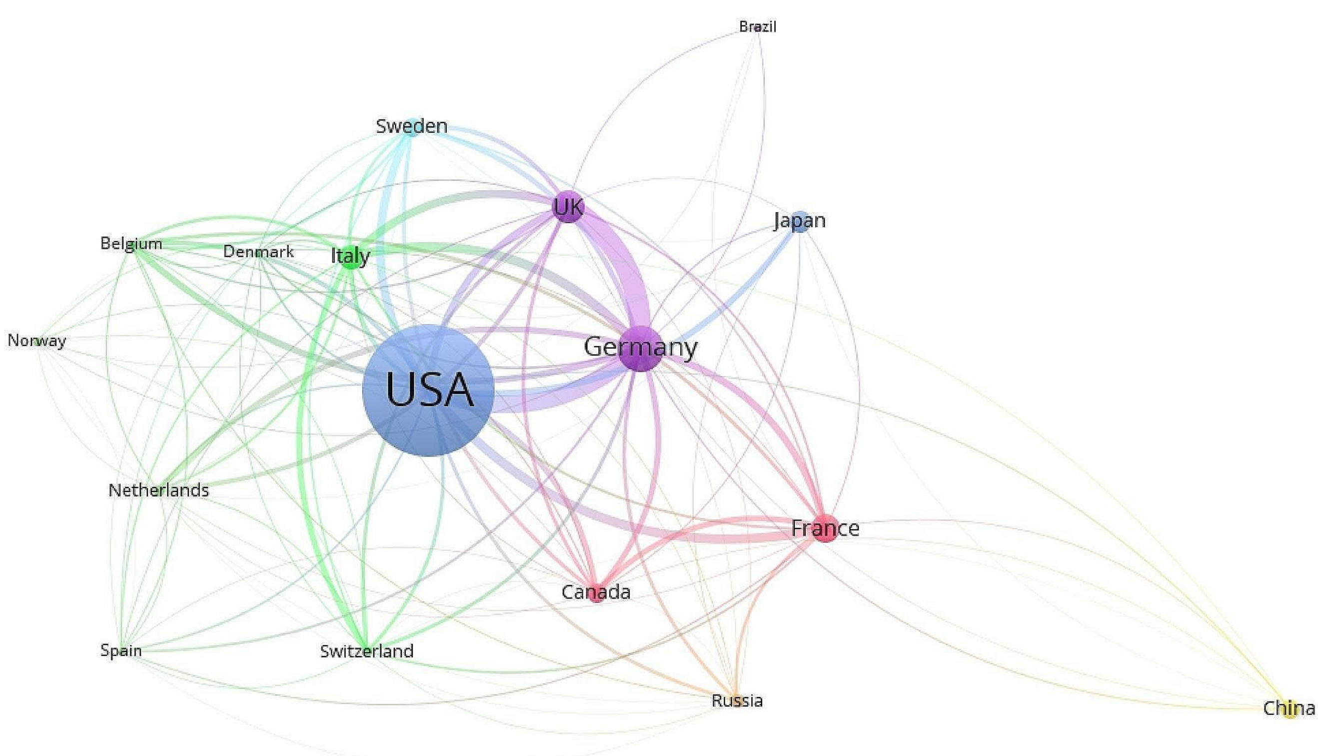

Fig. 4 Network visualization map of between countries scientific collaboration

Table 4 Research Institutes with most publications

Rank	Research Institution	Country	No. of publications	Total citation
1	NASA	USA	229	7113
2	Wyle	USA	106	2990
3	German Aerospace Center (DLR),	Germany	82	1199
4	Charité–Universitätsmedizin Berlin	Germany	55	1841
5	Karolinska Institute	Sweden	50	2008
6	Manchester Metropolitan University	UK	41	2175
7	University Space Research Association (USRA)	USA	40	1604
8	European Space Agency (ESA)	Europe	39	331
9	Texas A&M University (TAMU)	USA	38	1048
10	University of California San Diego	USA	37	1199
11	German Sport University Cologne	Germany	36	535
12	University of Houston	USA	27	577
13	Ball State University	USA	27	1816
14	University of Cologne	Germany	26	433
15	University of Texas	USA	26	1814
16	King’s College London	UK	22	216
17	University Texas Medicine Branch	USA	22	723
18	Massachusetts Institute of Technology (MIT)	USA	22	281
19	University of Udine	Italy	21	644
20	University of Milan	Italy	20	416
21	University of Michigan	USA	19	331
22	Baylor College of Medicine	USA	19	1198
23	Jozef stefan inst	Slovenia	18	390
24	University of California, Irvine	USA	18	517
25	Pennsylvania State University	USA	18	679
26	University of Colorado	USA	18	458
27	Beihang University	China	18	132
28	China Astronaut Research & Training Center (China ARTC)	China	18	162

NASA collaborated with multiple well-known universities and advanced laboratories could be an important reason for the high number of publication output. Following the USA, other strong research collaboration groups were the German Aerospace Center (DLR), the German Sport University Cologne and the University of Cologne in Germany. In addition, Wyle Laboratory has strong cooperation with the DLR and the European Space Agency (ESA).

China institutions, including Beihang University, the fourth military medical university, the China Astronaut Research and Training Center (China ARTC) has not established collaborations with the top institutions in the list. To further explore the local collaboration in China, China institutions that published at least 15 articles, including China ARTC (18 articles), Beihang University (18 articles), Fourth Military Medical University (15 articles) were identified. At the same time, a collaboration network of 12 China institutions with not less than 3 publications have been constructed, as shown in Fig. 6. China ARTC is the network core and key contributor to initiate and apply the space countermeasures research in China. The China ARTC is the most recognized instruction in space sport countermeasures in China and has strong relationship with Beihang University and the Fourth Military Medical University. The Fourth Military Medical University also played an important role in collaboration network, with 4 collaboration institutions.

Distribution Characteristic of Authors and Visualization Analysis

A total of 5343 authors participated in the 1,520 included articles, with an average of six co-authors per article. Among the top 16 authors (Table 5), eight of them were from the United States, six from Germany and two from Sweden. Dr. Rittweger from the German Aerospace Center/University of Cologne was the author who has contributed the most publications ($n = 59$). Dr. Felsenberg from the Charite Universitatsmedizin Berlin has published 40 articles. The number of citations per article could be used as an indicator to reflect the quality of an author’s article (Aksnes et al. 2019). The top 1 ranked author is Dr. Trappe (77 per article) from Ball State University, USA, followed by Dr. Tesch (59 per article) from Karolinska Institute, Sweden, and Dr. Smith (56.9 per article) from NASA. For China, Dr. Lianwen Sun from Beihang University ranked 33rd in the number of articles

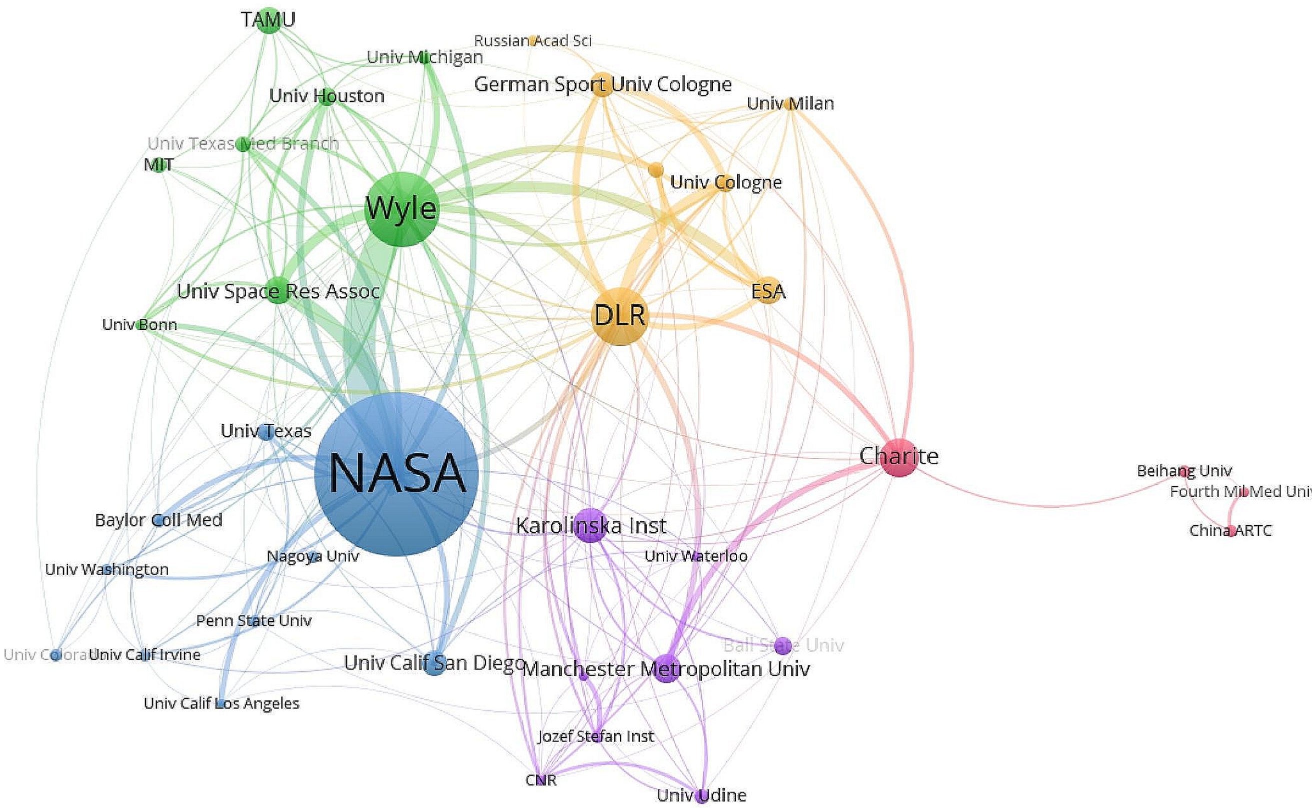

Fig. 5 Network visualization map of research collaboration among institutions worldwide

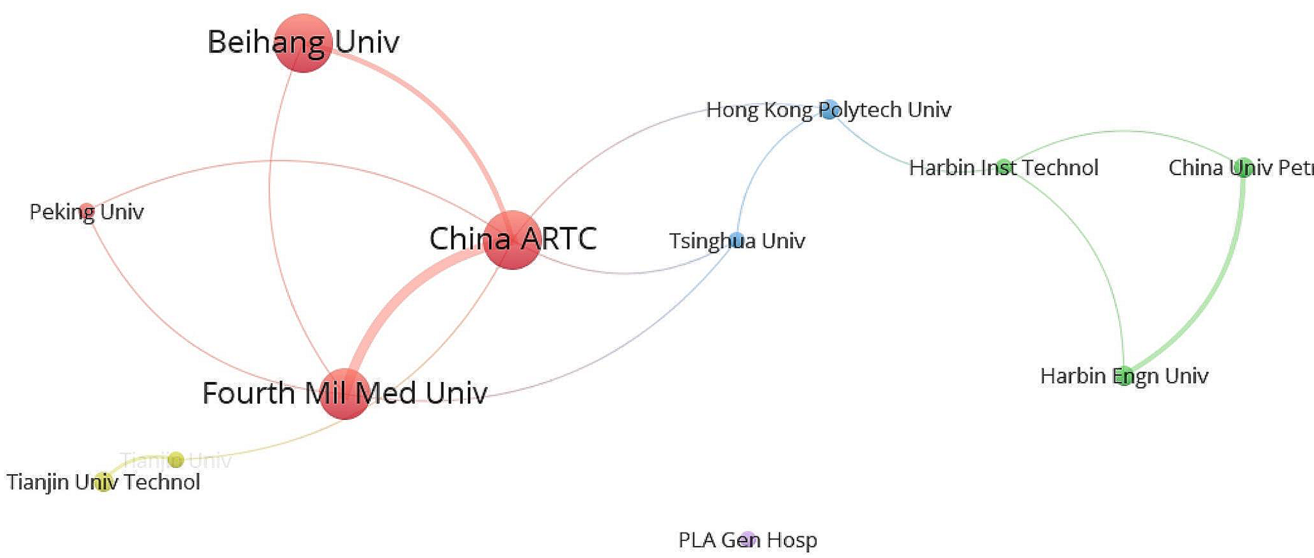

Fig. 6 Network visualization map of research collaboration among China institutions

published (13 articles) with the number of citations per article. He was one of the Chinese pioneers in this field.

The collaboration network between authors with more than 10 articles is shown in the clusters in Fig. 7. Dr. Felsenberg, Dr. Belavy and Dr. Aembrecht from the Charité–Universitätsmedizin Berlin in Germany, ranked top in the number of published articles (2nd, 3rd, and 10th, respectively). Dr. Felsenberg also established collaboration with Dr. Rittweger from the German Aerospace Center and University of Cologne in Germany. The collaboration network among US authors was led by Dr. Lee (Wyle Laboratory), Dr. Hargens (University of California, San Diego), Dr.

Table 5 Top authors with the most publications

Rank	Author	Country	Institution	No. of published articles	Total citation
1	Rittweger, J	Germany	German Aerospace Center/University of Cologne	59	1835
2	Felsenberg, D	Germany	Charité–Universitätsmedizin Berlin	51	2155
3	Belavy, DL	Germany	Charité–Universitätsmedizin Berlin	40	1229
4	Lee, SMC	USA	Wyle Laboratory	38	1318
5	Hargens, AR	USA	University of California, San Diego	36	1342
6	Smith, SM	USA	NASA Johnson Space Center	33	1876
7	Tesch, PA	Sweden	Karolinska Institute	29	1712
8	Ploutz-snyder, L	USA	University of Michigan/ Universities Space Research Association	27	705
9	Mulder, E	Germany	German Aerospace Center	26	525
10	Armbrecht, G	Germany	Charité University of Medicine	25	1043
11	Macias, BR	USA	NASA Johnson Space center	24	805
12	Watenpaugh, DE	USA	University of Texas Arlington	24	971
13	Zange, J	Germany	German Aerospace Center	22	339
14	Levine, BD	USA	University of Texas	21	1054
15	Trappe, SW	USA	Ball State University	21	1619
16	Linnarsson, D	Sweden	Karolinska Institute	21	354

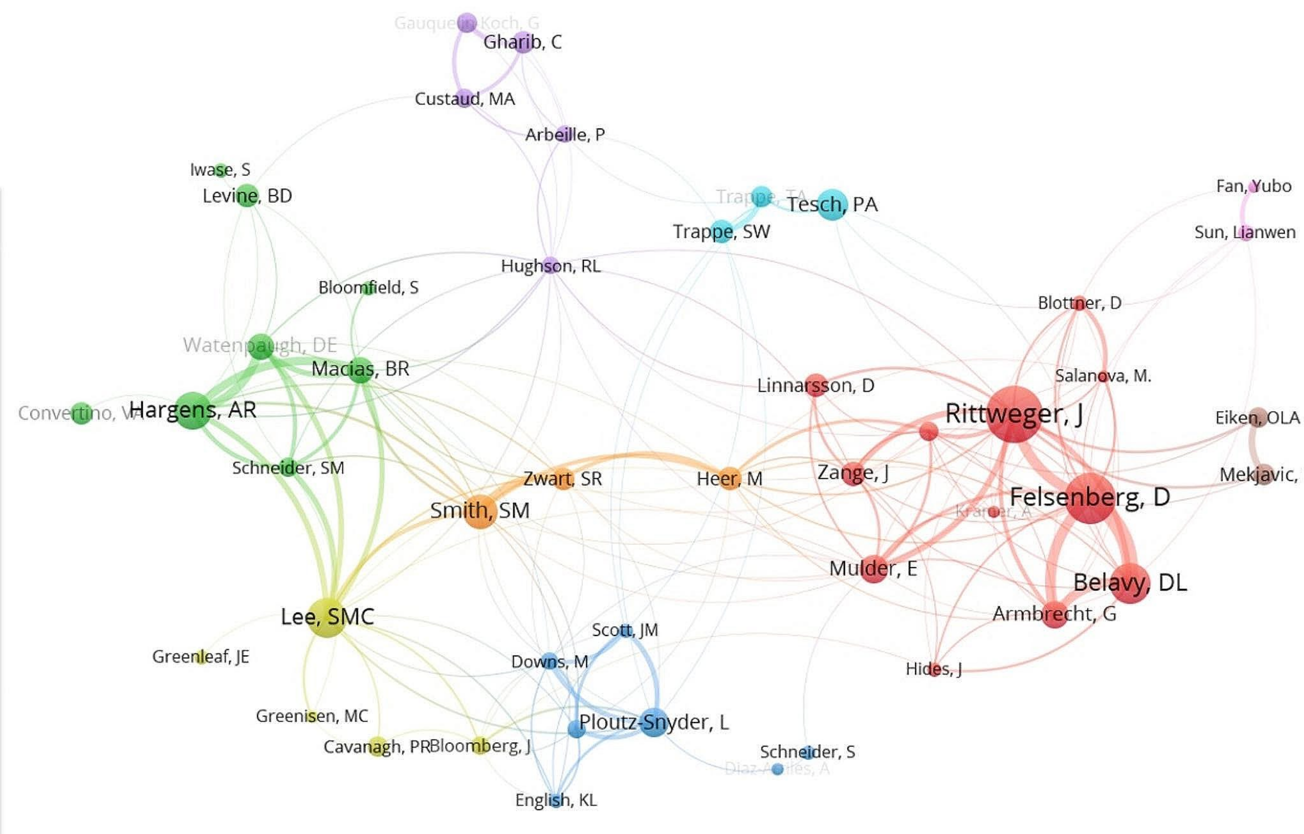

Fig. 7 Network visualization map of research collaboration among authors

Smith (Johnson Space Center), Dr. Macias (Johnson Space Flight Center), Dr. Levine (University of Texas), and Dr. Ploutz-snyder (Universities Space Research Association).

Dr. Sun Lianwen from the Beihang University was the leading author in China. She has closely collaborated with Dr. Fan Yubo from Beihang University. Besides, they have also worked with German leading authors, including Dr. Felsenberg, Dr. Belavy, Dr. Aembrecht and Dr. Blottner from the Charité–Universitätsmedizin Berlin.

Source Journals and Cited Journals

A total of 1,520 included articles were published in 530 journals. The analysis of source journals can help identify the mainstream journals in this field for readers and potential contributors. Table 6 shows the top 10 source journals and co-cited journals with the largest number of publications, as well as their impact factor (IF), H-index and Journal Citation Report (JCR) quartile (Q) rankings of the journals. The impact factors for the top 10 source journals ranged from 1.05 to 6.29 and the H-index ranged from 62 to 268. The *Aviation, Space and Environmental Medicine* (renamed the *Aerospace Medicine and Human Performance* after 2015) published the most publications, with 169 related articles.

Journal of Sports Medicine and Science received the highest IF ($n=52$; IF = 6.29; H-index = 203). The number of citations of the journal received can reflect its importance in the field of research (Aksnes et al. 2019). The more citations it received, the greater impact it will be. Table 5; Fig. 8 show that the highest cited journal was the *Journal of Applied Physiology* (IF = 3.88; H-index = 211), with a total of 6986 citations. The *Journal of Aerospace and Environmental Medicine* has the highest number of publications and the second highest number of citations. Three of the top 10 journals, *Journal of Astronautics, Sports Medicine and Science*, and *Frontiers in Physiology*, ranked Q1 according to the 2021 JCR. Four of the top 10 co-cited journals, *Sports Medicine and Science*, *Journal of Bone and Mineral Research*, *Acta Astronautica*, and *Journal of Physiology-London* also ranked Q1.

Time Evolution of Keywords

Analyzing the frequency of keywords used in the article can help understand the main theme of the research question. Our study identified 4,100 keywords from the 1520 articles. We extracted the top 40 most common keywords (van Eck and Waltman 2010) and are listed in Table 7. They spanned over areas of space environment, physiological mechanism, clinical significance, scientific experiment method, protection strategy and other directions.

Keywords related to space environment were microgravity ($n=241$), spaceflight ($n=202$), weightlessness ($n=49$), astronauts ($n=39$), and space ($n=15$). Keywords related to physiological mechanisms included humans ($n=32$), muscle ($n=31$), bone ($n=19$), skeletal muscle ($n=23$), heart rate ($n=18$), cardiac output ($n=18$) and blood pressure ($n=16$). Keywords related to clinical significance

Table 6 Top journals with the most publications of the field and their highly cited journals

Rank	Source journal	No. of published articles(n)	IF	H-Index	JCR Quartile Ranking	Cited journal	Citation	IF	H-Index	JCR Quartile Ranking
1	Aviation Space and Environmental Medicine	169	1.05	62	Q3	Journal of Applied Physiology	6986	3.88	211	Q2
2	Journal of Applied Physiology	137	3.88	211	Q2	Aviation Space and Environmental Medicine	2995	1.05	62	Q3
3	Acta Astronautica	98	2.95	68	Q1	European Journal of Applied Physiology	1480	3.35	118	Q2
4	European Journal of Applied Physiology	65	3.35	118	Q2	Medicine and Science in Sports and Exercise	1423	6.29	203	Q1
5	Medicine and Science in Sports and Exercise	47	6.29	203	Q1	Journal of Bone and Mineral Research	1062	6.39	223	Q1
6	Frontiers in Physiology	45	4.76	75	Q1	Journal of Physiology-London	998	6.23	216	Q1
7	Plos One	19	3.75	268	Q2	Bone	929	4.6	183	Q2
8	Bone	18	4.6	183	Q2	Acta Astronautica	831	2.95	68	Q1
9	American Journal of Physiology-Regulatory Integrative and Comparative Physiology	17	3.21	160	Q2	American Journal of Physiology	623	5.13	180	Q2
10	NPJ Microgravity	17	4.97	\	Q2	Acta Physiologica Scandinavica	576	2.55	\	Q2

Note: IF denotes impact factor from Web of Science core collection version 2021 published in Jul 2022; JCR denotes journal citation report quartile rankings; AVIATION SPACE AND ENVIRONMENTAL MEDICINE is now renamed as AEROSPACE MEDICINE AND HUMAN PERFORMANCE. The number of publications denotes the total before and after the name change. IF and H index are the results of the latter. NPJ MICROGRAVITY is supported by NASA and does not provide H-index

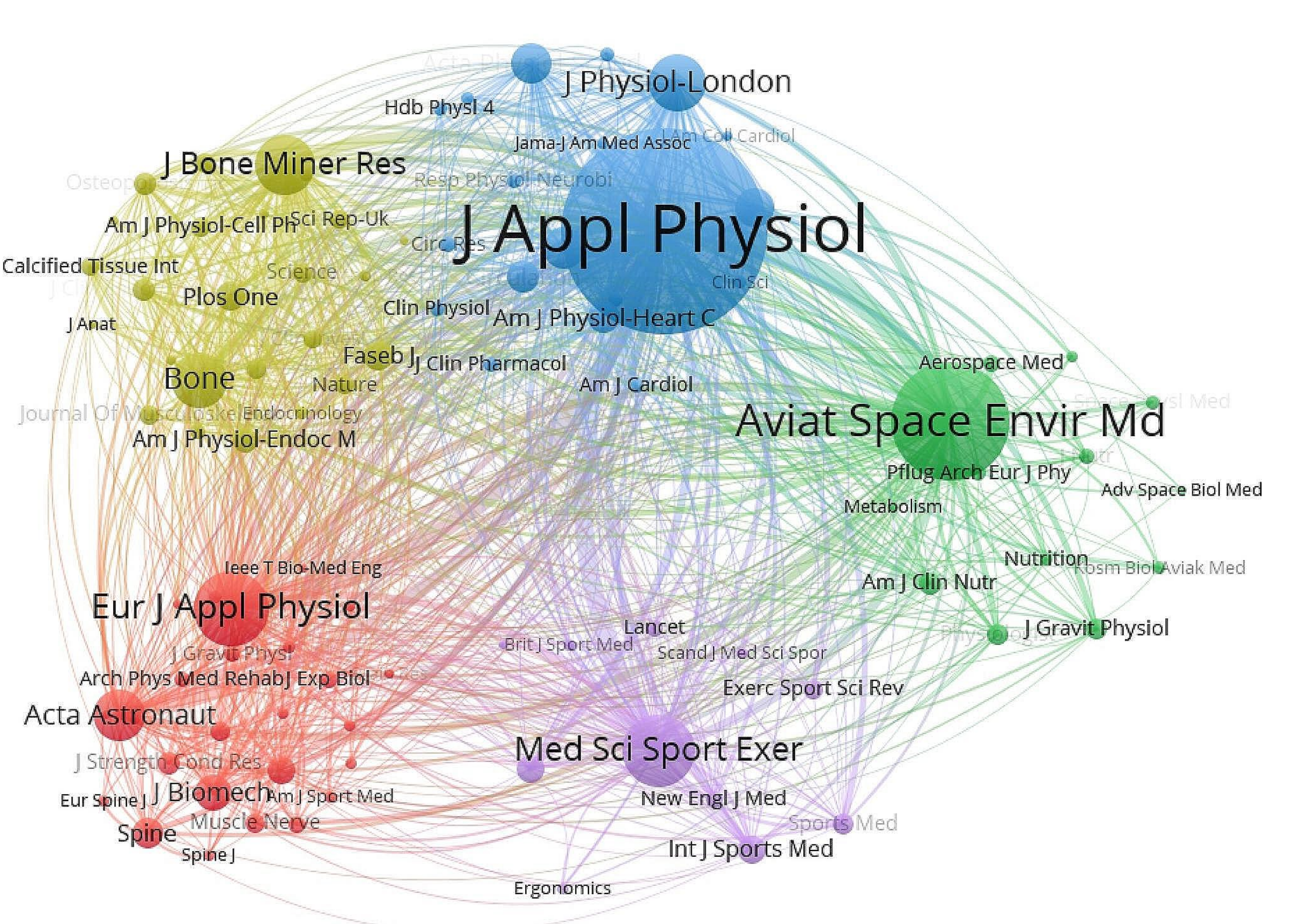

Fig. 8 Co-citation network by journals

included muscle atrophy ($n = 67$), bone loss ($n = 24$), deconditioning ($n = 24$), osteoporosis ($n = 21$), cardiovascular deconditioning ($n = 20$), orthostatic intolerance ($n = 15$) and strength ($n = 14$). Keywords related to experimental methods included bed rest ($n = 87$), artificial gravity ($n = 48$), simulated microgravity ($n = 30$), head-down tilt ($n = 30$), unloading ($n = 27$), hindlimb unloading ($n = 22$), hindlimb suspension ($n = 20$), immobilisation ($n = 27$), MRI ($n = 30$), electromyography ($n = 16$), rats ($n = 16$), inactivity ($n = 19$), lower body negative pressure ($n = 14$) and international space station (ISS) ($n = 14$). Keywords related to protection strategy were countermeasure ($n = 113$), exercise ($n = 106$), resistance exercise ($n = 30$), exercise countermeasure ($n = 29$) and rehabilitation ($n = 20$). Keyword related to physiological mechanism was biomechanics ($n = 16$).

The density map of the superposition of high frequency keywords (frequency ≥ 10) is shown in Fig. 9. Each of the high frequency keyword has a color representing density. The higher the weight and frequency of the keyword, the closer the color of the keyword is to red.

The evolution of keywords over time can reflect the change of research trend and frontier direction. Hotspot words refer to the keywords with high frequency change rate and fast growth rate in a period of time. The keyword emergence map visualizes the time evolution of each hotspot word, which can clearly illustrate the change of research hotspots.

We conducted a hotspot analysis based on a minimum frequency of keywords and annual hot words of five and three, respectively (van Eck and Waltman 2010), as shown in Fig. 10. The circle position in the Fig. 9 corresponded to the emergence word and the emergence year; The circle size represents the total frequency of emergent words. The larger the circle size indicates the higher frequency. The length of the horizontal line represents the duration of the hot keyword as an important keyword. The emergence intensity of keywords can reflect the hotspot topics and development trend in this field.

Microgravity was the centered hotspot surrounded by topics, including spaceflight, hind leg hanging, simulated microgravity, and simulated weightlessness. This hotspot

Table 7 Top 40 most common keywords

Rank	Keywords	Frequency	Proportion (%)
1	Microgravity	241	14.84
2	Spaceflight	202	12.44
3	Countermeasure	113	6.96
4	Exercise	106	6.53
5	Bed rest	87	5.36
6	Muscle atrophy	67	4.13
7	Weightlessness	49	3.02
8	Artificial gravity	48	2.96
9	Astronaut	39	2.40
10	Humans	32	1.97
11	Muscle	31	1.91
12	MRI	30	1.85
13	Head-down tilt	30	1.85
14	Resistance exercise	30	1.85
15	Simulated microgravity	30	1.85
16	Exercise countermeasure	29	1.79
17	Immobilization	27	1.66
18	Unloading	27	1.66
19	Disuse	24	1.48
20	Deconditioning	24	1.48
21	Bone loss	24	1.48
22	Skeletal muscle	23	1.42
23	Hindlimb unloading	22	1.35
24	Osteoporosis	21	1.29
25	Cardiovascular deconditioning	20	1.23
26	Hindlimb suspension	20	1.23
27	Rehabilitation	20	1.23
28	Bone	19	1.17
29	Inactivity	19	1.17
30	Heart rate	18	1.11
31	Blood pressure	16	0.99
32	Cardiac output	16	0.99
33	Biomechanics	16	0.99
34	Electromyography	16	0.99
35	Rats	16	0.99
36	Space	15	0.92
37	Orthostatic intolerance	15	0.92
38	ISS	14	0.86
39	Lower body negative pressure	14	0.86
40	Strength	14	0.86

cluster related to negative-inclined bed-rest experiments that could induce weightlessness to investigate its influence on the cardiovascular, nervous, respiratory, and musculoskeletal systems mainly through electromyography and magnetic resonance imaging. In fact, there was no hot keywords related to space countermeasures in published articles before 1998. From 1996 to 2000, studies targeted on orthostatic hypotension by measuring blood flow and volume using animal models. From 2001 to 2010, the research interest has shifted to the design of physical training exercises to tackle the health problems of osteoporosis, muscle atrophy, and abnormality on the nervous and cardiovascular systems. Artificial gravity was the main theme in the past decade (2011–2022) with interdisciplinary sports countermeasure research on physiology, brain science, biomechanics, and aerospace medicine. Mars mission was the hotspot trend after 2016, which aligned with the latest goal/destination of space exploration. Transdisciplinary physical medicine could be the future research direction on sports countermeasures.

Discussion

This study aimed to conduct a comprehensive bibliometric review on all related studies published in the *Web of Science Core Collection* database from 1992 to 2022. To explore the research and direction status, key information included the annual number of publications, influential institution, author, country/region, literature cited, key research topics, keyword distribution, global and local collaboration network were analyzed by using the visualization analysis of word cloud map and emergent word map. The research hotspots and emerging research directions in this field were also highlighted for the readers.

The current results indicated that the research on astronaut sports countermeasures covered a wide range of fields and diversified perspectives. The research on astronaut sports countermeasures shows an increasing trend and number of research fields included sports science, physiology, public environment and occupational health, engineering aerospace, general medicine, multidisciplinary science, neuroscience, biophysics, medical research and experimental biology. The new material, processes, technologies, protocols, and interdisciplinary perspectives could be analyzed and addressed the key health problems among astronauts (Des Marais et al. 2008).

In the past 30 years, core collaborations were developed among countries and institutions. International collaboration in the space field has become an inevitable solution among key contributing countries/institution. Collaboration can promote the experience sharing and facilities sharing, including international space station. Through international collaboration, technology bottlenecks can be overcome and new innovation can be driven for the development and impact of space science (Nair et al. 2008). The United States and Germany have been the pioneer in the space countermeasure research, working closely with other members in the International Space Station. The three collaboration alliances comprised of the group of the United States, Germany and the United Kingdom, the group of Germany, Italy and the United Kingdom, and the group of Russia, France, and Germany. NASA have led several renowned universities,

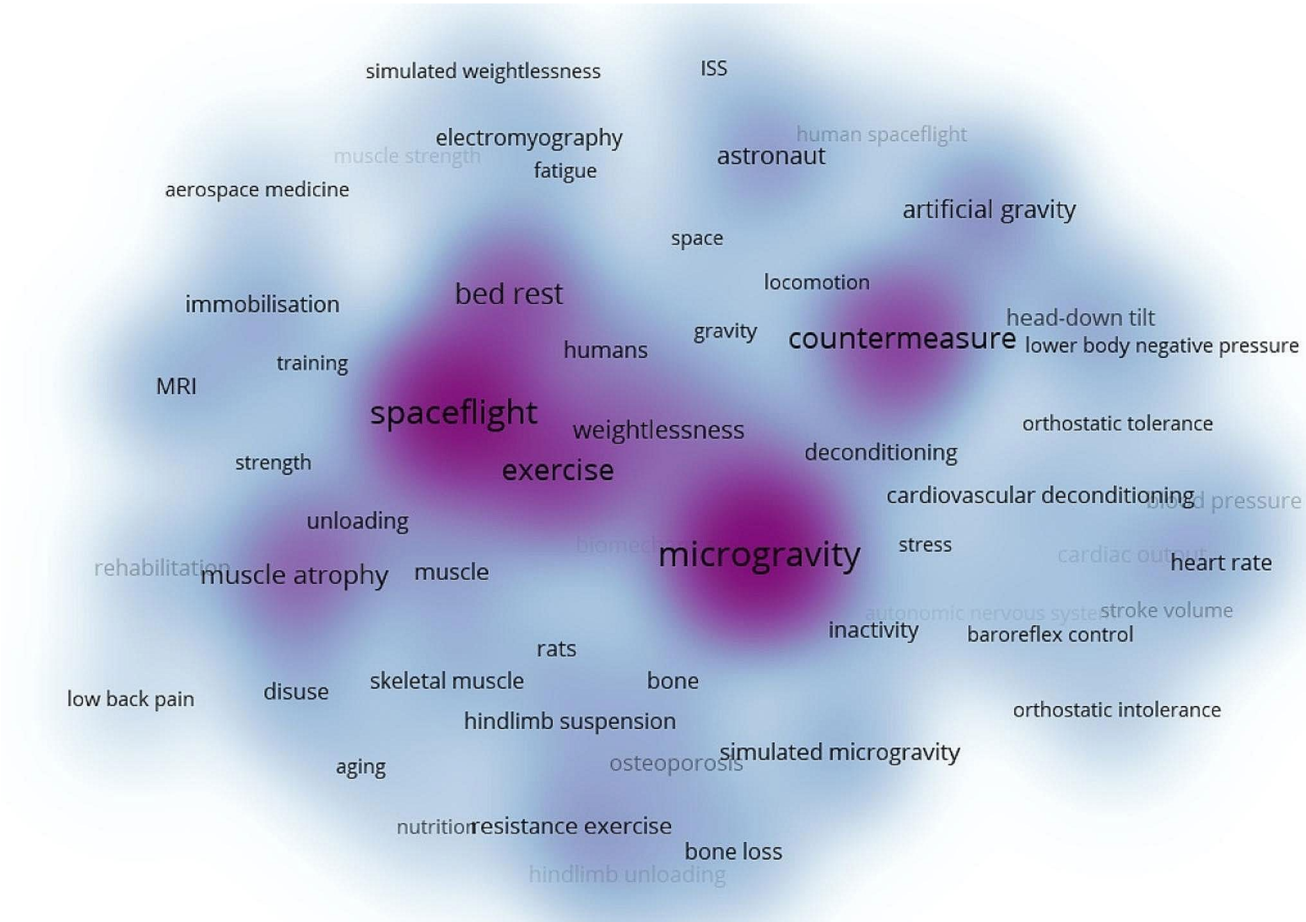

Fig. 9 Density and overlay visualization map of high frequency keywords

advanced laboratories, and top medical schools in the United States, forming the core research cooperation network.

While United States (NASA) is considered as the most influential leader in the collaboration network, international collaborations on sports countermeasures of astronaut remained low. In 2011, the US Congress passed the "Wolfe Amendment", which has prohibited NASA to initiate any China-US collaboration research (Grimsley 2021). Chinese officials are not allowed to visit any NASA facilities. The policy has isolated Chinese space scientists and research institutions from the US-centered collaboration network. In other words, China would encounter difficulties to collaborate with countries that partnered with US.

The new establishment of China space station in 2023 turns over a new leaf to the landscape of international collaborations (Gu 2022). Currently, a total of 42 projects from 27 countries have proposed to work in the Chinese space station (Zhao 2021). The first batch of nine projects from 17 countries (Switzerland, Poland, Germany, India, Russia, Belgium, Italy, Kenya, Mexico, Japan, Saudi Arabia, Norway, France, the Netherlands, Belgium, Peru, Spain) have been approved (Gu et al. 2020). These research projects investigations examined space tumors and pathogenic bacteria under microgravity (Zhao 2021). With the further opportunity from the China Manned Space Program, China has enormous potential to expand its global influence and advance scientific advancements in the research of space countermeasures. Although China has top-tier scientific institutes, they still need to be enhanced to strengthen the scientific research platforms for astronaut sports countermeasures. China Astronaut Research and Training Center is the main aerospace related research in China and plays an important role to nurture local collaboration network, with the Chinese Academy of Sciences, Chinese Academy of Sciences university, Tsinghua University, Peking University, Beijing University of Aeronautics and Astronautics, the Fourth Military Medical University, Chinese Academy of Medical Sciences, and other well-known institutions. Our bibliometric analysis revealed that China is still lagged behind the top-tiers and expanded collaborations and influential power.

There were some limitations in this study. Firstly, the literature search was confined to English-language articles, leading to potential language and selection bias. Notably,

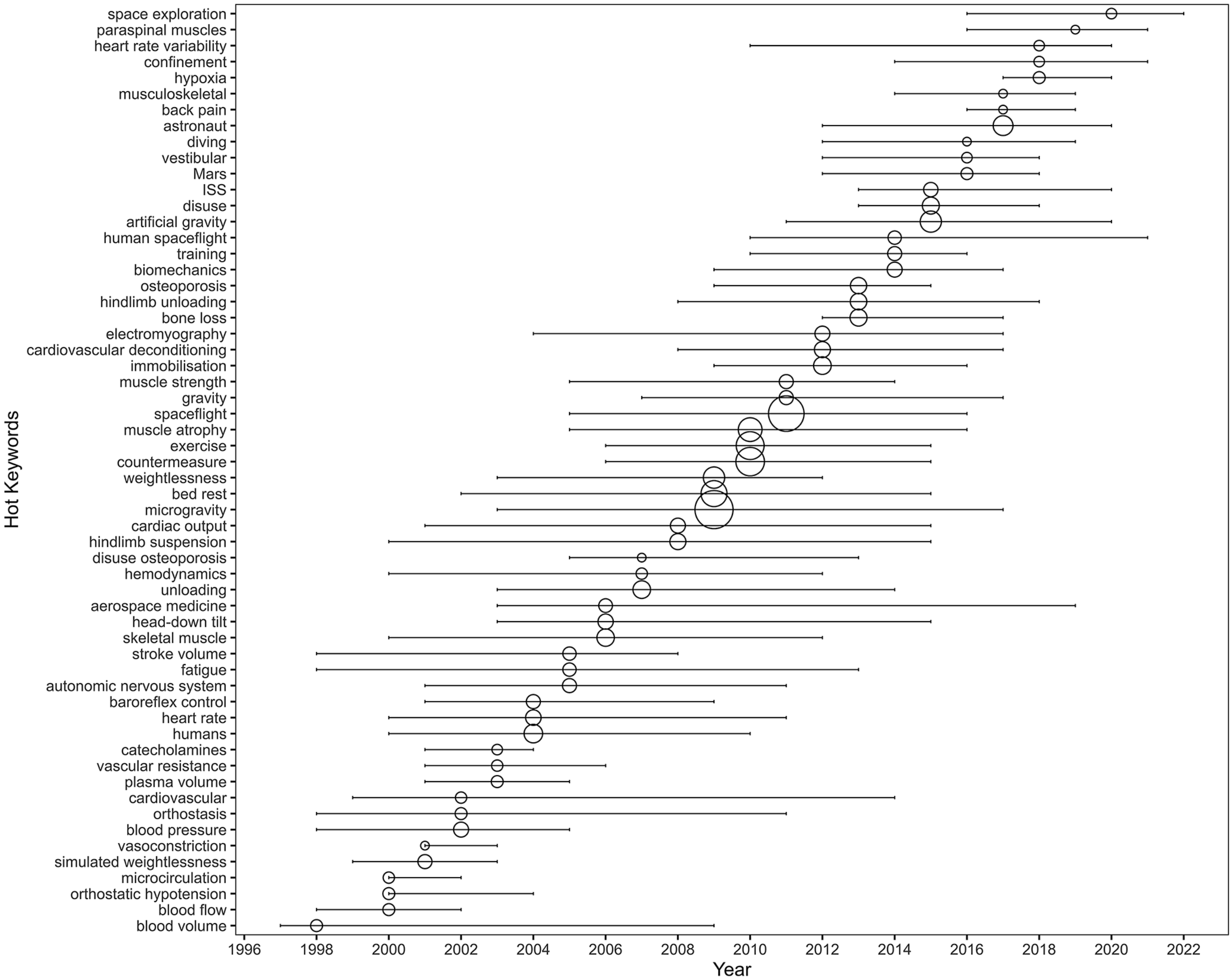

Fig. 10 The temporal evaluation graph of hot keywords

significant research contibutions from non-English-speaking countries such as China and Russia may be underrepresented. Secondly temporal lag could happen due to reliance on databases that may not include the most recent publications, resulting in an incomplete snapshot of the current research landscape. With respect to the contextual limitations, a considerable number of conutermeasures were examined on non-astronaut populations due to the scarcity of astronauts. Such studies may also be categorized under broader health and exercise disciplines rather than the specific space medicine or astronaunt research. Future bibliometric analyses that distinguish between countermeasures studies on astronaut and non-astronaut populations are recommended to summarize the trend across populations. Thirdly, considering that the needs of astronaut countermeasures are mission-specific and subject to the priorities and fundings by space agencies, the fluctuation of research focus across historical milestones in space mission agendas may lead to inconsistent research output to inform future direction. Lastly, while the current bibliometric analysis primarily focused on physical training as countermeasures for astronauts, future studies incorporated other countermeasures such as pharmacological interventions, nutrition strategies, and protective clothing can be considered to provide comprehensive understanding of multi-disciplinary measure approach to improve the health and fitness in astronauts.

In summary, assessment methods and countermeasures have increasingly examined and integrated into the space training over past 30 years. The design of physical training exercise to tackle the problems on osteoporosis, muscle atrophy, and abnormality on the nervous and cardiovascular system and artificial gravity with interdisciplinary sports countermeasure research on physiology, brain science, biomechanics, and aerospace medicine could be future research trend of the field. We believed that incorporating “medicine” into astronaut sport countermeasures could be the key future direction. Machine learning, deep learning, reinforcement learning, and other artificial intelligence techniques are recommended to emerge all parameters to optimize the countermeasures.

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Data Availability The data that support the findings of this study are available from the corresponding author (Z.Y.), upon reasonable request.

Declarations

Ethical Approval Not applicable, as this study did not involve either human or animal studies.

Competing Interests The authors declare no competing interests.

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