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Exploring the research trend and development of sports science technology in the last 4 decades: systematic review

Explorando la tendencia de la investigación y el desarrollo de la tecnología de las ciencias del deporte en las últimas 4 décadas: revisión sistemática

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Abstract. This study systematically reviews the trends and developments in sports science technology over the past four decades. Utilizing a comprehensive systematic review analysis of 1,127 articles from the SCOPUS database, we aimed to identify key subject areas, contributing countries, and prevailing keyword patterns in the field. The analysis highlights a significant increase in publications and citations, indicating the growing importance and recognition of sports science technology. Japan leads in contributions with the highest number of publications and citations, followed by the United States and China. Medicine and engineering emerged as the most influential subject areas, underscoring the interdisciplinary nature of the research. Keyword analysis revealed a strong emphasis on human studies, sports, and the integration of science and technology, reflecting the field's evolving landscape. Findings show that technological advancements such as sensor technology, big data analytics, and virtual reality have revolutionized sports science by enhancing performance monitoring, injury prevention, and rehabilitation processes. The study identifies critical trends and provides insights into future research directions, advocating for continued interdisciplinary collaboration and global cooperation to further advance the field. These insights offer a comprehensive overview of the historical and current state of sports science technology, serving as a roadmap for future innovations and applications. By understanding the development and current trends in sports science technology, researchers and practitioners can better plan and implement effective strategies for improving athletic performance and health, ultimately contributing to the broader field of sports science and technology.
Keywords: technological advancements, sensor technology, big data analytics, virtual reality in sports

Resumen. Este estudio revisa sistemáticamente las tendencias y la evolución de la tecnología de las ciencias del deporte en las últimas cuatro décadas. Mediante un exhaustivo análisis sistemático de 1.127 artículos de la base de datos SCOPUS, se pretende identificar las áreas temáticas clave, los países contribuyentes y los patrones de palabras clave predominantes en este campo. El análisis pone de relieve un aumento significativo de las publicaciones y citas, lo que indica la creciente importancia y reconocimiento de la tecnología de las ciencias del deporte. Japón encabeza las contribuciones con el mayor número de publicaciones y citas, seguido de Estados Unidos y China. La medicina y la ingeniería aparecen como las áreas temáticas más influyentes, lo que subraya el carácter interdisciplinar de la investigación. El análisis de palabras clave reveló un fuerte énfasis en los estudios humanos, los deportes y la integración de la ciencia y la tecnología, lo que refleja el panorama cambiante del campo. Los resultados muestran que los avances tecnológicos, como la tecnología de sensores, el análisis de macrodatos y la realidad virtual, han revolucionado la ciencia del deporte al mejorar la supervisión del rendimiento, la prevención de lesiones y los procesos de rehabilitación. El estudio identifica las tendencias críticas y proporciona información sobre las futuras direcciones de investigación, abogando por la colaboración interdisciplinaria continua y la cooperación global para seguir avanzando en este campo. Estas reflexiones ofrecen una visión global del estado histórico y actual de la tecnología de las ciencias del deporte y sirven de hoja de ruta para futuras innovaciones y aplicaciones. Al comprender el desarrollo y las tendencias actuales de la tecnología de las ciencias del deporte, los investigadores y profesionales pueden planificar y aplicar mejores estrategias eficaces para mejorar el rendimiento deportivo y la salud, contribuyendo en última instancia al campo más amplio de la ciencia y la tecnología del deporte.
Palabras clave: avances tecnológicos, tecnología de sensores, análisis de macrodatos, realidad virtual en el deporte

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Introduction

Modern sport is not only simply focusing on the physical activity aspect but is also concerned about more complex aspects that influence physical activity. Understanding the complex aspects of sports has led to the development of a field known as sports science. Sports science combines scientific principles with practical aspects of sport to improve performance, prevent injury, and optimize athlete health. The development of the world of sports science is supported using increasingly sophisticated technology. The development of sport science technology not only includes technological innovation itself but also reflects a scientific paradigm shift in understanding sport (Scott et al., 2021). Over the past four decades, there has been a shift from classical approaches based on manual observation and simple physical measurements to the use of high-level technologies such as sensors (Z. Chen, 2016), data analysis (Hughes & Bartlett, 2019), and computer simulation (C. Park & Moon, 2013). This paradigm shift makes it possible to understand the epistemological and methodological transformations that have occurred in sports science technology (Lee, Song, Kim, Park, & Han, 2023).

Research into sports science technology over the last four decades has deep relevance to several critical aspects of sports and physical fitness (Ashley, 2020). Furthermore, the utilization of technology is now accessible for everyone to maintain fitness (Figueredo, Giraud, Orihuela, Sánchez, & Ceballos, 2022). This phenomenon reflects a significant

transformation in the scientific approach to sport, which continues to evolve in tandem with technological advances (H. Liu, Zhang, Hu, & Zhang, 2016). Understanding developments in sport science technology can also be identified through personalizing training programming and evaluating athlete performance (Zhen, Wang, & Hao, 2015). This is not only applicable on a professional level but is also relevant for the development of more effective fitness programs for the public (Enomoto, 2016). This personalization includes an in-depth understanding of an individual's response to exercise, health monitoring, and program adjustments based on the data collected (Schweinbenz, 2016).

Sports injuries are a constant challenge facing athletes and injury risk management is becoming an important element in sports (Mehta, 2019). The development of sports science technology has explored the role of technology in the identification and management of injury risk (Köhne & Waibel, 2022). Data sensing and analysis not only provide information on the movement patterns and physical strength of athletes but also help in designing more effective injury prevention strategies (Vellios, Pinnamaneni, Camp, & Dines, 2020). This research embraces the aspiration to create safer and more sustainable sports.

The development of sports science technology over the past four decades can potentially lead to the identification of areas that require further research. These innovations not only include the development of new hardware and software but also extend to new concepts in the understanding of sport (da Silva, Silva, Batista, Patrício, & Batista, 2023). The application of technology in sports science requires not only scientific understanding but also the active involvement of scientists and researchers (Tsumori, 2013). This creates an ecosystem where scientists, coaches, and athletes can complement each other and work together to achieve common goals. Research on the development of sports science technology is key to strengthening these collaborative relationships and shaping a future where science and sport support each other.

Studies related to the development of sports science technology, research methods, implications, and research results from previous publications are very interesting and varied. Therefore, the authors were interested in conducting systematic review research to explore research trends in sports science technology to illustrate its development in the last 40 years and discover possible new areas for development. This systematic review research aims to look at the development of sports science technology research trends in the last 40 years with the following research questions:

1. To analyze sports science technology research documents in the last 40 years.
2. To evaluate the countries that contributed to sports science technology research in the last 40 years.
3. To discover the subject areas related to sports science technology research in the last 40 years.
4. To analyze the keyword trends of sports science technology research in the last 40 years.
5. To analyze the top 10 cited publications of sports science technology research trends in the last 40 years.

Methods

This study was conducted by a systematic review of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Figure 1). Article searches were carried out using a comprehensive strategy on Scopus research journal databases. The keyword used was "sports science" AND "technology". 1.129 articles from SCOPUS were mined on November 20th, 2023. Exclusion criteria in this study are documents that are not in the form of articles and articles that are not written in English. Meanwhile, the inclusion criteria are documents in the form of articles and English. There were 10 articles selected as the most cited and relevant articles which were selected for this systematic review. The researcher used the screening feature on the SCOPUS website to determine the articles with the most citations and relevance. The annotation method was also carried out to ensure that the selected articles were following the research topic. The researcher used the annotation method also because some of the identification results showed research that was not relevant to sports, for example, only in the field of technology without any relation to sports.

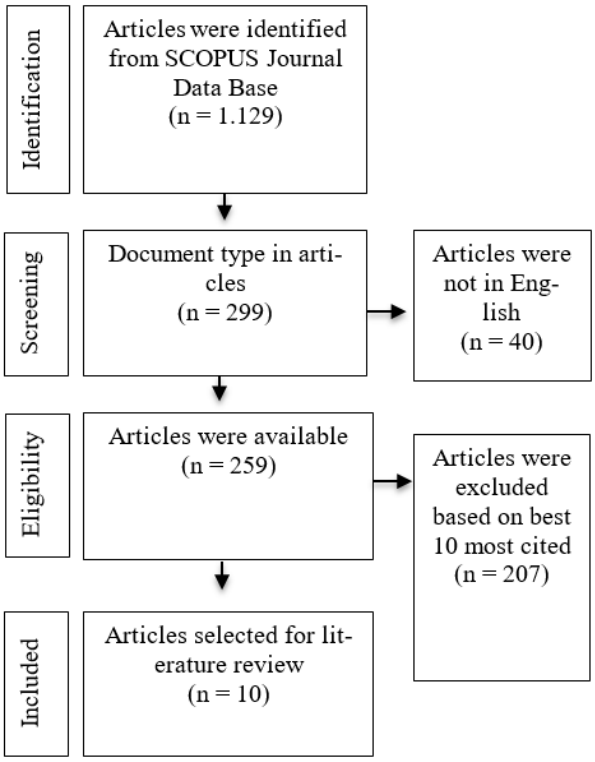

Figure 1. PRISMA flowchart of the article selection process

Results

The research results are presented in five sections or topics. Interpretation of research data in the form of the results of identifying research documents in the last 40 years, is presented in the results below.

Sports Science Technology Documents in the Last 40 *Years*

In the period 1984-1987, publications in the field of sports science technology were still very limited with only one published document that did not receive significant citations (see table 1). This can be interpreted that in the early 1980s, research in this field had not received wide attention from both academics and practitioners. This situation changed slightly in the 1988-1991 period with only one document published but 16 citations, indicating an increase in attention to the topic. Significant changes began to be seen in the period 1992-1995 where the number of published documents increased to four with a total of 273 citations. This indicates that sports science technology was gaining ground among researchers and was beginning to be considered an important area to explore. The average number of citations per document in this period was also very high at 138.5, signaling that the published research was having a significant impact on the scientific community.

Table 1.
Document of sport science technology in the last 40 years

Year	*f*	Total Cited	Average Cited
1984-1987	1	0	0.50
1988-1991	1	16	8.50
1992-1995	4	273	138.50
1996-1999	2	7	4.50
2000-2003	43	506	274.50
2004-2007	125	1209	667.00
2008-2011	124	2005	1064.50
2012-2015	198	2645	1421.50
2016-2019	289	3696	1992.50
2020-2023	342	1543	942.50
Total	1129	11900	6514.50

In the period 1996-1999, the number of documents published decreased to two, and the total citations also decreased dramatically to seven. The average citations per document also decreased to 4.5, indicating that the interest and impact of research in this period was not as strong as in the previous period. However, this trend changed dramatically in the 2000-2003 period with a surge in the number of documents published to 43 and total citations reaching 506. The average number of citations per document also increased significantly to 274.5. This increase shows that sports science technology is starting to receive greater attention and is beginning to be recognized as an important area of research. The 2004-2007 and 2008-2011 periods showed a consistent increase in both the number of documents and total citations. In the 2004-2007 period, the number of documents published reached 125 with a total of 1209 citations, and the average citations per document was 667. This trend continued in the 2008-2011 period with almost the same number of documents published at 124, but the total citations increased sharply to 2005 with an average citation per document reaching 1064.5. This surge reflects the growing recognition of the contribution of research in the field of sports science technology and its increasing relevance within the scientific community.

The period 2012-2015 marked an initial peak in the number of publications with 198 documents published and total citations reaching 2645. The average citations per document in this period was also very high at 1421.5, indicating that the published research had a significant impact and high relevance. This trend continued to increase in the 2016-2019 period with the number of published documents reaching 289, which was the highest number in the analyzed period. The total citations in this period were also very high at 3696 with the average citations per document reaching 1992.5, signaling that this period was the peak of attention and recognition of research in the field of sports science technology. In the period 2020-2023, the number of documents published reached 342, which is the highest number in history. Although the total citations in this period decreased slightly to 1543, the average citations per document were still quite high at 942.5, indicating that research in the field of exercise science technology continues to receive great attention and have a significant impact. Overall, this analysis shows that the field of exercise science technology has undergone rapid development and gained greater recognition within the scientific community over the past four decades, with a significant spike in the number of publications and an ever-increasing research impact.

Country Contributed to Sports Science Technology in the Last 40 *Years*

Japan is dominant in sports science technology research, with 533 published documents and 4355 total citations (see Table 2 and Figure 2). The very high average citation of 2444 indicates that research contributions from Japan are not only large in number but also of very high quality and significant relevance in the scientific community. This reflects the strong and sustainable research ecosystem in Japan, which may be supported by large investments in research and development, as well as collaboration between universities, research institutes, and the sports industry. The United States, despite publishing far fewer documents at 97, still showed significant impact with a total of 2124 citations and an average citation of 1110.5. This shows that research from the US is highly valued and often referenced in subsequent studies, signaling a focus on innovation and practical applications of technology in sports that attracts global attention.

Table 2.
Top 10 Countries Contributed to Sport Science Technology in the Last 40 Years

Country	*f*	Total Cited	Average Cited
Japan	533	4355	2444.00
United States	97	2124	1110.50
China	93	146	119.50
United Kingdom	78	2345	1211.50
Germany	46	1332	689.00
Australia	38	1122	580.00
Spain	34	734	384.00
Italy	31	597	314.00
Russian Federation	20	55	37.50
Turkey	19	167	93.00
Total	989	12977	6983.00

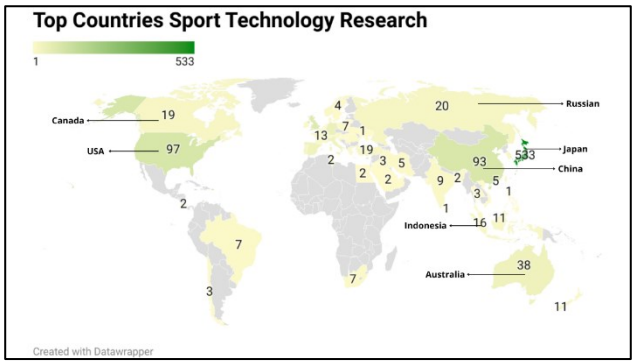

Figure 2. Top countries in sport technology research

China came in third with 93 documents, but only 146 citations, resulting in a low citation average of 119.5. This suggests that while China is prolific in publications, the impact and quality of research still need to improve. Factors such as a lack of international collaboration, the quality of the journals in which they are published, or the relevance of research that may be more focused on the local context could be responsible for the low citations. Even so, China has great potential to improve the quality and impact of its research in the future. The UK, Germany, and Australia also made significant contributions to sports science technology research. The UK with 78 documents and 2345 citations, and Germany with 46 documents and 1332 citations show that these two countries have high-quality research with great impact. Australia with 38 documents and 1122 citations shows that although the number of publications is not as large as the UK and Germany, research from Australia is also recognized and valued. The high average citations in these countries show the relevance of their research and are important references in the field of sports science technology.

Spain, Italy, Russia, and Turkey show great contributions to sports science technology research. Spain and Italy published 34 and 31 documents respectively with 734 and 597 total citations and 384 and 314 average citations, signaling that their research has relevance, despite the lower number of documents published. The Russian Federation and Turkey, with 20 and 19 documents and 55 and 167 total citations respectively, had the lowest number of publications and citations, indicating that their contribution to sports science technology research is limited. This suggests a gap in research contributions between countries, which may be due to differences in research investment, access to resources, or national priorities in sport. Overall, the total number of documents published by these 10 countries was 989 with a total of 12977 citations and an average of 6983 citations, indicating that the global contribution to sports science technology varies greatly in both number and impact. This information provides an overview of the global landscape of sports science technology research and identifies areas that require further attention to drive progress in this field. With a better understanding of the existing contributions and gaps, countries can plan better strategies to increase international research and collaboration, strengthening the global impact of sports science technology.

Subject Areas Related to Sport Science Technology Research in the Last 40 Years

The field of medicine tops the list of contributions to sports science technology research over the past 40 years with 317 published documents and a total of 5236 citations (see Table 3). The average citation of 2776.5 indicates that research in this field is highly valued and has a great impact on the scientific community. This dominance reflects the importance of medical aspects in sports science, particularly in terms of understanding athlete physiology, injury prevention and management, and optimizing athlete health and performance. The health professions field also contributed significantly with 164 documents and 3188 total citations, as well as an average citation of 1676, signaling that research related to health practice and sports therapy is also of high relevance. The focus on health shows that technology in sports science is not only used to improve athletes' performance but also to ensure their long-term well-being and health.

Table 3.
Top 10 Subject Areas Contributed to Sport Science Technology in the Last 40 Years

Subject Area	*f*	Total Cited	Average Cited
Medicine	317	5236	2776.50
Engineering	287	1869	1078.00
Computer Science	273	1371	822.00
Social Sciences	269	1529	899.00
Health Professions	164	3188	1676.00
Biochemistry, Genetics and Molecular Biology	106	1865	985.50
Physics and Astronomy	90	552	321.00
Mathematics	76	456	266.00
Energy	48	282	165.00
Business, Management, and Accounting	44	190	117.00
Total	1674	16538	9106.00

The fields of engineering and computer science also play an important role in the technological development of sports science. Engineering, with 287 documents and 1869 total citations and an average of 1078 citations, shows that many technological innovations in sport come from engineering research, such as the development of sports equipment, sensors, and performance monitoring devices. Computer science follows with 273 documents and 1371 total citations and 822 average citations, reflecting the important role of information technology in sports data analysis, simulation, and the development of technology-based applications for training and performance evaluation. These contributions show how engineering and computer science disciplines have integrated advanced technologies in sports practice to create more efficient and data-driven solutions.

In addition to medicine, engineering, and computer science, various other fields also made significant contributions to sports science and technology research. Social sciences with 269 documents and 1529 total citations and 899 average citations show that the psychological and sociological aspects of sport are also an important focus of research.

The fields of biochemistry, genetics, and molecular biology contributed 106 documents with 1865 total citations and a citation average of 985.5, indicating that research at the cellular and molecular level is also relevant to understanding the biological mechanisms underlying sports performance. Physics and astronomy, mathematics, energy, business, management, and accounting each contributed a smaller number of documents but still showed significant relevance with varying total citations. The energy field, for example, shows how research on energy efficiency can be applied in a sporting context to improve athletic performance. Meanwhile, the business and management field highlights the importance of managerial and economic aspects in the sports industry. Overall, the total contribution from these 10 subject areas is 1674 documents with a total of 16538 citations and an average of 9106 citations, reflecting how sports science technology research is a highly interdisciplinary field, with various disciplines contributing to the advancement and application of technology in sport.

Keyword Pattern Related to Sports Science Technology Research in the Last 40 *Years*

In sports science technology research over the last 40 years, the keyword 'Human' emerged as the most dominant with a frequency of 246 and a total of 5237 citations (see Table 4). The average citation of 2741.5 indicates that research involving the human aspect of exercise science technology is highly valued and has a major impact. This reflects the importance of understanding how technology affects and can be applied to the human body, whether in the context of improving athletic performance, health, or overall well-being. The keyword 'Sports' also stood out with a frequency of 139, total citations of 1571, and an average citation of 855. This suggests that research directly related to sport as a discipline or activity remains a major focus. The combination of these two keywords indicates that research in this field focuses heavily on the practical application of technology to improve and understand human performance in the context of sport.

Table 4.
Top 10 Keyword Patterns in Sport Science Technology in the Last 40 Years

Keyword Pattern	*f*	Total Cited	Average Cited
Human	246	5237	2741.50
Sports	139	1571	855.00
Science and Technology	139	584	361.50
Education	87	617	352.00
Sports Science	86	830	458.00
Students	65	226	145.50
Human Experiment	46	1263	654.50
Biomechanics	36	1004	520.00
Sports Medicine	33	949	491.00
Training	32	574	303.00
Total	909	12855	6882.00

The keywords 'Science and Technology' and 'Education' also show significant contributions to sports science technology research. 'Science and Technology' had a frequency of 139 with 584 total citations and an average citation of 361.5. This reflects the importance of research that combines scientific and technological principles in developing solutions to challenges in sports. The keyword 'Education' appeared 87 times with a total of 617 citations and an average citation of 352, indicating that the educational aspect of sports science technology is also an important focus. This could be related to athlete training, health education, or the integration of technology into the sports education curriculum. In addition, the keyword 'Sports Science' with a frequency of 86, total citations of 830, and an average citation of 458 shows that the discipline of sports science as a field of study is also growing, with research increasingly focusing on the application of technology to understand and improve athletic performance and health.

The keywords 'Human Experiment' and 'Biomechanics' demonstrate the importance of experimental research and mechanics in exercise science technology. 'Human Experiment' appeared 46 times with a total of 1263 citations and an average citation of 654.5, indicating that experimental research involving human subjects is highly valued as it provides direct insight into the effects of technology on human performance and health. The keyword 'Biomechanics' with a frequency of 36 and total citations of 1004 and a citation average of 520 indicates that the study of movement and body mechanics is also an important focus in this research. This shows that the understanding of human body mechanics and how technology can measure, analyze, and improve these aspects is highly valued in the scientific community. In addition, keywords such as 'Sports Medicine' and 'Training' with frequencies of 33 and 32 respectively, and total citations of 949 and 574 emphasize the importance of medical and training research in the context of sports technology. Overall, a total of 909 documents with 12855 total citations and an average citation of 6882 show that research in sports science technology is highly diverse and interdisciplinary, with a strong focus on the practical application of technology to improve health, performance, and understanding of sport and the human body.

Top 10 Cited Publications of Sport Science Technology Research in the Last 40 *Years*

This topic aims to identify the focus or topic of previous research (see Table 5). The selection of articles based on the most citations and relevance to the topic discussed, shows a correlation with current research. Topics that are often raised in sport science technology research, show the development of sports science technology research trends.

Table 5.
Top 10 cited and relevant publications of sport science technology in the last 40 years

Author	Total Cited	Research Purpose	Method	Result
(Aquino et al., 2020)	67	The purpose of this study was to investigate the independent and interactive effects of situational variables, opposition team formation, and playing position on running performance and network analysis in Brazilian professional soccer players.	Experimental Studies	The results from this study provide practical information to potentially impact on physical, tactical, and technical training.
(Massaroni et al., 2021)	58	The purpose of this review is to provide insight into the use of fiber Bragg grating sensors (FBGs) for cardiorespiratory monitoring.	Review Studies	At present, the use of FBGs applied to cardiorespiratory monitoring is still in its infancy and the systems based on FBGs currently available to monitor cardiorespiratory activities.
(Zrenner et al., 2020)	15	Evaluate whether the sensor position of IMUs mounted to running shoes has an impact on the accuracy of different spatio-temporal parameters.	Experimental Studies	Integrate IMU sensors in a cavity in the sole of a running shoe under the foot's arch, because the raw data of this sensor position is best suitable for the reconstruction of the foot trajectory during a stride.
(Gamble et al., 2020)	15	Describe the pervasive forces driving the adoption of technology solutions and critically examine the logic underpinning the present drive for metrics-based practice in football.	Descriptive Studies	Assist practitioners in being purposeful in their use of these tools and leverage the benefits of technology and data in a way that better supports decision-making and complements coaching practice
(Massaroni et al., 2020)	12	Investigate the influence of the torso movements that occur during walking and running activities on the signals recorded by a multi-sensor garment	Experimental Studies	Movements related to the torso rotation (arms and shoulders swing) cause motion artifacts on the garment sensors' signals.
(Slaughter & Adamczyk, 2020)	10	Investigated the in-game cutting maneuvers performed by female ultimate frisbee athletes to understand the movements that could put them at risk of ACL injury.	Experimental Studies	Current wearable movement sensors provide accurate enough estimates of lower body kinematics to characterize important aspects of athletic maneuvers such as cutting, while being unobtrusive enough to wear during competition in some sports.
(Kristiyanto et al., 2020)	10	Describe patterns of sports science and technology transfer process to community and analyze the level of accessibility and familiarity of the tools of technology-based physical ability test among coaches and sport community.	Experimental Studies	98.7% respondents felt that most coaches are ready to make improvements by training themselves in using sports science and technology.
(Ito et al., 2020)	9	Investigate and compare the association of quadriceps setting and knee extension strength with health-related physical fitness.	Experimental Studies	More health-related physical fitness parameters with quadriceps setting strength than knee extension strength.
(Di Tocco et al., 2020)	9	Test a wearable device composed of two elastic bands embedding conductive textiles during a running session of approximately 9.5 km.	Experimental Studies	The wearable system was able to perform a good estimation of both respiratory and gait parameters allowing a better understanding of the relationship between the fatigue and the respiratory activity, enabling a more accurate running performance evaluation.
(F. Chen, 2021)	8	Create these two assessment science composing and give an extensive audit of the game medicine that can be worn with devices starting at now accessible.	Experiential research and process-based research	Principles and practices to measure the external and internal load has been relatively well-defined.

Discussion

Sports science is a field that has various aspects of its science. It does not only include aspects of sport or physical activity, but technology is also part of sports science. The integration of technology has led to the expansion of sports science, such as sports and medicine. Injury prevention and rehabilitation are optimized through the consolidation of these two fields. This study aims to explore and analyze the development of research in the field of sports science technology in the last four decades.

The results of the systematic review in this study show that the research trend is dynamically increasing from year to year. The development began to experience a significant increase from the beginning of 2000 until the end of 2023. Based on the results of the analysis in this study, Asian countries such as Japan, made a huge contribution with the number of publications five times that of other countries. This proves that Japan has a very high interest in science in the field of sports technology. The results of the literature review are categorized into five topics that are comprehensively reviewed in the discussion below.

Early Era: The Classical Approach

In its early days, sports science relied heavily on classical research methods such as direct observation and manually conducted physical fitness tests. Technology was limited at the time, however, the passion for understanding sport and human performance inspired researchers to develop innovative approaches (Balagué, Torrents, Hristovski, & Kelso,

2017). Simple measuring equipment such as stopwatches and heart rate meters are the main tools for evaluating reaction times and fitness levels (Neshitov et al., 2023). Despite its simplicity, it marked the beginning of the scientific approach to sport. In this period, the classical studies on exercise physiology and biomechanics began to form the basis of knowledge in sports science.

In addition, researchers in this era also began to develop basic techniques in data collection and analysis that would later become the foundation for more sophisticated research methods. For example, simple motion analysis methods and manual recording of physiological parameters, although limited, provided early insights into the relationship between physical activity and human body responses (Hamill & Bates, 2023). The application of these techniques helped broaden the understanding of how the body functions during physical activity and became an important foundation for further developments in the field of sports science.

During this time, researchers also faced challenges in terms of limited tools and technology (Song, Sárosi, Cen, & Bíró, 2023). For example, measuring metabolic rate or aerobic capacity required specialized equipment that was not always easily accessible. However, these limitations encourage innovation and creativity in research methodology (Cooper & De Luigi, 2014). Researchers often have to design their equipment or modify existing tools to meet the specific needs of their study. In addition, interdisciplinary collaborations began to form, with physiologists working alongside biomechanics experts and psychologists to gain a more comprehensive picture of athlete performance. The development of basic theories in sports science, such as the principle of overload in training and the concept of homeostasis, laid the foundation for subsequent research (Brazil, Exell, Wilson, & Irwin, 2020). Research in this era was also more descriptive and exploratory, with a focus on collecting empirical data that was then analyzed to identify specific patterns in sports performance and athlete health (C. Liu, Hao, & Huo, 2023). This created a strong foundation for the evolution of research methodologies and technological applications in sports science in the following decades.

Sensor Revolution and Performance Monitoring

In the 2000s, sports science started using sensor technology and performance monitoring (James, Lee, & Wheeler, 2019). Sensors embedded in sports equipment, clothing, and other wearable devices are changing the way we view and analyze physical activity (Xie, Xiang, & Liu, 2013). One of the major milestones of this period was the use of GPS to track athletes' movements (Rossi et al., 2017). Track and distance monitoring that was previously done manually can be assisted by the role of GPS. Researchers also use GPS to collect high-accuracy data in sports Science analysis such as speed, distance, and movement patterns of athletes can be accessed in real-time (Bastida Castillo et al., 2018). This provides greater insight into game tactics and training strategies. Apart from GPS, other sensor technologies are also making their way into the world of sports. Heart rate sensors, body temperature sensors, and other sensors provide a more complete picture of the body's physiological response to exercise (Buyrukoğlu & Bayindir, 2023). This allows coaches to adapt training programs with greater precision according to the athlete's physical condition.

The sensors also enable continuous and non-invasive monitoring, so data can be collected in a variety of conditions and environments without interrupting the athlete's activities (Renner, Lang, Langenstein, Struck, & Bertsch, 2020). This performance monitoring technology has enabled the development of more personalized and data-driven training programs, where coaches can identify individual strengths and weaknesses more accurately. For example, biomechanical sensors can detect movement patterns that are inefficient or could potentially lead to injury, so preventative measures can be taken early (Carling & Court, 2013). This technology has also paved the way for more in-depth research into the effects of different types of exercises and interventions on athlete performance and recovery, ultimately contributing to improved safety and effectiveness of training programs. Furthermore, the integration of data from various sensors allows for more comprehensive and holistic analysis, providing insights into the interactions between the various physiological and mechanical factors that affect athlete performance (Ren & Li, 2021). With the rapid development of technology, the use of sensors and performance monitoring devices is predicted to continue to grow and become more sophisticated, providing greater benefits to the world of sports and exercise science in the future.

Big Data and Data Analytics

In the current technological era, the term "big data" has become key in the transformation of sports science. With the ever-increasing amount of data, data analysis is becoming a more complex and detailed research center (Wang & Liu, 2023). Machine learning and artificial intelligence algorithms help identify patterns, trends, and relationships that are difficult to see through conventional analysis (Y. Liu & Liu, 2023). Big data opens up opportunities to dig deeper into the factors that influence athlete performance (Liang & He, 2023). Sophisticated statistical analysis can give an idea of how factors such as nutrition (Keen, 2018), sleep patterns, and environment can affect performance (Reis et al., 2019). Thus, injury risk management, development of training programs, and game strategy optimization can be done more effectively.

Big data allows coaches and researchers to make more accurate predictions about athlete performance and injury potential. By utilizing large historical data, predictive models can be built to anticipate training needs and appropriate strategies (Sangeethalakshmi et al., 2023). For example, data from previous seasons can be used to identify fatigue patterns that could lead to injury, so that preventative interventions can be planned in advance. The technology also

enables the personalization of training programs based on individual athlete data, providing a more targeted and effective approach to improving performance (Ae, 2020). The use of Big Data has also changed the way decisions are made in the management of sports teams and organizations. Data analytics provide deep insights into team performance, allowing managers to make data-driven decisions in terms of player selection, match strategy, and resource management (Lease, Lim, Phang, & Chiam, 2024). For example, data analysis can help determine the most effective team formation based on individual and collective performance. With the ability to integrate data from various sources, such as medical data, physical performance, and match statistics, team managers can develop more holistic and sustainable strategies.

Computer Simulation and Virtual Reality

Computer simulation and virtual reality (VR) take sports science to the next level by creating simulated environments for athletes to interact with simulated exercise scenarios (Honma et al., 2022). Computer simulations allow researchers to test hypotheses and exercise scenarios without involving the risk of injury or athlete fatigue (Müller et al., 2023). In addition, VR technology allows athletes to train in near-reality conditions, creating a more immersive and relevant training experience (Honma et al., 2021). VR technology also allows coaches to observe and analyze athlete performance in a fully controlled environment, where certain variables can be manipulated to see their impact on performance (M.-J. Park & Park, 2019). For example, coaches can simulate different match situations, from weather conditions to competition pressure, to train athletes in various scenarios without any real risk. This not only helps in physical preparation but also in mental aspects, such as managing stress and making quick decisions under pressure (Zhang & Tsai, 2021).

In addition, VR technology can also be used for the rehabilitation of injured athletes. Using specially designed simulations, athletes can perform rehabilitation exercises in a safe and controlled environment, which can speed up the recovery process and reduce the risk of re-injury (Xu, Huang, Yao, & Zeng, 2022). This technology also allows for more accurate monitoring of rehabilitation progress, providing real-time data that can be used by physiotherapists to tailor rehabilitation programs to the athlete's individual needs (Gokeler et al., 2016). The integration of computer simulation and VR in Sport Science also opens up opportunities for collaboration between various disciplines, including engineering, psychology, and health sciences. This interdisciplinary research can lead to new innovations in exercise and recovery technologies, which not only improve athletes' performance but also their overall well-being (Kaur, 2023). As technology continues to evolve, the use of computer simulation and VR in sports is expected to become more widespread, bringing sports science into a new, more advanced, and integrated era.

Rehabilitation Technology

In addition to supporting performance enhancement, technology also plays an important role in the injury rehabilitation process (Moylan & Horne, 2013). In the last three decades, breakthroughs in rehabilitation technology have changed the approach to athlete recovery after injury (Kanschik et al., 2023). Advanced devices such as rehabilitation robots, the use of augmented reality (AR) in movement rehabilitation, and electromedical devices provide innovative solutions to speed up the recovery process (de Crignis et al., 2023). This not only reduces recovery time but also provides a more precise and efficient method of dealing with sports injuries (G. Wang, 2023). Rehabilitation technology also allows for more individualized and specific treatment to suit the needs of each athlete. For example, rehabilitation robots can be customized to provide optimal levels of resistance and support, enabling safe and effective exercises for different types of injuries (Feng et al., 2020). AR in movement rehabilitation allows athletes to train in a virtual environment that stimulates real conditions, helping them adapt back to normal activities more quickly and confidently (Ivaschenko, Aleksandrova, Zheikov, Zakharova, & Kolsanov, 2024). In addition, electromedical devices such as neuromuscular electrical stimulation can help accelerate tissue healing and reduce pain, which is crucial in the early phases of recovery (S. H. Park & Silva, 2004; Rajendran, Challen, Wright, & Hardy, 2021).

The role of technology in rehabilitation also includes more accurate monitoring and assessment of recovery progress. Sensors and monitoring devices can measure physiological parameters in real time, providing data that can be used by medical teams to dynamically adjust rehabilitation programs (Zsidai et al., 2023). This allows for early detection of potential problems and faster intervention, which can prevent re-injury and ensure a more comprehensive recovery. In addition to the physical benefits, rehabilitation technology also has a positive impact on the psychological aspects of an athlete's recovery (Shushardzhan, Eremina, Shushardzhan, Allik, & Mukasheva, 2023). The use of advanced technology can increase athlete motivation and engagement in the rehabilitation process, providing a more interactive and engaging experience (An, Moon, Kang, & Yang, 2016). This is important to maintain the athlete's enthusiasm and commitment to undergoing rehabilitation programs that are often long and challenging. As technology continues to evolve, the future of sports injury rehabilitation is expected to become more sophisticated and effective. The integration of new technologies will continue to open up opportunities for innovation in recovery methods, providing hope for athletes to return to their peak performance more quickly and safely.

The discussion based on the results of the literature review above, shows the significant development of sports science technology. The transition from conventional methods to modern methods marks the digitization of sports science. Similar to the systematic review research by (Toto, 2022), which explains that the development of

sports science technology research has begun to develop sensor technology and artificial intelligence. According to Thomas & Gilbert, (2016) in his systematic review research, they stated that technological developments such as sensors can have a significant impact on the future of an athlete.

This research has several limitations that allow it to be refined in further research. This research only uses a single database, namely SCOPUS, thus making the identification results less varied and complex. Then, this research only focuses on the integration of technology in sports science. A review of integration in technology and other fields, such as sports health, coaching, and sports education can be done in future research. In addition, the analysis conducted in this study was only limited to the screening method on PRISMA. Blibiometry analysis using VosViewer can be done to provide trend visualisation and more comprehensive analysis.

Conclusion

The development of technological research in sports Science in the last four decades has been rapid. Sports science has undergone a profound transformation from classical approaches to the utilization of high-level technologies such as big data analysis and virtual reality. These innovations not only provide deeper insights into human performance in sports, but also open the door to optimizing training programs, preventing injuries, and improving athlete health. Research into Sport Science Technology trends and developments helps create new directions for future research. By understanding the past developments of technology research in sports science, we can plan smarter and more targeted research steps. This creates a foundation for further exploration, innovations, and technology development that can shape the future of sport.

The evolution of technologies such as the use of sensors, computer simulation, and technology-based rehabilitation has changed the way we approach sports from various aspects, from training and competition to recovery and injury prevention. Sensor technology and wearable devices have enabled real-time monitoring of athlete performance and health, providing invaluable data for more informed decision-making. Computer simulation and virtual reality have provided new tools for coaches and athletes to simulate various scenarios without real physical risk, which is crucial for competition preparation and strategy development. In addition, rehabilitation technology has offered new, more efficient, and effective methods for injury recovery, allowing athletes to return to their peak performance more quickly and safely. The use of technologies such as rehabilitation robots and augmented reality in rehabilitation programs has shown promising results in accelerating the healing process and improving the quality of life of injured athletes.

Going forward, researchers and practitioners in the field of sports science need to continue to explore and adopt new emerging technologies. Collaboration between various disciplines such as engineering, medicine, and computer science will be key in creating innovations that can take sports to the next level. This interdisciplinary research will not only enrich our understanding of human performance in the context of sport but also pave the way for the development of better and more effective technological solutions. With the right support from various parties, including academic institutions, industry, and government, research and development in sports science technology can continue to flourish. This will not only provide direct benefits to athletes and sports teams but also contribute to improving the health and fitness of the general public. Therefore, the future of sports science looks very bright with unlimited potential for innovation, which will continue to push the boundaries of human capabilities in sports.

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