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Development Trend and Hotspot Analysis of Brain Plasticity Research of Motor Skill Experts Based on Magnetic Resonance Imaging Technology

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Abstract. Since the emergence of neuroscience, brain plasticity has been a key topic in cognitive research. Many factors can induce changes in plasticity in the brain. However, the unique neuroplasticity shown by individuals who have undergone long-term motor training (i.e. motor skills experts) has become a key window to understand the mechanism of human learning and adaptation. Although extensive research confirms that continuous physical training can enhance the plasticity of the brain, there is no systematic review that comprehensively describes the development trajectory and key research areas of this field. This article examines 142 publications from the Web of Science Core Collection, PubMed, PsycINFO and CNKI between 1995 and 2025. e between 1995 and 2025. Using literature metrology analysis and scientific knowledge atlas technology, the research progress of brain magnetic resonance imaging research of motor skills experts is systematically presented, aiming to provide reference for future research. The research results show that the annual publication volume shows a significant upward trend; there is insufficient collaborative network between authors in different countries (regions); journals in the fields of neuroscience, clinical neurology and psychology show high publication volume and influence; technical methods have developed from a single MRI technology to a combination of recent red Comprehensive methods of external brain imaging and other cognitive neuroscience and technology. The research theme centred on the knowledge system of sports experts is still prominent, mainly focussing on movement observation, motion prediction and concussion-related research. The research paradigm has transitioned from task-based research to the investigation of brain function in the resting state of athletes, and attention has shifted from local brain areas to key brain networks. Future efforts should enhance research coordination, strengthen interdisciplinary cooperation, promote ecological and longitudinal research design, and expand the depth and breadth of research.

Keywords: motor skills expert, brain plasticity, magnetic resonance imaging, motor neuroscience, knowledge graph

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1. Introduction

1.1. Research background

In recent years, with the development of research technology and methods, many developed countries in the world, including China, have successively launched and started the research project of "Brain Plan", which is committed to combining neuroscience and information science analysing [1], exploring and mining the massive brain science data under the background of big data at different levels, so as to deepen the understanding of the human brain and achieve the scientific goal of "understanding the brain, protecting the brain and creating the brain". It can be seen that brain science has become the most cutting-edge research field in the 21st century. As a complex system, the structure and function of the brain will be continuously modified and reorganised with the changes of internal and external environment, showing significant plasticity.

Studies have shown that acquired factors such as learning, training and individual experience have an important impact on brain plasticity [2]. In recent years, more and more studies have used neuroimaging techniques to explore the impact of long-term exercise training on the structural and functional plasticity of the brain. Among them, MRI uses the difference between local oxygen consumption and blood flow increase after neuronal excitation to achieve non-invasive observation of brain structure and activity of specific brain regions, providing an important means for in-depth understanding of the relationship between exercise training and brain plasticity. At present, a large number of studies have confirmed that exercise training can change the activity and structure of task-related brain regions [3].

Motor skill experts mainly refer to those who can skilfully and accurately operate a professional skill action in the field of motor skills, and they generally have excellent motor performance ability [4]. They usually have unique cognitive advantages in attention, perceptual expectation, working memory and decision-making [5]. In addition, they also show a coping mode superior to ordinary people in emotion regulation and overcoming psychological fatigue. This is related to the brain plasticity changes of motor skill experts caused by long-term motor skill learning, which is mainly reflected in the structural and functional levels of the brain. The changes in the structural level of the brain reflect the changes in the neuroanatomical structure, such as the changes in the thickness of the grey matter cortex in the cerebral cortex, the changes in the cortical area, the changes in the volume of the grey matter, and the changes in the white matter fibre structure. The changes in the functional level of the brain describe the changes in the recruitment characteristics of neuronal tissues when individuals participate in certain specific cognitive tasks, sports or are in a resting state.

1.2. Basis for topic selection

In recent years, many scholars have adopted cross-sectional studies to compare the differences in brain structure or functional plasticity between motor skill experts and ordinary subjects based on magnetic resonance imaging technology [6]. Some scholars have also employed the ALE meta-analysis method to quantitatively integrate neuroimaging data on brain plasticity induced by long-term training in athletes [7]. However, there is no research on the development trend and hot spot analysis of athletes' brain plasticity based on magnetic resonance imaging technology.

Based on the above research background, this paper systematically reviews studies conducted between 1995 and 2025 that primarily employed magnetic resonance imaging (MRI) technology to investigate the brain function and structure of motor skill experts. The search covered databases including Web of Science, PubMed, PsycINFO, and CNKI. It presents a comprehensive overview

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and key trends in this field through a scientific and intuitive approach, providing a reference framework for future research directions, academic exchange, and developmental trajectories.

2. Research tools and data sources

2.1. Research tools

The visualisation tool CiteSpace (version 6.1.R4 Advanced Edition) jointly researched and developed by Professor Chen Chaomei of the School of Information Science and Technology of Drexel University in the United States an d the WISE Laboratory of Dalian University of Technology is used for the visualisation analysis of knowledge maps. The tool is a software for tracking and visualising analysis of international cutting-edge research. It is suitable for multivariate, time-sharing, and dynamic complex network analysis, and can measure documents in specific fields to present the research structure and development trend of a discipline. CiteSpace can select the most important and critical information from a large amount of data, examine the literature from various perspectives and classify and summarise it, and conduct visualisation analysis of institutions, author cooperation networks, keyword co-occurrence, etc., and draw a series of observable scientific knowledge maps [8].

2.2. Data sources

2.2.1. Sources of information

This paper mainly focusses on the review of brain magnetic resonance imaging studies of athletes and original research findings, and formulates retrieval formulas in combination with the variants of various expression forms actually used in scientific research practice. The search formula TS=(sport OR athlete OR player OR sports experts OR sport expertise OR motor expertise OR skill expertise) AND (MRI OR fMRI OR FMRI OR magnetic resonance imaging OR functional magnetic resonance imaging) was used to search the Web of Science,Pub Med,Psyc INFO and CNKI database. The retrieval period is from January 1, 1995 to December 10, 2025. According to the research needs, choose the literature types as Article and Review, and the literature language is English.

2.2.2. Inclusion and exclusion criteria

1) Inclusion criteria: Use magnetic resonance imaging technology to explore the literature on the plasticity of athletes' brains in sports science, psychology, neuroscience and other fields, including clinical research, systematic review, review articles, etc.

2) Exclusion criteria: Conference papers, patents, newspaper articles, project reports and other irrelevant literature, as well as incomplete or duplicated published research.

2.2.3. Literature screening

A total of 1496 documents have been retrieved. Use EndNote X9 software to delete duplicate records. The researchers screened the literature according to the inclusion and exclusion criteria, and finally excluded 1,360 documents. In the end, 136 valid articles were included. The specific literature retrieval and screening process is shown in Figure 1.

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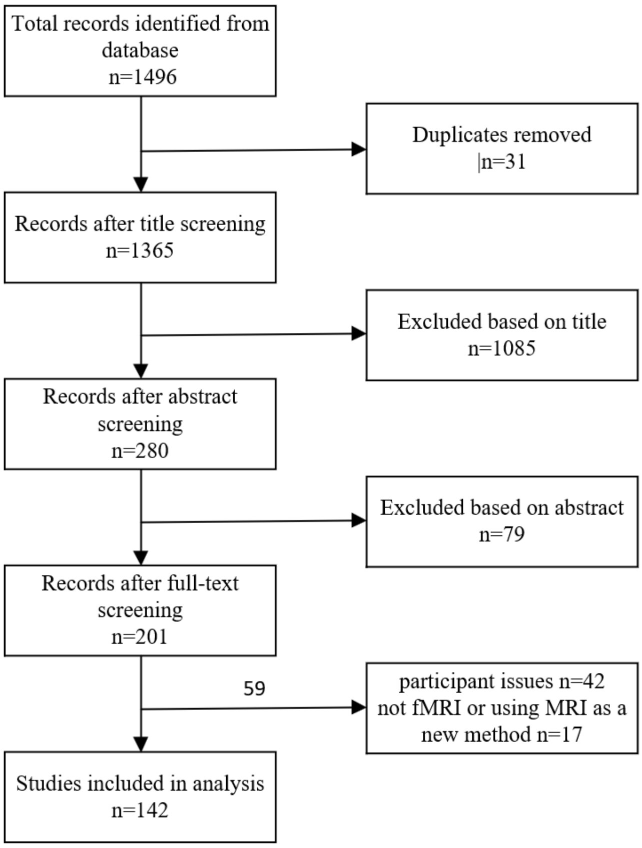

Figure 1. Literature screening flow chart

3. Analysis of the basic characteristics of relevant research

3.1. Analysis of the development trend of literature

The fluctuation and distribution pattern of research publications in a certain period of time can clearly show the current situation and development trajectory of a discipline. For this reason, this article draws a trend chart of publications based on the annual output data of Web of Science from 1995 to 2025, as shown in Figure 2. In general, in the past 30 years, the volume of publications in the field of "Athlete Brain Magnetic Resonance Imaging" has shown a pattern of "stable in the early stage and rapid growth in the later stage", as shown in Figure 1. Before 2010, the annual volume of publications in this research area remained relatively low. From 2011 to 2025, the volume of publications showed a continuous and steady upward trajectory, reflecting the increasing attention of scholars in cognitive neuroscience, sports science and related fields. This growth trend indicates that there is a possibility of increasing research investment in the future.

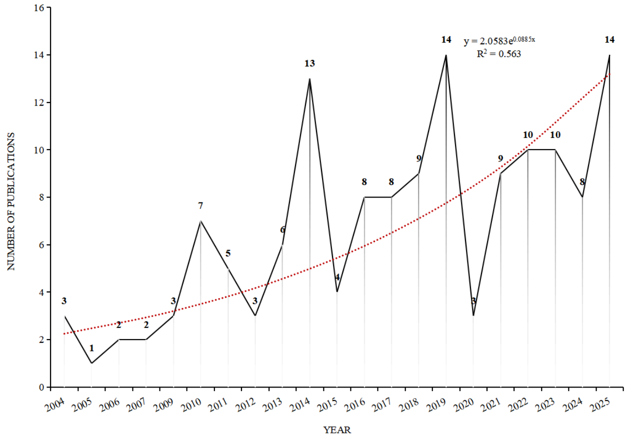

Figure 2. Academic research annual trend chart from 1995 to 2025

3.2. Discipline distribution analysis

The source journals of the sample literature are classified and visualised by discipline, as shown in Figure 3. In general, the research on magnetic resonance imaging of athletes mainly focusses on three major disciplines: neuroscience, clinical neurology and psychology. At the same time, it has expanded to the fields of sports science, behavioural science and intensive care medicine.

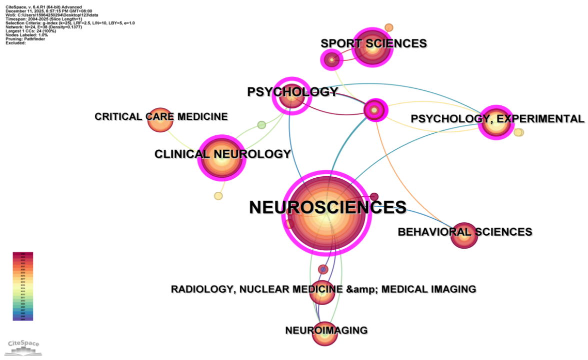

Figure 3. Analysis of the main developmental subject categories of athletes ' brain imaging

3.3. Analysis of high-yiet authors and cooperative networks

Using the Vosviewer tool to visually analyse the high-output authors in related studies (as shown in Figure 4), revealing the core authors in the field and their collaborative relationship. Each node in the figure represents an author, and the radius of the node represents the number of papers published by the author. The connection lines between nodes reflect the collaboration between authors, and the thickness of the connection describes the number of collaborative outputs between the connected authors. It can be seen that there is collaboration and communication between the authors, but the cooperation is relatively scattered and the contact is relatively weak. The knowledge atlas contains 445 network nodes (N=445), 34 connections (E=1017), and the network density is 0.0103 (density =0.0103), indicating the degree of collaboration and communication between the authors included in the literature.

As shown in Table 1, the authors are ranked according to the number of publications, and 5 authors have published ≥5 papers. Wang Yingying's papers have been published the most (7

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articles), mainly through fMRI, DTI and EEG to observe the motor cognitive processing and brain plasticity of athletes who have undergone different types of long-term sports training.

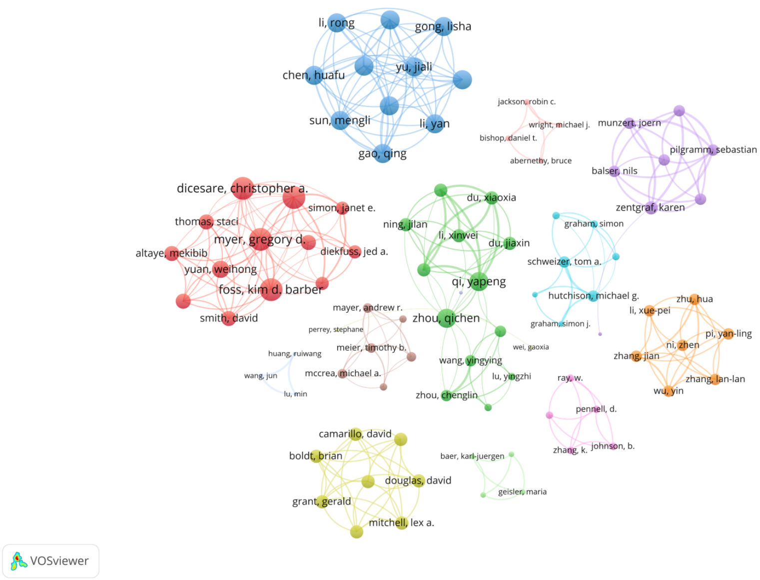

Figure 4. Author co-occurrence knowledge map

Table 1. Statistics of high-yield authors (select the top 5 authors)

Rank	Author	Documents
1	Wang, Yingying	7
2	Schweizer, Tom A	5
3	Grooms, Dustin R	5
4	Qi, Yapeng	5
5	Zentgraf, Karen	5

3.4. Analysis of key countries (regions) and collaborative networks

Co-occurrence analysis of countries / regions using VOSviewer provides a relatively intuitive representation of the geographical distribution of nations engaged in 'MRI studies of athletes' brains' (As shown in Figure 5). In Figure 5, each node represents a country/region, and the radius of the node represents the corresponding number of publications. The connection between nodes reflects the collaborative relationship between different countries/regions in the field, and even the density and thickness of connection indicate the frequency of collaboration and co-authoring publications between regions.

In this knowledge graph, there are 28 network nodes (N=28), 32 connections (E=32), and the network density is 0.0032 (Density=0.0032), indicating that the cooperation among different regions is not very tight.

In terms of the number of published articles (Table 2), the top five countries are the United States (48 articles), China (33 articles), Japan (20 articles), Canada (17 articles), and the United Kingdom (15 articles). There are more than 15 articles in the top three countries, and the number of articles from the fourth place and below are all less than 15. In terms of the clustering structure, the United States, China and Germany, which have the highest number of articles, belong to different clustering

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groups. In terms of the number of collaborations, the number of collaborations of these three countries with other countries (regions) is relatively close, ranging from 15 to 20 times. To be specific, the United States has the closest collaboration with South Korea, China has the highest frequency of collaboration with England, and Germany has the most frequent connection with Luxembourg.

Through a comprehensive analysis of the collaboration network, it is evident that while China possesses substantial academic influence and technological advantages in this research field, it lacks core coordination and connectivity within the global collaborative framework. There is insufficient breadth in collaborative coverage, an underdeveloped structure for diversified partnerships, and an urgent need to enhance the depth of cooperation. In the future, relevant research should pay attention to strengthening international cooperation, achieving complementary advantages, and jointly promoting the development of this research field.

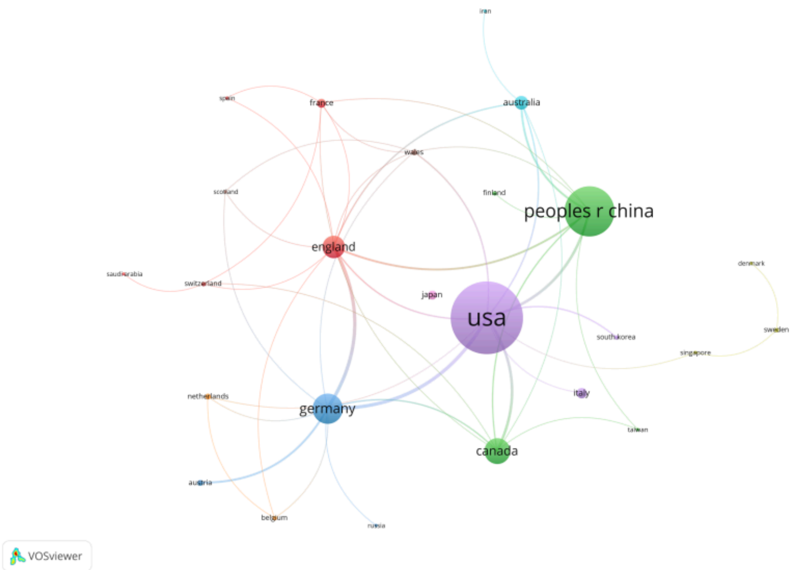

Figure 5. National (regional) collinear map

Table 2. Statistics of high-yielding countries (regions) (Top 10 papers were selected)

Country	Documents	Centrality	Year	Rank
Usa	48	0.62	2004	1
China	33	0.19	2007	2
Germany	20	0.32	2009	3
Canada	17	0.18	2004	4
England	15	0.33	2005	5
Australia	9	0.13	2009	6
Italy	7	0	2010	7
France	6	0.04	2005	8
Japan	6	0	2004	9
Austria	4	0	2016	10

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3.5. Journals of publications

Table 3 indicates that 11 journals have published four or more studies on brain imaging in athletes. However, the total number of articles remains modest, and these studies predominantly appear in non-sports-related English- language journals. The Journal of Neurotrauma has published the highest number of articles, followed by Frontiers in Human Neuroscience in second place, and Human Brain Mapping and Neuroimage tied for third. The impact factors of these 11 journals ranged from 2.6 to 5.9. In terms of total citations, Cerebral Cortex, Journal of Neurotrauma, and Neuroimage ranked first, second, and third respectively. Notably, Journal of Neurotrauma and Cerebral Cortex topped both the citation count and publication volume rankings, reflecting their significant influence and standing within this field.

Table 3. Main journals (more than 3) and citations

Ranking	Source	Documents	Citations	IF
1	Journal of Neurotrauma	14	893	4.5
2	Frontiers in Human Neuroscience	13	279	3.3
3	Human Brain Mapping	7	179	4.4
4	Neuroimage	7	432	5.9
5	Brain Research	5	258	2.8
6	Brain Sciences	5	40	3.1
7	Neuropsychologia	5	136	2.6
8	Cerebral Cortex	4	1559	3.4
9	Frontiers in Neurology	4	50	3.3
10	Neural Plasticity	4	56	3.7
11	Neuroscience	4	119	3.0

3.6. Analysis of highly cited papers

The co-citation network diagram facilitates analysis of a research topic's evolution through key nodes, clusters, and colour coding. Highly cited publications embody 'impact' and are suitable for rapidly identifying core literature within a field. Co-citation analysis of references was conducted using CiteSpace software (see Figure 5). This knowledge map comprises 721 network nodes (N=721) and 1,832 connections (E=1,832).

Table 4 lists the top 10 most cited publications in the field of athlete brain imaging. These 10 highly cited papers have accumulated between 68 and 792 citations since their publication. Most studies employed an expert versus novice research paradigm to examine differences in brain imaging or specific functional regions between groups. Among these, the pioneering original research by Italian scholar Aglioti SM [9], combining psychophysics and transcranial magnetic stimulation, explored the dynamics of action anticipation in professional basketball players and its underlying neural correlates. To date, this study ranks first with 792 citations. The research themes addressed by these highly cited scholars encompass athletes' action anticipation and its neural mechanisms; the neurobiological basis of perceptual-cognitive advantages in motor prediction; patterns of neural activation- inhibition; and the relationship between brain injury and neural efficiency.

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Table 4. The top 10 most cited papers

Rank	First Author (Publication Year)	Article Title	Journal Name	Cited Count
1	Aglioti SM (2008)	Action anticipation and motor resonance in elite basketball players	Nature Neuroscience	792
2	Williams AM (2011)	Perceptual-Cognitive Expertise in Sport and its Acquisition: Implications for Applied Cognitive Psychology	Applied Cognitive Psychology	225
3	Abreu AM (2012)	Action anticipation beyond the action observation network: a functional magnetic resonance imaging study in expert basketball players	European Journal of Neuroscience	143
4	Abernethy, B (2008)	Expertise and attunement to kinematic constraints	Perception	116
5	Wright MJ (2010)	Functional MRI reveals expert-novice differences during sport-related anticipation	NeuroReport	95
6	Abbas K (2015)	Alteration of default mode network in high school football athletes due to repetitive subconcussive mild traumatic brain injury:a resting-state functional magnetic resonance imaging study	Brain Connectivity	86
7	Wright, MJ (2011)	Cortical fMRI activation to opponents' body kinematics in sport-related anticipation: Expert-novice differences with normal and point-light video	Neuroscience Letters	79
8	Bishop DT (2013)	Neural Bases for Anticipation Skill in Soccer: An fMRI Study	Journal of Sport & Exercise Psychology	74
9	Li LX (2013)	Neural Efficiency in Athletes: A Systematic Review	Journal of Sport & Exercise Psychology	71
10	Balser N (2014)	Prediction of Human Actions: Expertise and Task-Related Effects on Neural Activation of the Action Observation Network	Human Brain Mapping	68

4. Analysis of hotspots and trends of relevant research

Keywords is the high refinement and summary of the literature theme of the journal. Keyword coexistence analysis helps to find research hot topics and trends in specific fields. Based on the research method of literature metrology, analysing the frequency of literature keywords can identify research hotspots in a certain field. Those keywords with high centrality and prominent frequency of words indicate the issues of common concern to scholars and indicate the hot areas of the research field.

4.1. Keyword co-occurrence analysis

Through the CiteSpace visualisation tool, the literature in the field of "brain magnetic resonance imaging of athletes" is analysed by keyword sympathology, and a visual scientific atlas is drawn (see Figure 5). Each node in Figure 5 represents a keyword. The more times the keyword appears, the greater the circle radius of the corresponding node. In addition, the thickness of the connection between the keyword nodes represents the tightness of the connection between the keywords. The following knowledge atlas contains 308 network nodes (N=308) and 1,030 connections (E=1030). In order to further understand the hot content of this field in the past 30 years, the data after keyword co-analysis is exported to the Excel table, and the keyword frequency table is generated in descending order, as shown in Table 3. Generally speaking, the frequency and centre of the keyword can be used to judge the importance of the word. The greater the centre, the greater the connection between the keyword and other keyword nodes. If it is greater than 0.1, it indicates that the keyword is more central and more important in the whole network.

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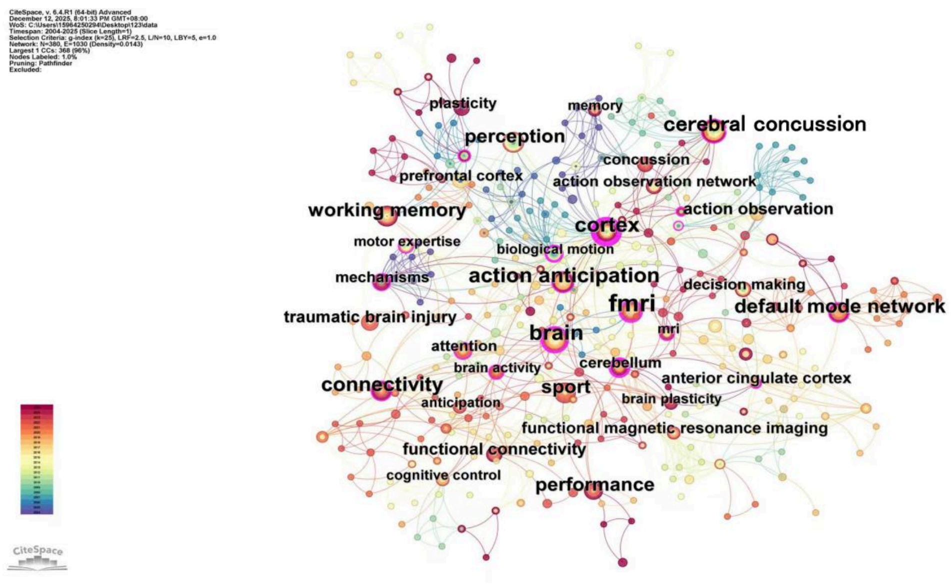

Figure 6. Keywords co-occurrence network

Table 5. High-frequency keyword table (the top 20)

Rank	Frequency	Centrality	Keywords
1	26	0.21	fmri
2	17	0.32	brain
3	17	0.12	cerebral concussion
4	15	0.19	action anticipation
5	15	0.67	cortex
6	14	0.11	connectivity
7	13	0.12	default mode network
8	12	0.05	performance
9	11	0.03	working memory
10	11	0.02	perception
11	11	0.01	sport
12	8	0.07	action observation
13	8	0.02	functional connectivity
14	8	0.00	traumatic brain injury
15	7	0.19	anterior cingulate cortex
16	7	0.05	functional magnetic resonance imaging
17	6	0.16	mechanisms
18	6	0.12	attention
19	6	0.01	concussion
20	6	0.03	action observation network

As a result, it was found that a total of 11 keywords appeared frequently ≥10 times. The keywords with the highest frequency were fmri, brain and concussion, and the keywords with the highest centrality were cortex, brain and fmri in order. The top 10 literature keywords are shown in Table 4.

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4.2. Keyword cluster analysis

Keyword clustering can reveal the core theme of the research field and its dynamic evolution. It is to use the statistical method of clustering to simplify the co-emergative network relationship into a relatively small number of clustering processes. This paper conducts cluster analysis of the obtained keywords and obtains the keyword clustering knowledge atlas of the research field (see Figure 6), generating a total of 5 cluster groups (the average contour value of the cluster S>0.6), and the cluster module value Q=0.3806, S=0.6992. Generally speaking, the Q value is generally within the [0,1) range, and Q>0.3 means that the divided community structure is significant. When the S value is above 0.5, clustering is generally considered reasonable. It can be seen that this result shows that the cluster structure is remarkable, and the clustering results are convincing.

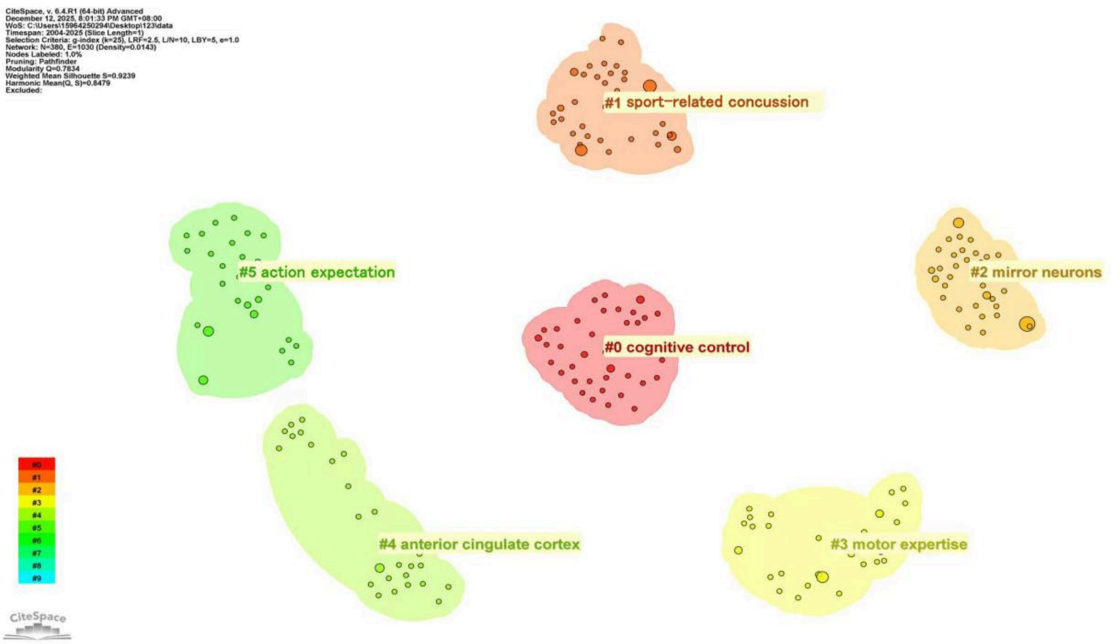

Figure 7. Keyword clustering diagram

Figure 6 shows the clustering results of 5 main high-frequency keywords, which are extracted and placed in Table 4. The cluster themes include: #0cognitive control, #1sports-related concussion, #2mirror neurons, #3, motor expertise, #4anterior cingulate cortex, #5action expectation.

4.3. Keyword emergence analysis

Emergence words refer to the key words in a certain discipline field that increase sharply in frequency and research enthusiasm in a certain period of time, which can often reflect the evolution of the corresponding research hotspots to a certain extent.

This paper uses the CiteSpace visualisation analysis tool to visualise the appearance time, end time and intensity of keywords in the research related to "magnetic resonance imaging of athletes' brains", and draw a keyword emergence atlas (see Figure 10), so as to refer to the relevant research on "Magnetic resonance imaging of athletes' brains" Realise visualisation according to the trend. "Year" represents the time (year) when the keyword begins to appear, and "Strength" indicates the mutation intensity of the keyword. The larger the value, the more times the keyword appears in a short period of time. "Begin" and "End" represent the starting time (year) when the keyword

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becomes a sudden word and End time (year), the red and bold line segment on the right characterises the corresponding period of the keyword with the nature of a sudden word..

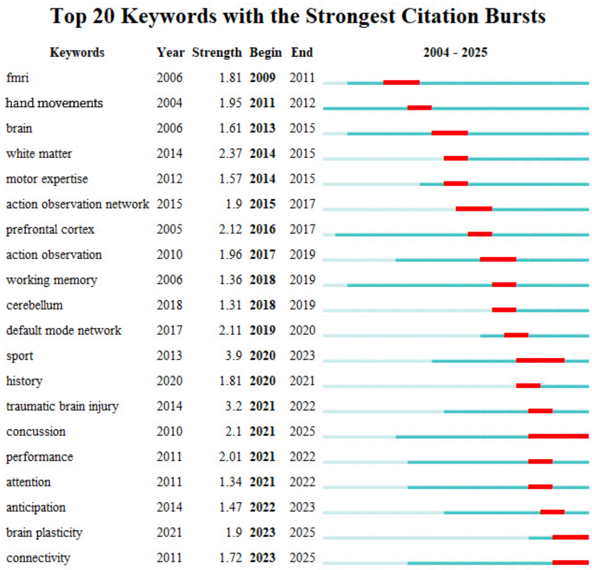

Figure 8. Keyword burst map

As shown in Figure 7, high-frequency keywords began to emerge slowly from 2009, and no emerging words appeared from 1995 to 2009, which is likely to be related to the small number of articles published in the early days.

From the perspective of time, the hot words in the field can be divided into three stages of development. In the early stage (2009-2012), the research focussed on the use of magnetic resonance imaging for hand movement tasks, which coincides with the initial application status in the field of magnetic resonance imaging. Subsequently, entering the stage of empirical deepening (2013-2017), the hot spot turned to the relationship between brain structure and motor expertise. The integrity of white matter, the prefrontal cortex and the movement observation network became the key to understanding the neural matrix of motor specialisation. After 2018, the research perspective expanded to brain network and advanced cognitive functions. The emergence of default mode network, cerebellum and working memory marked the attention to the movement-related neural network mechanism. In the past five years (2020-2025), the research has shown a strong application and health orientation. Exercise, traumatic brain injury and concussion have become the forefront of the highest intensity of research. At the same time, keywords such as attention, movement expectation and movement performance have emerged, focussing on cognition and brain health in sports situations. At present, the frontier of research has clearly converged on brain plasticity and connectivity, which means that the field is moving from positioning specific brain areas to exploring how motor training drives the functional and structural reorganisation of the whole brain network. This paradigm shift will be the core direction of future research.

5. Discussion

Analysis of keyword co-occurrence and clustering reveals that the knowledge systems of sports specialists constitute the core research focus within this field. Over the past three decades, researchers have consistently endeavoured to explore the advantageous effects demonstrated by

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sports specialists across various domains. The subsequent sections will engage in detailed discussion of these research directions.

5.1. Discussion of research methods

First of all, the rise of cognitive science in the past 10 years has greatly broadened the application population and traditional scientific research issues. For example, resting-state fMRI requires resting-state functional magnetic resonance imaging of the brain without systematic thinking, closing eyes or opening eyes, not entering sleep, and imaging by collecting low-frequency signals (< 0.1 Hz) of the brain in a lying, quiet and motionless state. During the data scan, subjects are not required to perform complex cognitive tasks, nor do researchers design complex experimental tasks, only subjects are required to maintain a relaxed and clear-headed state [10]. Therefore, the application of this sequence is more convenient and easy to be accepted by children, the elderly and patients with neurological diseases. At present, the existing neuroscientific evidence shows that the default mode network plays an important role in the monitoring of internal and external environment, the processing of emotions and the extraction of episodic memory. Therefore, influenced by the mainstream disciplines of neuroscience and psychology, researchers in the field of sports have recently begun to use resting state as a technical means to reflect the functional activities of athletes ' brains, and have carried out a series of pioneering studies on brain functional connectivity. Researchers in the field of sports have recently begun to use resting state as a technical means to reflect the functional activities of athletes ' brains, and have carried out a series of pioneering studies on brain functional connectivity [11].

In addition, in addition to magnetic resonance imaging technology, some researchers have also begun to combine technical means such as electroencephalography, near-infrared imaging and transcranial magnetic stimulation technology to discuss the changes in the brain area caused by motor behaviour. Different technical means have different advantages [12]. For example, fMRI has high spatial accuracy and is suitable for the study of brain function and plasticity in the static state; fNIRS can be worn for monitoring and supports the observation of brain area activity during exercise. ERP and EEG reveal the cognitive decision-making process in fast sports scenarios with millisecond-level time resolution. In addition, TMS and tDCS, as interventions, improve the level of motor skills by stimulating specific brain areas.

In recent years, the combination of various technologies has made the research topic gradually shift from the traditional single exploration of athletes ' brain function activities under special conditions to the multimodal brain imaging research that integrates brain structure and function. The use of these techniques has led to the development of research on the unique brain structure characteristics and optimal brain function activity patterns of sports experts.

5.2. Discussion on research topic

A study conducted 13 years ago, using a scientific speculative approach, reviewed the sporadic sparks that emerged in the field of motor cognitive neuroscience 15 years ago and discovered that during the exploration period of this field, scholars focused on multiple cognitive themes centered on the expert knowledge system of motor skills, including motor attention, motor imagery, and motor decision-making. In the past 13 years of research, the expert knowledge system in motor skills has remained a primary research focus within mainstream cognitive science, manifesting chiefly in investigations into action observation and the mirror neuron system, action prediction and

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decision-making, and concussion-related motor impairments. The following sections explore these research directions in greater detail.

5.2.1. Discussion on the theme of action observation and action anticipation

Action observation is a cognitive process underpinned by mirror neurons [13], holding significant importance for human survival and development. The earliest investigations into action observation occurred in primates. When monkeys performed an action or observed other monkeys or experimenters executing a similar movement, neurons in their premotor cortex exhibited electrophysiological activity [14]. Similarly, the phenomenon of action observation has been identified in infants during early developmental stages [15]. Observing others' actions facilitates the internalisation of their behaviours, enabling learning and imitation. A meta-analysis employing Activation Likelihood Estimation (ALE) has now characterised the action observation network. Associated brain regions include the medial premotor cortex, dorsolateral premotor cortex, primary sensorimotor cortex, visual areas, inferior parietal lobule, superior parietal lobule, inferior frontal gyrus, precentral gyrus, intraparietal sulcus, fusiform gyrus, superior temporal sulcus, and middle-posterior temporal gyrus [16]. Among these, the inferior frontal gyrus/primary motor cortex, inferior parietal lobule/intraparietal sulcus, and posterior middle temporal gyrus/superior temporal sulcus represent the most critical nodes within the action observation network. Researchers employed tennis players and volleyball players as experts and novices respectively, instructing them to predict ball trajectories during tennis and volleyball tasks. Findings revealed activation in the supplementary motor area, cerebellum, and superior parietal lobule within the action observation network. This activation proved independent of specific domain expertise, potentially reflecting consistent neural adaptations following prolonged training.

Action anticipation represents a higher-order cognitive process involving the perception and processing of visual information from observed movement sequences to predict outcomes. It entails observing and forecasting the behaviour of others, such as opponents. Accurate action anticipation is crucial for athletic success, enabling athletes to better leverage prior knowledge. A review indicates that movement experts consistently outperform novices in anticipatory tasks, with significant neurophysiological differences observed between the two groups [17]. For instance, electroencephalography studies reveal greater fronto-parieto-occipital activity in experts. Task-based magnetic resonance imaging studies on action prediction indicate that sports experts exhibit heightened activation across numerous brain regions, with particular emphasis on the prefrontal cortex, visual cortex, supplementary motor area, and premotor cortex. However, researchers also note that the consistency of these activation differences between experts and novices is limited. Recently, increased research has focused on action anticipation, supplementing existing neuroimaging evidence. Compared to novices, badminton experts exhibit stronger activation in the left medial frontal cortex during action anticipation, alongside enhanced functional connectivity with other regions such as the right posterior cingulate cortex [18]. Following 12 weeks of badminton training, participants demonstrated significantly improved performance in action prediction tasks, with increased N2 amplitude in the prefrontal cortex and P3 amplitude in the parietal cortex [19]. Studies have further highlighted a non-linear relationship between training experience and nodes within the action observation network during action prediction [20]. Additionally, research indicates that during action prediction tasks, activation in the striatum, thalamus, sensorimotor cortex, and cerebellum is higher during correct predictions than during incorrect predictions.

Although current research posits that action observation underpins action prediction, and that action prediction activates corresponding regions of the action observation network, studies have

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also suggested cerebellar involvement in this process. Consequently, the precise mechanisms of interregional coordination during action prediction warrant further investigation.

5.2.2. Thematic discussion on sport-related concussions

Sport-related concussion (SRC) is caused by a direct blow to the head, face, neck or other parts of the body, with the force transmitted to the head, usually resulting in a rapid onset of transient neurological dysfunction that resolves spontaneously. However, symptom resolution does not necessarily indicate physiological recovery [21]. SRC is a major public health issue, and there is currently no effective treatment. It is considered one of the most complex injuries in sports medicine to diagnose [22], assess and manage, especially in high-intensity contact sports such as rugby, football, ice hockey and boxing. A large number of studies have shown that the risk factors and severity of SRC are not only affected by the cumulative number and intensity of head impacts, the athlete's competitive level, the duration of their career, and the age at which they first participated in collision sports, but may also be related to non-repetitive head impact factors, such as genetic susceptibility, drug and alcohol abuse, and other complex external environmental factors.

Research mainly focuses on improving the diagnosis and assessment, treatment and rehabilitation, and return-to-play assessment of sports-related brain injuries.

Firstly, in terms of diagnosis and assessment, among the many SRC diagnostic tools, the Sport Concussion Assessment Tool (SCAT) is widely used internationally. Its latest version, SCAT-5, was approved at the Consensus Conference on Concussion in Sport held in Berlin in October 2016 [23]. It includes the assessment of symptoms at different stages, level of consciousness, cognitive ability, cranial nerve function, balance ability, and indicators for identifying potential severe brain injuries. The biggest drawback of SCAT is that its assessment results are highly dependent on the athlete's subjective symptom report and cooperation level. Under competitive pressure, athletes may hide or downplay their symptoms, leading to missed diagnoses.

Secondly, in terms of treatment and rehabilitation, scholars in the relevant field have begun to explore various rehabilitation paths, including drug treatment, physical therapy and cognitive rehabilitation. However, drug treatment is rarely used in SRC because when athletes recover and return to the field, they should not only be free of concussion-related symptoms but also not be taking any drugs that may mask or alter SRC symptoms. Moderate aerobic exercise has become a research hotspot in the treatment of SRC due to its significant therapeutic effect [24]. Previous meta-analyses have also been conducted, but the included literature included non-sports-related mild traumatic brain injuries and did not conduct detailed analyses of factors such as injury severity, exercise intensity and gender.

Thirdly, in terms of return-to-play assessment, athletes who have suffered a concussion can only return to the field after being evaluated and given a medical clearance by a licensed medical professional trained in concussion assessment and management (Return to sport, RTS). Premature RTS increases the risk of repeated concussions or other injuries, thereby delaying recovery. Therefore, the assessment before returning to play is particularly important. Currently, there is a clear consensus that athletes diagnosed with concussion should not return to play on the same day, and rest after concussion is the foundation of recovery [25]. Traditional rest protocols recommend strictly avoiding physical activity and cognitive-stimulating activities such as electronic products and books. However, more and more people now believe that this can lead to anxiety symptoms and social isolation. Currently, after 24 to 48 hours, if the athlete's cognitive and physical activities remain below the threshold for symptom exacerbation, they can be encouraged to gradually resume these activities [26]. When athletes are asymptomatic during rest, they may initiate a stepwise

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return-to-sport strategy. Table 6 presents a commonly used 6-stage return-to-sport strategy [27]. Generally speaking, the intensity of physical activity at each stage gradually increases. When the patient completes the current stage without symptoms, they should progress to the next stage. Each stage should last at least 24 hours. If concussion symptoms occur at a certain stage, the athlete should return to the previous stage for at least 24 hours. According to this strategy, athletes diagnosed with concussion usually resume full-contact sports within 5 to 6 days after the initial injury. However, athletes with a history of repeated concussions or prolonged recovery after concussion may require a longer return-to-sport strategy. It is worth noting that both prolonged complete rest and intense exercise after concussion can affect recovery.

Table 6. Six-stage return to the stadium recovery strategy

Stage	Description	Goal
1	Activity Development	Resume normal daily activities without worsening of symptoms.
2	Low-Intensity Aerobic Exercise	Walking, stationary cycling, controlled activities to increase heart rate
3	Sport-Specific Exercise	Aerobie exercises such as running, skating, or other sport-specific activities: avoid risk of head impact
4	Non-Contact Training	Sport-specific non-contact drills, including coordination and cognitive challenges: gradually introduce resistance training
5	Full-Contact Practice	Resume normal training activities; assess psychological readiness
6	Return to Play	Return to competition/game

During the RTP process of concussion, baseline scores are helpful in accurately determining the baseline level of functional recovery after injury, so the baseline cognitive state must be taken into account. In addition, preventing concussions is also very important. Protective equipment should be properly matched, preseason training should be optimized, and sport-specific collision techniques should be taught to athletes. Therefore, all levels of sports should pay more attention to concussions. Moreover, the recovery process from a concussion is highly variable. Although the best recovery advice can be given, these strategies must be individually adjusted for each patient based on the severity of symptoms, treatment goals, and previous concussion experiences. The inconsistency in diagnostic and treatment standards also fully demonstrates the multi-factorial and multi-disciplinary nature of concussions, which urgently requires further research.

6. Research findings and future revelations

6.1. Research findings

This study employs multiple literature visualisation tools, including Citespace, to conduct an in-depth analysis of the field's literature through bibliometric methodologies. It provides a relatively intuitive reflection of the research status, focal points, and frontier trends in 'magnetic resonance imaging of athletes' brains' over the past three decades, yielding the following conclusions:

First, regarding the phased evolution of the research process.

The volume of literature exhibits a three-stage pattern: 'early exploratory phase (1995-2012) — mid-term growth phase (2013-2020) — recent deepening phase (2020-2025)'. Early studies concentrated on the preliminary application of task-related fMRI and structural MRI. During the mid-term phase, with the widespread adoption of multi-modal techniques such as resting-state fMRI and DTI, research gradually expanded to brain networks and white matter structures. while recent years have seen a marked shift towards multi-technique integration, longitudinal designs, and

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applications in brain health, reflecting an evolutionary trajectory from 'phenomenological description' towards 'mechanistic elucidation' and 'practical translation'.

Second, from the perspective of the academic community's structural characteristics.

The density of author collaboration networks stands at merely 0.0103, while the density of country/region collaboration networks is as low as 0.0032, indicating that this field has yet to establish a tightly knit, stable international collaborative framework. Collaboration among high-output authors and institutions remains fragmented. Although China ranks second in publication volume, it does not occupy a central hub position within the global collaboration network. Research capacity remains concentrated in a few leading neuroscience and psychology institutions, indicating that an academically mature community centred on movement science has yet to emerge.

Third, regarding the focal points of research hotspots.

Keyword sympreence and cluster analysis show that three research plates have been formed in this field: first, the technical means section, with "fMRI", "quiescent state", "DTI" and "multimodal state" as the core, reflecting the evolution and integration of research tools; second, the brain mechanism plate, focussing on "action observation and mirror nervous system", "dynamic Expectations and decision-making", etc., reveal the neural function and structural reorganisation behind the sports expertise; Third, the application and health plate, highlighting the keywords of "sports-related concussion" and "returning to the field" and other keywords, reflecting the application-oriented extension of research to brain protection and performance improvement.

Fourth, regarding the distribution of subjects.

The journals are highly concentrated in neuroscience, clinical neurology and psychology journals (accounting for more than 70% in total), and the number of articles in sports science journals is relatively limited. Although the problem essentially belongs to the category of sports science, its research results are more published in the journals of neuroscience and psychology, and the discourse system and publication platform of sports science in this field still need to be strengthened.

In general, the international magnetic resonance imaging research on "athlete brain plasticity" has accumulated rich results. From the research perspective, it has experienced the expansion from local brain area activation to whole brain network reorganisation, from single time point to long-term tracking depth, and has gradually extended from pure mechanism exploration to Brain health monitoring and exercise performance optimisation. However, there are still structural problems in the field, such as loose cooperation networks, insufficient integration of disciplines, and lack of subjectivity in sports science.

6.2. Future revelations

Based on a systematic review and visual analysis of research concerning brain plasticity in athletes from 1995 to 2025, this study identifies significant progress in theoretical development, methodological innovation, and practical application within this field. Nevertheless, several areas warrant further exploration. To advance this domain towards deeper, more systematic, and application-oriented development, the following future research directions are proposed to provide insights and guidance:

First, promote method integration and ecological applications.

A multimodal and highly ecologically effective research system should be built, integrating rest state and task state fMRI, DTI, EEG/ERP and fNIRS and other technologies to comprehensively observe the changes in brain structure and function. In particular, it is necessary to promote the application of wearable neural imaging devices in real training and competition scenarios to capture

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brain activity in the natural state. In addition, the current research is mostly based on cross-sectional design, and it is difficult to distinguish whether brain differences are the cause or effect of training. In the future, longitudinal tracking and intervention experiments should be strengthened, combined with neuroregulation technologies such as transcranial magnetic stimulation, to reveal the causal relationship between "training-brain plasticity-behavioural performance".

Second, expanding the depth and breadth of the research topic.

Key priorities include: Utilising dynamic causal modelling and computational neuroscience methods to elucidate neural mechanisms and brain network coordination patterns underlying action observation and anticipation; Establishing multimodal neuroimaging biomarker systems for concussion to aid diagnosis and rehabilitation, while investigating the restorative effects of different aerobic exercises; Comparing the specific effects of different exercise types (e.g., open-ended vs. closed-ended skills, team vs. individual sports) on brain plasticity; extending research to the neural foundations of higher cognitive and emotional regulation, such as psychological resilience and stress coping.

Third, Strengthen the intersection of disciplines and the centrality of sports science.

We should promote the deep integration of neuroscience, psychology, sports science, rehabilitation medicine and computer science and other disciplines, and jointly design and promote research. Sports science journals are encouraged to set up special issues or columns of "Sports Neuroscience" to build a theoretical and methodological system oriented by sports practice.

Fourth, strengthening international collaboration and sharing.

We advocate transnational and multi-centre cooperative research, promote the formulation of standards for the collection and sharing of sports brain image data, build open databases (such as OpenNeuro special data sets), and promote data integration and cross-sample verification. By introducing advanced methods such as brain network dynamics and machine learning, the overall methodology level and result comparability of the field can be improved.

6.3. Research outlook

The brain plasticity research of sports skills experts is not only an important window to understand the mechanism of human learning and adaptation, but also a key scientific support for promoting the "integration of physical medicine", optimising exercise training and promoting brain health. Future research should further highlight multidisciplinary collaboration, multimodal integration, vertical design and application orientation. While deepening the analysis of brain mechanisms, it should effectively serve the full-cycle development of athletes and the health promotion of ordinary people, and finally contribute to the unique wisdom of sports science to the grand goal of "understanding the brain, protecting the brain and shaping the brain".

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