*Review article*

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# Global trends and hotspots in research on extended reality in sports: A bibliometric analysis from 2000 to 2021

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## Abstract

**Objective:** Extended reality technologies (e.g. virtual reality (VR), augmented reality (AR) and mixed reality (MR)) are gaining popularity in sports owing to their unique advantages. This study aims to analyse the progress of the application of extended reality technology in sports and reveal its cooperative features, research hotspots and development trends.

**Methods:** We searched the literature in the Web of Science Core Collection (WoSCC) database within the period 2000 to 2021 and conducted a bibliometric analysis. The analysis methods included statistical, co-occurrence, hierarchical clustering and social network analyses.

**Results:** A total of 340 articles were gathered. The literature related to its research showed an increasing trend over time. The paper collaboration rate was 90.88% (309/340 papers), and the degree of author collaboration was 3.96 (1345/340). *VR* was found to be the most productive journal, and Queen's University Belfast was the most productive institution. The United States, China and the United Kingdom were the three main contributors to the field. The foundational themes in sports extended reality research were (i) sports games and extended reality systems, (ii) virtual simulation devices and artificial intelligence, (iii) sports training and performance and (iv) age-appropriate physical activity, sports rehabilitation and physical education.

**Conclusion:** The level of author collaboration was low, but the degree of author collaboration is largely on the rise. The closeness of the collaboration between institutions and countries was also low. In addition, the subject of sport extended reality is relatively fragmented. Therefore, more research is needed to strengthen it in the future.

## Keywords

Extended reality, virtual reality, augmented reality, mixed reality, sports, bibliometric analysis, visualised analysis, trend

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## Introduction

In recent years, researchers have shown great interest in the application of computer technologies in sports.[1] These technologies include computer modelling techniques, multi-sensor technologies, data analysis technologies and network-sensing and recognition technologies.[2] Virtual reality (VR) has gained particular attention in the sports field as an emerging interaction and display technology.[3] However, it was first applied to sports research in the 1990s.[4] Today, it is used in many fields, such as sports training,[5,6] physical education,[7,8] sports mental health,[9,10] sports rehabilitation[11] and sports events.[12]

VR uses three-dimensional computer technology to simulate the creation of virtual worlds with multiple

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sensory experiences that allow or force the user to have the sensation of physically experiencing another situation.[13] VR has three important characteristics, namely immersion, interactivity and imagination.[14] In sports, it allows athletes to immerse themselves and directly interact with the virtual environment.[15] For example, Petri et al.[16] used VR for sport-specific reaction training to improve the reactions of karate practitioner to virtual character attacks. With the advancement and development of VR, augmented reality (AR) and mixed reality (MR) are gradually becoming popular in sports.[17] AR is a variant of the virtual environment that combines virtual and real environments.[18] AR superimposes virtual objects in the real world for display and interaction.[19] MR combines aspects of VR and AR to bring together the real world and the virtual world to produce a new environment that achieves a high degree of coexistence and interaction of objects.[20,21] To avoid the repetition of ‘VR/AR/MR’, they are collectively referred to by the term extended reality henceforth.[22]

The key elements that define the application of extended reality to sports are the use of extended reality technology to generate sports-related content and the interaction of athletes with the virtual environment.[1] The application of extended reality in sports has many advantages. Extended reality is used as an aid in sports training to build virtual training scenarios based on the specific requirements of the training.[23] It can enable some sports (e.g. surfing) to complete training tasks without environmental requirements such as wind or waves.[24] Extended reality also provides personalised training for the tactics of specific opponents and the ability to improve athletic skills in a three-dimensional way.[25] In sports rehabilitation, extended reality is an important tool for the rehabilitation training of impaired motor functions.[26] Virtual rehabilitation systems break through the limitations of traditional training methods and provide accurate measurement, assistance, monitoring and training techniques to ensure the effectiveness of sports rehabilitation training.[27] In addition, extended reality is involved in live sports events. Researchers have developed an immersive ‘tabletop soccer’ system that presents World Cup matches in three dimensions on a private tabletop to watch the action from a close distance.[28]

Extended reality technology is becoming increasingly popular in the field of sports technology. However, there is a lack of systematic generalisation of the progress of research applications of extended reality in sports, and the effectiveness of the applications. In this context, it is necessary to explore the progress of research on the application of extended reality to sports. Bibliometric analysis is a method of analysing literature using bibliometric theory and applying mathematical and statistical methods to analyse relevant literature.[29] Visualisation tools are necessary for bibliometric analysis because of the abstract nature of the target textual information. With its advantages of comprehensive quantitative statistics, visual presentation of information, objective description and evaluation, bibliometric analysis has become an important method for global analysis and investigation in various scientific fields.[30] Calabuig-Moreno et al.[31] conducted a bibliometric analysis of articles on physical education technology using HistCite, BibExcel and VOSviewer to reveal research hotspots and evolutionary pathways in the field. Guo et al.[32] analysed the prospects for the use of extended reality technologies in education using the bibliometric analysis tools of VOSviewer and CiteSpace. Shen et al.[33] collected 2704 articles in the field of mHealth and used HistCite, CiteSpace, bibliographic information co-occurrence mining system (BICOMS), UCINET and IBM SPSS Statistics bibliometric tools to reveal current research hotspots and developments in the field of mHealth. Taj et al.[34] analysed the literature related to persuasive technologies and health behaviour change using HistCite, CiteSpace, BibExcel and Science of Science (Sci2) software to derive the current state of research, research hotspots and frontier issues in the field.

To explore and analyse the current state of development, research frontiers and research hotspots in sports extended reality research, we used bibliometric analysis. This study focuses on the following questions: How has current research on sports extended reality evolved over time? What research forces and research directions have been the main areas of focus? Which countries, institutions and journals pay the most attention to extended reality in sports research? What are the current and future research hotspots and frontiers?

## Materials and methods

### Data collection

This study used the Web of Science Core Collection (WoSCC), an important database for accessing global academic information, as the data source. WoSCC contains more than 12,400 authoritative and high-impact academic journals worldwide and is continuously and dynamically updated. To search as comprehensively as possible for publications related to extended reality research in sports, the following search strategy was developed: #1 TS = ((‘virtual reality’ OR ‘augmented reality’ OR ‘mixed reality’)); #2 TS = ((‘virtual environment’ OR ‘virtual system’ OR ‘virtual world’ OR ‘virtual partner’)); #3 TS = ((‘sport*’ OR ‘Physical Education’ OR ‘athletes’ OR ‘physical training’ OR ‘sports performance’ OR ‘physical exercises’)); and #4 ((#1 OR #2) AND #3). The time range was 2000–2021, and 946 bibliographic records were retrieved after the removal of duplicate records.

To refine the study, JZ and JT independently screened the retrieved papers under the supervision of JM to determine whether they met our inclusion and exclusion criteria.

Disagreements were discussed until a consensus was reached. The inclusion criteria were as follows: (i) the content of the article focused on the field of sports and (ii) the article dealt with at least one of the extended reality technologies. The exclusion criteria were as follows: (i) records related to announcements and book reviews rather than regular papers, and in addition, conference papers were excluded because the distribution of journals was analysed; and (ii) studies focusing on rehabilitation training for patients with chronic diseases (e.g. concussions) rather than athletes. A total of 340 literature records published from 2000 to 2021 were obtained as the basis for the subsequent bibliometric analysis. Figure 1 shows the search and selection flowchart of this study.

## Design of the data analysis method

In this study, MS Excel 2007 and HistCite[35] (visual analysis tool) were used to analyse the distribution of literature and journals, and HistCite and CiteSpace[36] (visual analysis tools) were used to analyse authors, institutions, countries and collaborations. Research hotspots were analysed using the BICOMS,[37] Sci2[38] (knowledge graph analysis software), IBM SPSS Statistics[39] (statistical analysis software) and UCINET[40] (social network analysis software). The analysis methods included statistical, burst, co-occurrence, hierarchical cluster and social network analyses. The analysis indicators included years, journals, authors, institutions, countries and keywords.

In this study, we used MS Excel 2007 and HistCite to analyse the distribution of literature and journals on sports extended reality and to identify core journals. The literature in this field is published in core journals with high frequency and high academic level, which often indicates a concentration of research hotspots and development trends.

In this study, the visual analysis tool HistCite was used to analyse authors, institutions and countries. The total local citation score (TLCS) and total global citation score (TGCS) were calculated. TLCS, which indicates the frequency with which the literature is cited in the current dataset, focuses on the impact of the literature in a specific research area. TGCS, which indicates the total frequency with which the literature is cited in the Web of Science (WoS) database, indicates the impact of the literature in the WoS database.[41] In addition, the average local citation score (ALCS) is the average of the TLCS and refers to the average frequency of articles being cited within the current dataset. The average global citation score (AGCS) is the average of the TGCS and refers to the average frequency of articles cited in the WoS database.[42] Overall, TLCS and TGCS are vital indicators that enable the relevance of the included research papers to be assessed.[43] In addition, CiteSpace generates visual maps of three types of collaborations: author collaborations, institutional collaborations and country collaborations. The nodes in the

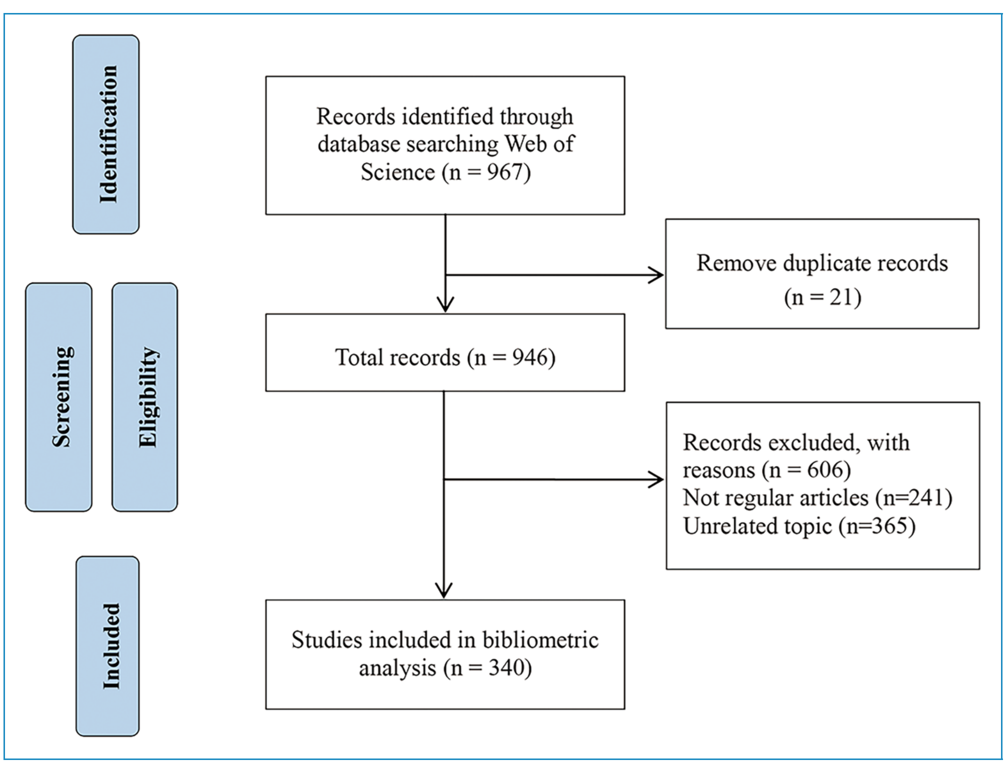


**Figure 1.** Flowchart of search and study selection.

visual map often represent authors, institutions and countries. The size of the nodes is proportional to how often they are cited; the larger the nodes, the more frequently they are cited, and the more attention they receive. The lines between nodes reflect the degree of cooperation between nodes; more lines indicate closer cooperation between nodes.[44]

Analysis of the research hotspots was divided into four stages. First, we counted the frequency of the keywords using BICOMS and created a co-word matrix. The keywords identified in the literature were cleaned up and merged by two authors independently, and in case of disagreement, a third author was consulted until a consensus was reached. The keywords were processed according to the following principles: (i) combining keywords with the same meaning (i.e. the words 'virtual reality', 'VR', 'virtual reality technology' are combined into 'virtual reality'); (ii) the keywords are standardised (e.g. 'training' is replaced by 'sports training'); (iii) merging of singular and plural keywords (e.g. 'sport' and 'motor skill' are replaced by 'sports' and 'Motor skills'). Subsequently, we performed word frequency statistics on the keywords and selected 76 keywords with frequencies of 3 or greater to generate a $76 \times 76$ co-word matrix.

Keyword burst detection was then performed, and keyword burst bar graphs were created. Kleinberg's burst detection algorithm[45] can detect sudden changes in the frequency of words or phrases, and obtain meaningful burst words. This algorithm is used in Sci2 to calculate burst words, so we used Sci2 for burst detection of keywords in bibliographic records to identify burst keywords and calculate burst intensity. A total of 109 keywords with burst strengths of 1 or greater were obtained. The keywords with a frequency of 3 or greater and burst strength of 1 or greater were further calculated, resulting in 63 keywords.[46] Sci2 was used to plot the burst visualisation for the top 20 keywords. The left side of each bar has the corresponding burst word, the length of the bar represents the burst time span of the burst word, the two ends of the bar represent the start and end times of the burst occurrence, and the area of the bar indicates the burst intensity.[42]

Next, the $76 \times 76$ co-word matrix created by BICOMS was subjected to a hierarchical clustering analysis. We calculated the intersection of 76 high-frequency words and 63 high-burst words and removed rows or columns that did not intersect in the $76 \times 76$ co-word matrix to obtain a $48 \times 48$ co-word matrix. Similar to prior studies of hierarchical cluster analysis,[47–49] it was converted into a similarity matrix using SPSS 26.0 in order to eliminate the effects brought on by frequency disparities between keywords in the co-word matrix. In this matrix, the values in the cells represent the degree of similarity between two keywords. The larger the value, the closer the relationship between the two, and the greater the degree of similarity.[50] The similarity matrix tends to cause excessive errors in the results. To further reduce the error, the similarity matrix was converted to a dissimilarity matrix using MS Excel 2007. Hierarchical clustering analysis of the dissimilarity matrix was performed using SPSS 26.0, with Ward's method as the cluster method[39] and Squared Euclidean distance as the distance measure to obtain a keyword clustering dendrogram.[51]

Finally, the similarity matrix was analysed using UCINET 6 to obtain a visual network graph. UCINET 6 was used to calculate the network density, which has values in the range [0, 1] and reflects the closeness of the connections between the nodes in the network.[51] The network density scores are interpreted on the following scales: low level (<0.3), medium level (favourable) (0.3–0.5) and high level (>0.5).[52] The Netdraw function of UCINET was then used to create a social network diagram. The network relationships of keywords are connected by nodes, and the position of a node represents its influence on the organisation; the closer the position is to the centre, the higher the level of importance and the greater the influence.[53]

## Results

### *Literature distribution*

*Growth of literature.* The publication output of sports extended reality research from 2000 to 2021 is shown in Figure 2, indicating that the number of papers in sports extended reality research has risen annually, from 2 in 2000 to 82 in 2021. The average number of articles published per year before 2015 was <10. After 2015 there was a great increase, reaching a maximum of 82 articles in 2021, which is 27.33 times more than that of the number published 12 years ago (2009). It can be seen that research related to extended reality in sports has received increasing attention. In terms of publication language, the vast majority were written in English (97.06%, 330/340), followed by Spanish, Portuguese and Russian.

Over the past 20 years, the number of cumulative publications has increased from 2 to 340 (Figure 3). Based on the literature logistic growth curve,[42] the formula is calculated as follows:

$$y = A / (1 + Be^{-kt})$$

The equation was obtained by fitting the curve: $y = 18154.84 / (1 + 15243.61e^{-0.26t})$, ($R^2 > 0.937$), where y is the cumulative number of papers and t is the number of years since 2000. The number of relevant publications by 2022 can be inferred to be approximately 100. The inflection point of the equation is $t = \ln(15243.61)/0.26 = 37.05 \approx 37$

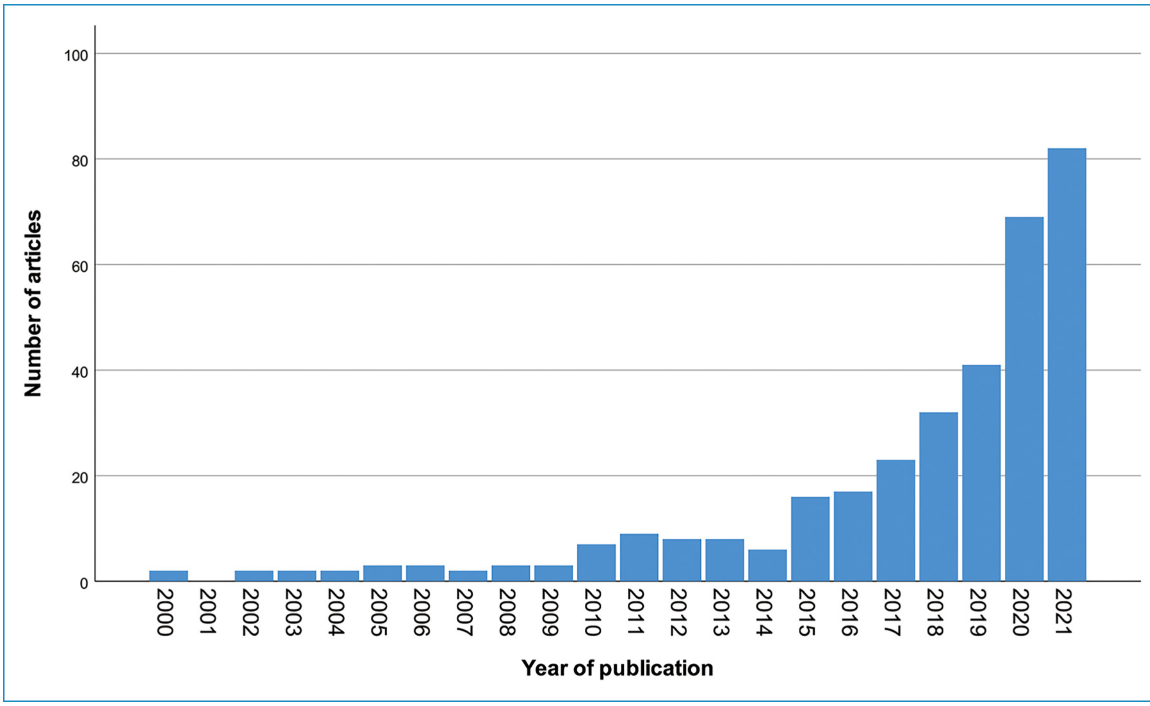


**Figure 2.** Number of publications by year.

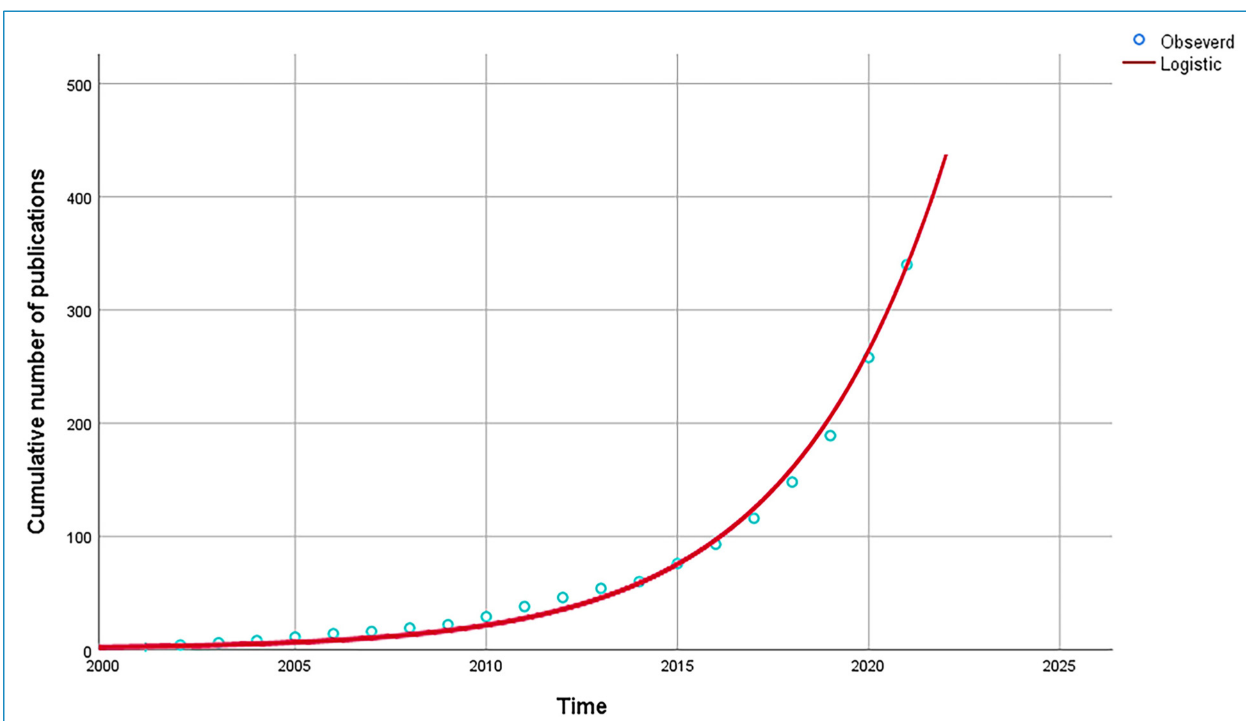


**Figure 3.** The relationship between the cumulative number of articles published and year since 2000.

(i.e. 2036). It can be inferred that extended reality research in sports is now in a period of rapid growth and will enter a phase of slower growth by 2036.

*Distribution of journals.* Literature related to extended reality in sports was published in 141 journals between 2000 and 2021. These journals were arranged in descending order of article volume, and the number of articles was divided into three regions of approximately equal numbers: core region, related region and discrete region journals. As shown in Table 1, the core region journals covered the top 20 journals (14.18%, 20/141) with 115 papers, accounting for 33.82% of the 340 papers. Among them, *Virtual Reality* was the most prolific, with 10 publications. The relationship between the number of journals in the core region and the number of journals in the subsequent relevant and discrete regions was approximately 1:2:$2^2$, which is consistent with Bradford's law of scattering.[54]

The journal impact factor (IF) is used to assess the quality of journals, and excellent journals usually have a high IF.[55] Table 1 shows that 15 of the 20 journals showed an increase in IF in 2021 compared with 2020, except for four journals: *Frontiers in Psychology*, *International Journal of Emerging Technologies in Learning*, *Applied Sciences-Basel* and *Presence-Teleoperators and Virtual Environments*. In addition, the average IF of the top 10 journals reached 3.75 in 2021.

## Cooperation features

**Author collaboration.** Statistical analysis shows that the total number of authors publishing in sports extended reality research is 1117, of which 27.75% (310/1117) are first

**Table 1.** Top 20 most prolific journals on the topic of extended reality research in sports.

| No. | Journals | IF (2020) | IF (2021) | Articles, n (%) | Cumulative percentage |
|---|---|---|---|---|---|
| 1 | *Virtual Reality* | 3.634 | 5.095 | 10 (2.84) | 2.84 |
| 2 | *PLoS One* | 2.74 | 3.24 | 8 (2.35) | 5.29 |
| 3 | *Frontiers in Psychology* | N/A | 2.99 | 7 (2.06) | 7.35 |
| 4 | *Microprocessors and Microsystems* | 1.161 | 1.525 | 7 (2.06) | 9.41 |
| 5 | *Sensors* | 3.275 | 3.576 | 7 (2.06) | 11.47 |
| 6 | *International Journal of Emerging Technologies in Learning* | N/A | N/A | 6 (1.76) | 13.24 |
| 7 | *JMIR Serious Games* | 3.526 | 4.143 | 6 (1.76) | 15.00 |
| 8 | *Journal of Sports Sciences* | 2.597 | 3.337 | 6 (1.76) | 16.76 |
| 9 | *Sustainability* | 2.576 | 3.251 | 6 (1.76) | 18.53 |
| 10 | *Agro Food Industry Hi-Tech* | 4.8 | 6.592 | 5 (1.47) | 20.00 |
| 11 | *Applied Sciences-Basel* | N/A | N/A | 5 (1.47) | 21.47 |
| 12 | *Human Movement Science* | 2.096 | 2.161 | 5 (1.47) | 22.94 |
| 13 | *IEEE Transactions on Visualization and Computer Graphics* | 4.558 | 4.579 | 5 (1.47) | 24.41 |
| 14 | *Mathematical Problems in Engineering* | 1.009 | 1.305 | 5 (1.47) | 25.88 |
| 15 | *Multimedia Tools and Applications* | 2.313 | 2.757 | 5 (1.47) | 27.35 |
| 16 | *Presence-Teleoperators and Virtual Environments* | N/A | N/A | 5 (1.47) | 28.82 |
| 17 | *Scientific Reports* | 3.998 | 4.379 | 5 (1.47) | 30.29 |
| 18 | *Journal of Medical Internet Research* | 5.034 | 5.428 | 4 (1.18) | 31.47 |
| 19 | *Computers & Graphics-UK* | 1.351 | 1.936 | 4 (1.18) | 32.65 |
| 20 | *IEEE Access* | 3.745 | 3.367 | 4 (1.18) | 33.82 |

IF: impact factor; N/A: not applicable.

authors. Among all the authors, 986 (88.27%) published only one paper (986/1117). Table 2 shows the top 7 authors with 5 or more outputs, who have published a total of 40 papers, that is, an average of 5.71 papers per author for the period 2000 to 2021. In addition, the author with the highest number of published papers on sports extended reality research is Kerstin Witte (with seven).

Core authors are those authors in the field who publish with high frequency and influence, calculated according to Price's law,[56] using the following formula:

$$M = 0.749(N_{max})^{\frac{1}{2}}$$

where M is the minimum number of published articles for core authors and $N_{max}$ the maximum number of published articles for core authors. According to the above formula, the minimum number of published papers for core authors is approximately 1.98 ($0.749 \times 7^{1/2}$), implying that each core author has published at least two articles. A total of 126 core authors with 125 published articles were found in this study, accounting for 36.76% (125/340) of the total number of published articles. According to Price's law, a core group of authors has not yet been formed.

The paper collaboration rate is the proportion of co-authored papers to the total number of papers, and the author collaboration degree is the average number of authors per paper at a defined time, both of which reflect, to some extent, trends in collaborative research.[33] A total of 309 co-authored papers were identified in this study, with a paper collaboration rate of 90.88% (309/340). The total frequency of author publications between 2000 and 2021 was 1345, with an author collaboration rate of 3.96 (1345/340). Figure 4 shows a line graph of the degree of author collaboration by year, showing significant fluctuations from 2000 to 2015, with a gradual increase from 2015 onwards.

*Institutional cooperation.* Statistical analysis of institutional data shows that papers on sports extended reality research are distributed among 530 institutions, of which 399 are higher education institutions, accounting for 75.28% (399/530). This shows that higher education institutions are the main sources of research. Table 3 shows the top 10 research institutions in terms of the number of publications and the authors of these research institutions published 53 papers

**Table 2.** Top seven authors on the topic of extended reality research in sports.

| Author name | ORCID | Recs[a] | Percentage[b] | Type of extended reality | Main affiliation | Country |
|---|---|---|---|---|---|---|
| Kerstin Witte | 0000-0001-8711-9335 | 7 | 2.06 | VR(N = 7) | Sports Engineering & Movement Science Otto von Guericke University: Magdeburg | Germany |
| Benoît Bideau | N/A | 6 | 1.76 | VR(N = 6) | (Movement, Sport, Health) Laboratory at the University of Rennes | French |
| Richard Kulpa | 0000-0002-1863-8921 | 6 | 1.76 | VR(N = 6) | Inria Centre de Recherche Rennes Bretagne Atlantique, M2S Lab – University of Rennes 2 | French |
| Petri Katharina | 0000-0002-8099-9285 | 6 | 1.76 | VR(N = 6) | Deutsche Vereinigung für Sportwissenschaft, Otto von Guericke University Magdeburg | Germany |
| Abi Fisher | 0000-0001-9284-6780 | 5 | 1.47 | VR(N = 4)/ AR(N = 1) | University College London, London | The United Kingdom |
| Adrian Hon | 0000-0003-1658-5069 | 5 | 1.47 | VR(N = 4)/ AR(N = 1) | Six to Start, London | The United Kingdom |
| Henry W W Potts | 0000-0002-6200-8804 | 5 | 1.47 | VR(N = 4)/ AR(N = 1) | Institute of Health Informatics, University College London, London | The United Kingdom |

[a]Number of author publications.
[b]Percentage of papers published by the author.
AR: augmented reality; N: number of articles; N/A: not applicable; ORCID: Open Researcher and Contributor ID; VR: virtual reality.

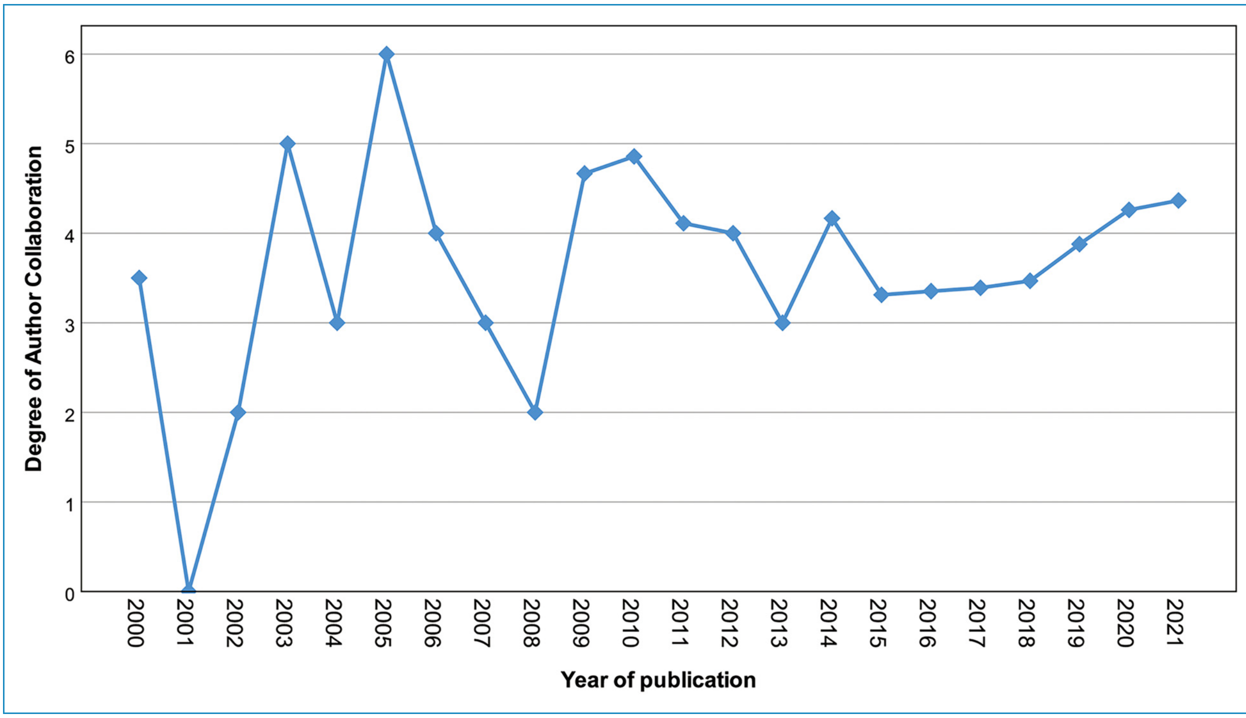


**Figure 4.** The degree of author collaboration by year.

(15.59%, 53/340). Queen's University Belfast performed well, followed by Kyung Hee University and Otto von Guericke University in Magdeburg. The top 10 institutions are all universities, 8 of which are located in Europe and the United States. Queen's University Belfast has the highest TLCS and TGCS among all institutions, indicating its high academic impact and collaboration in the study of extended reality in sports.

The institutional collaboration network graph of sports extended reality research was obtained after pruning, using 20 threshold levels of citation frequency as the benchmark analysis (Figure 5). The figure shows the institutions with three or more publications. There are only a few links between the institutions in the chart; Queen's University Belfast and Université Rennes 2 – Haute Bretagne have collaborated. Nanyang Technological University, Ecole Polytech Fed Lausanne and the University of Tsukuba have collaborated. Monash University and National University of Singapore have collaborated. This indicates a low level of collaboration between institutions. Intermediary centrality can be used to measure the importance of a node in the structure, and higher centrality indicates close logical connections with other institutions and similar research contexts.[57] From the centrality analysis, all research institutions had a centrality of 0. A centrality of 0 and less connectivity between institutions indicate less collaboration between institutions publishing extended reality literature in sports, less intimacy and less similarity in research contexts.

*Country cooperation.* In total, researchers from 48 countries or regions have contributed to research on extended reality in sports. We compiled the top 10 countries and regions (Table 4), which have published a total of 282 papers. China is active in the field of extended reality in sports, and its output is dominant, accounting for approximately 19.71% of the total (67/340), ranking first, followed by the United States and the United Kingdom. In addition, the United States had the highest TGCS, followed by France and the United Kingdom, and the United Kingdom had the highest TLCS, followed by Germany and the United States. The top six countries ranked by AGCS from highest to lowest are Germany, France, the United States, Canada, Switzerland and the United Kingdom.

Figure 6 shows a collaborative network diagram of countries related to sports extended reality research, showing the collaborative relationships between countries or regions. The United States is clearly the most active country and plays a leading role in sports extended reality research. Three countries are indicated by purple circles in the figure that indicates a high degree of centrality: the United States (0.26), the United Kingdom (0.19) and the Netherlands (0.12). Further, Australia ranked 4th in centrality (0.1); China and France tied for 6th (0.06); Canada ranked 7th (0.05); Spain, Brazil, Japan and South Africa tied for 8th (0.04); Switzerland and Northern Ireland tied for 12th (0.02); Italy, Portugal and Northern Ireland tied for 14th (0.01); and the other countries are all 0. High centrality indicates that the research directions of the United

Table 3. Top 10 institutions on the topic of extended reality research in sports.

| Institutional | Recs[a] | Publication (%) | Cumulative percentage | TLCS | TGCS | AGCS |
|---|---|---|---|---|---|---|
| Queen's University Belfast | 8 | 2.35 | 2.35 | 53 | 258 | 32.25 |
| Kyung Hee University | 7 | 2.06 | 4.41 | 2 | 25 | 3.57 |
| Otto von Guericke University | 6 | 1.76 | 6.18 | 6 | 14 | 2.33 |
| Northeastern University | 5 | 1.47 | 7.65 | 1 | 56 | 11.20 |
| University College London | 5 | 1.47 | 9.12 | 0 | 32 | 6.40 |
| University of Exeter | 5 | 1.47 | 10.59 | 2 | 18 | 3.60 |
| University of Granada | 5 | 1.47 | 12.06 | 0 | 23 | 4.60 |
| Anglia Ruskin University | 4 | 1.18 | 13.24 | 0 | 32 | 8.00 |
| McGill University | 4 | 1.18 | 14.41 | 0 | 28 | 7.00 |
| Nanyang Technological University | 4 | 1.18 | 15.59 | 0 | 68 | 17.00 |

[a]Number of published papers.
AGCS: average global citation score; TGCS: total global citation score; TLCS: total local citation score.

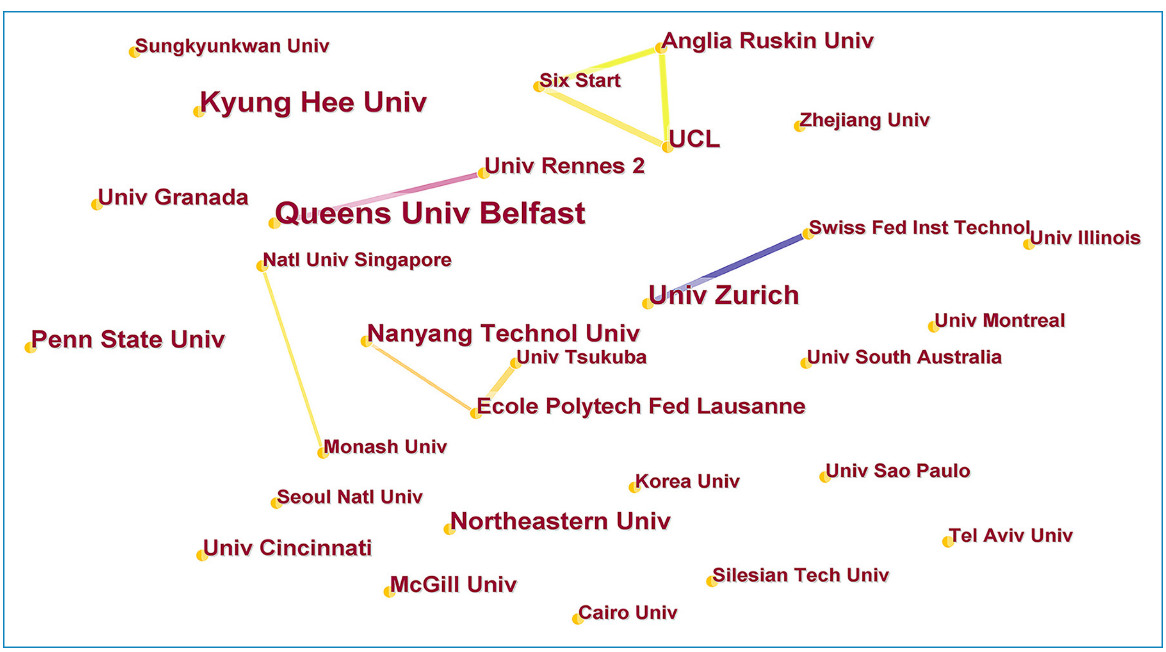


Figure 5. Cooperation network diagram of institutions related to sports extended reality.

States, the United Kingdom, and the Netherlands in this field are relatively concentrated, and their research theories are more closely connected with those of other countries. The United States is ranked first in centrality; this implies that the country is more closely connected to related research in other countries in sports extended reality research and is the country with the broadest research orientation, leading the field. In general, research on sports extended reality is mainly concentrated in developed countries, such as Europe and the United States, and Asian countries (e.g. China, Korea and Japan) also have good performance.

**Table 4.** Top 10 countries on the topic of extended reality research in sports.

| Country | Recs[a] | TLCS | TGCS | ALCS | AGCS |
|---|---|---|---|---|---|
| People's Republic of China | 67 | 2 | 396 | 0.03 | 5.51 |
| The United States | 54 | 39 | 1097 | 0.72 | 20.31 |
| The United Kingdom | 33 | 65 | 476 | 1.97 | 7.32 |
| France | 30 | 22 | 688 | 0.73 | 22.93 |
| Australia | 22 | 20 | 147 | 0.91 | 6.68 |
| Germany | 19 | 60 | 455 | 3.16 | 23.95 |
| South Korea | 19 | 10 | 73 | 0.53 | 3.84 |
| Spain | 16 | 2 | 68 | 0.13 | 3.63 |
| Canada | 15 | 12 | 281 | 0.80 | 18.73 |
| Switzerland | 13 | 4 | 135 | 0.31 | 10.38 |

[a]Number of published papers.
AGCS: average global citation score; ALCS: average local citation score; TGCS: total global citation score; TLCS: total local citation score.

## Research hotspots

*Burst keyword analysis.* A total of 938 keywords were counted from the sports extended reality research literature. There were 63 keywords with burst strength $\geq 1$ and frequency $\geq 3$ (see online Appendix A for a list of keywords). The 63 keywords covered, to a large extent, the research frontiers of sports extended reality. In addition, these keywords appeared 512 times; that is, 6.72% (63/938) of the keywords accounted for 35.02% (512/1462) of the total keyword frequency.

Figure 7 shows a burst bar chart of the top 20 keywords, which clearly demonstrates the update and alternation of keywords in different periods. As shown in the figure, VR emerged during 2006 to 2015, AR expanded during 2011 to 2017, and MR became popular during 2017 to 2020, with the three keywords alternating in sequence. This indicates that sports extended reality research is starting to receive more attention. The main burst keywords from 2000 to 2010 were virtual and distributed environments, focusing on the construction of virtual environments in sports. After 2010, some major devices have been used in sports, including encountered-type haptic displays and helmet-based display devices. From 2010 to 2016, the main burst keywords were Kinect, head-mounted display devices and artificial intelligence, indicating that the research trend shifted towards artificial intelligence and somatosensory interaction methods. Researchers have begun exploring methods to improve the sense of realism in virtual environments. From 2017 to 2021, the representative burst keywords were deep learning, physical education, mental health and sports rehabilitation. This indicates that the combination of deep learning and sports extended reality research has become a major research hotspot in recent years.

*Research theme distribution.* We performed a hierarchical cluster analysis to group the 48 keywords collated from the sports extended reality study into seven clusters. These keywords are listed in Table 5, and the names of each cluster are summarised according to the keywords in the respective cluster. Cluster 1 is about adolescent physical activity; Cluster 2 is related to virtual devices, sports games, sports psychology and biomechanics; Cluster 3 includes physical education, sports training and rehabilitation; Cluster 4 focuses on motion capture and team sports performance; Cluster 5 relates to human–computer interaction and mobile learning; Cluster 6 is about wearable devices and human motion analysis and Cluster 7 is related to age-appropriate sports training.

*Social network analysis.* To show the network relationships more clearly and obtain more powerful and intuitive results, we analysed the $48 \times 48$ similarity matrix to generate a social network graph (Figure 8). The graph visually reflects the relationship between high-frequency and high-explosive keywords. The shape of the keyword social network diagram shows the characteristics of circular concentric circles. Keywords such as 'sports', 'kinect', 'virtual reality', 'physical education', 'sport performance', 'sport training', 'head-mounted displays', 'visualisation', 'eye-tracking', 'behaviour' and 'real-time systems' are in the centre, and the nodes are marked in yellow. These keywords have a high frequency and form the core research circle. Keywords such as 'health', 'augmented reality', 'motion capture', 'sports biomechanics', 'adolescent', 'rehabilitation', 'artificial intelligence', 'human–computer interaction', 'sport psychology', 'e-sports', 'physical activity' and 'leisure activities' were used as representatives to build an intermediate research circle, and the nodes are marked in purple. Keywords such as 'wearable', 'motor skills', 'mixed reality', 'children', 'elderly', 'human movement', 'gait analysis' and 'multitasking' form a fringe research circle, with nodes marked in green. The frequency of these keywords is relatively low, indicating that research in sports extended reality technology is weak in these areas. The overall density of the network was further calculated to be 0.1120, indicating that the 48 high-frequency keywords have not yet established a close connection, and related research in the middle and edge research circles must be further strengthened. Four research directions can be found: (i) the top-left subnetwork is related to sports games and extended reality systems, (ii) the top-right

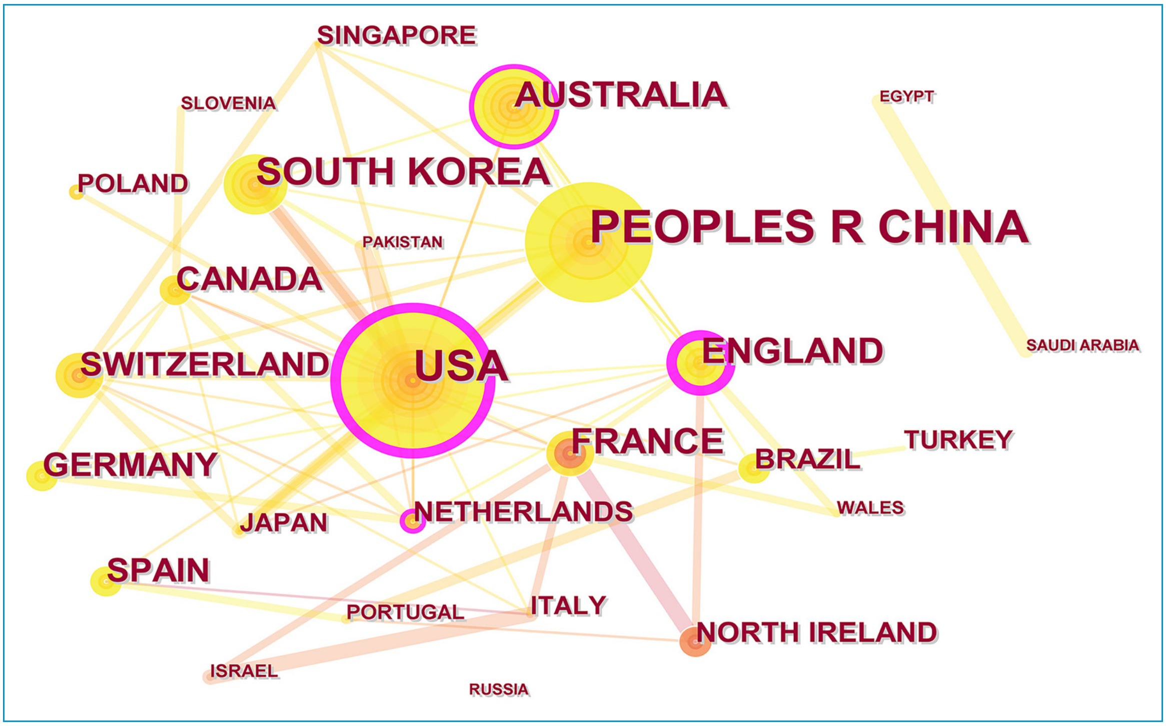


**Figure 6.** Cooperation network diagram of country related to sports extended reality.

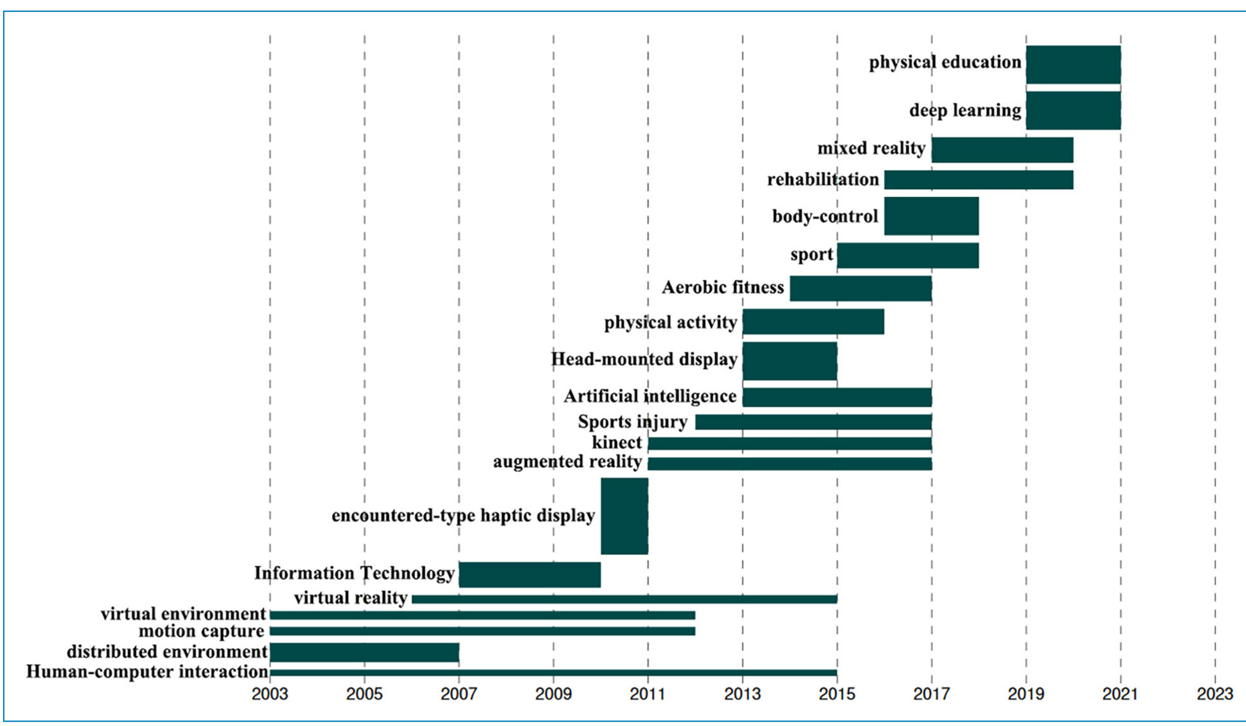


**Figure 7.** Burst bar chart for the top 20 keywords.

subnetwork is research on virtual simulation equipment and artificial intelligence, (iii) the bottom right connects research on sports training and sports performance and (iv) the bottom left is related to research on age-appropriate physical activity, sports rehabilitation and physical education.

**Table 5.** Seven clusters of sports extended reality research.

| Cluster | Number of keywords | Cluster name | Keywords |
|---|---|---|---|
| 1 | 4 | Adolescent physical activity | leisure activities; adolescent; exercise; health |
| 2 | 12 | Virtual equipment, sports games, sports psychology and biomechanics | virtual reality; behavior; human-computer interaction; e-sport; eye-tracking; sports psychology; sports biomechanics; sports games; virtual environment; real-time systems; artificial intelligence |
| 3 | 9 | Physical education, sports training and rehabilitation | physical education; technology; rehabilitation; sport simulation; visualization; skill acquisition; sport training; sports; television |
| 4 | 6 | Motion capture and team sports performance | sport performance; decision-making; perceptual-cognitive skills; dual-task training; motion capture; team sports |
| 5 | 5 | Human-computer interaction and mobile learning | human-computer interaction; Kinect; augmented reality; mobile learning; martial arts |
| 6 | 6 | Wearable devices and human movement analysis | wearable; gait analysis; human pose estimation; mixed reality; human movement; sports skill |
| 7 | 6 | Age-appropriate sports training | children; motor skills; older adults; balance; multitasking; dance |

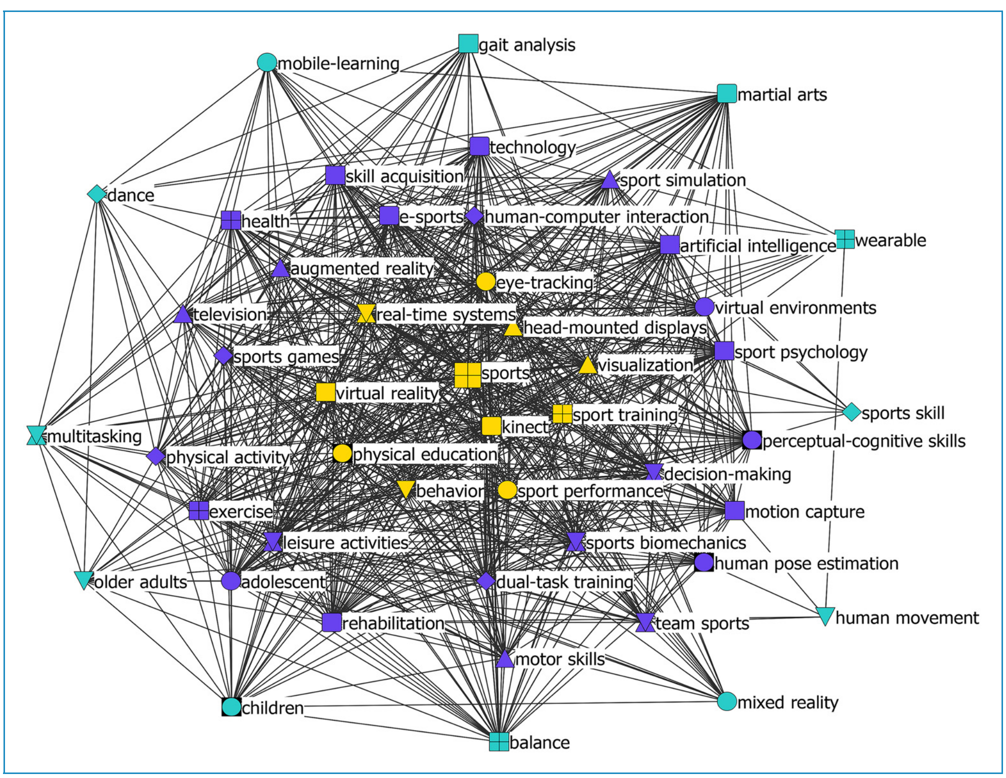


**Figure 8.** Social network graph of $48 \times 48$ similarity matrix.

## Discussion

This study conducted a comprehensive bibliometric analysis of sports extended reality research to show the state of research, research hotspots and evolution of sports extended reality. Bibliometric analysis is a tool used in many studies to analyse the contributions of researchers across research areas, as well as possible trends and correlations in the results of these studies.[58] This study will contribute to a better understanding of how extended reality research in sport is conducted, how it has increased over the past 20 years, in which fields and disciplines it is conducted, which journals have the highest output, and the characteristics of author, institutional and national collaborations.

The analysis results indicate that the growth rate and impact of sports in the extended reality research literature have accelerated. In particular, the number of published papers increased drastically between 2016 and 2021. Based on the fitted logistic growth curve equation of the literature, it can be reasonably inferred that the number of papers in 2022 will be approximately 100. The distribution of journals follows Bradford's law of scattering with 20 core journals. The IF of major journals related to sports extended reality has shown an upward trend over the past year.

The results of the study show that the total number of authors publishing papers on sports extended reality research was 1117. The level of author collaboration was low, and a core group of authors has not yet been formed, but the level of author collaboration is largely on the rise. In addition, 530 institutions were involved in research in this field, with universities being the mainstay of research. Cooperation between institutions was weak and publications were not evenly distributed among institutions. Therefore, in the future, it will be necessary to further strengthen cooperation among institutions to achieve complementary advantages and to share resources and results.

Among national collaborations, major developed countries (e.g. the United States, the United Kingdom, France, Germany, Canada and the Netherlands) are mostly at the core of country cooperation networks. This indicates that the level of research activity in a country is roughly correlated with its gross national product or other economic output capacities. In addition, developing countries (e.g. China) have significant performance and pay much attention to research on extended reality in sports, with the number of publications taking the lead in the field. The country cooperation map shows that institutions in each country prefer to cooperate with domestic institutions, and have a relatively low tendency for international cooperation. Therefore, countries should support domestic scholars who focus on sports extended reality research to study and exchange with developed countries, such as Europe and America, to enhance mutual connections and cooperation.

From the 938 keywords identified in the sports extended reality literature, the 63 high-frequency and high-burst keywords largely demonstrate the research frontiers in the field. The keyword burst bar chart shows that the focus of research has begun to shift from the construction of virtual sports environments to research on deep learning, physical education, mental health and sports rehabilitation. In the past 2 years, the combination of deep learning and sports extended reality research has become a major research hotspot.

Using hierarchical cluster analysis, high-frequency and high-burst keywords were grouped into six clusters, each representing a relevant research topic in sports extended reality. However, current research topics are relatively scattered. Four main research directions were derived from the social network analysis: (i) research on sports simulation and VR devices; (ii) research on physical activity, physical education and E-sports; (iii) research on sports skills and sports rehabilitation and (iv) research on data visualisation and sports psychology. Overall, research in these four directions needs to be further strengthened, and future research topics need to be further focused on.

## Study limitations

The results of this study provide a foundation for a comprehensive understanding of sports extended reality research and have the potential to guide new research in the future; however, this study has limitations. First, it only searched WoSCC as the data source and did not search other databases, which may have resulted in some papers related to sports extended reality research not being covered. In addition, some conference papers were excluded because they were not general papers. All of these factors affect, to some extent, the accuracy of the research results. Second, there may be some authors with the same name in the study, or some authors may only be token co-authors in some papers, leading to some possible bias when analysing authorship collaboration.

## Conclusions

This study used WoSCC as the data source and multiple statistical analysis tools to conduct a comprehensive bibliometric analysis of extended reality research in sports. Analysis methods, including statistical, temporal, high-frequency word, hierarchical cluster and social network, were used. Valuable research results on extended reality in sports were obtained, including information on literature distribution, collaboration characteristics and research hotspots. This makes it easier for researchers to understand future research trends and promote the development of the field of sports extended reality.

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