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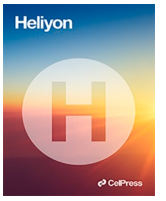

Research article

The interaction of digital economy, artificial intelligence and sports industry development --based on China PVAR analysis of provincial panel data

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ABSTRACT

Under the leadership of China's "dual-carbon" goal, clarifying the interaction between the digital economy, artificial intelligence, and the sports industry is an important guarantee to promote the structural upgrading of China's sports industry and achieve low-carbon development. Therefore, a panel vector autoregression (PVAR) model is constructed based on the panel data of 15 provinces in China from 2014 to 2020 to investigate the interaction between the three. It is found that (1) every 1-unit increase in the level of digital economy in the lagged period can cause a 0.008-unit increase in the level of AI application in the current period at the 10% significance level, i.e., the digital economy has a short-term and weakly facilitating effect on AI. (2) Every 1 unit of digital economy level in the lagging period can cause 9.539 units of value added to the sports industry at a 1% significance level. That is, the digital economy has a short-term but strong enhancing effect on the development of the sports industry. (3) Their internal driving force mainly drives the development of digital economy and artificial intelligence, and the self-contribution rate is 72.7% and 91.5% respectively. In contrast, the self-driving force of the sports industry is weaker, and the self-contribution rate is only 68.2%. (4) The contribution rate of the digital economy and artificial intelligence to the development of the sports industry is 12.3% and 19.6% respectively, i.e., the sports industry is more affected by the degree of application of artificial intelligence than the level of development of digital economy.

1. Introduction

In October 2021, the CPC Central Committee and the State Council issued the National Standardization Development Outline, which puts forward the new requirements of building new requirements to establish and improve carbon peak and carbon neutral ("dual carbon") standards, and to promote economic growth and green development through carbon emission reduction [1]. During the 14th Five-Year Plan period, China's ecological civilization construction entered a critical period in which carbon reduction is the key strategic direction, promoting synergies between pollution reduction and carbon reduction, and promoting a comprehensive green transformation of economic and social development [2]. Influenced by the traditional development of the sports industry, there are still many small and medium-sized sporting goods manufacturing enterprises at the low end of the industrial chain, presenting the

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characteristics of "low value-added and high energy consumption", and at the same time, with the continuous expansion of China's sports events and the continuous growth of the construction area of the stadiums, the carbon emissions are also increasing year by year. How to promote the sports industry to reduce pollution and carbon synergies, and promote the coordinated development of the sports industry scale and ecological civilization has become an important issue to ensure the sustainable development of China's sports industry.

The digital economy, driven by Information and Communication Technology (ICT), has emerged as a significant contributor to economies worldwide [3]. The digital economy, with artificial intelligence technology as an important driving engine, can achieve industrial structural adjustment and transformation and upgrading of traditional industries through digital industrialization and industrial digitization, and can also effectively reduce information asymmetry through the use of data elements, promote the free flow of factors of production in the market, and thus achieve Pareto improvement in the allocation of factor inputs, which can provide an opportunity to achieve the goal of "dual-carbon" and "sustainable development". "In 2022, the scale of China's AI core industry reached 508 billion yuan, an increase of 18% year-on-year. In the same year, the scale of China's digital economy exceeded 50 trillion yuan, accounting for 41.5 percent of GDP, and the digital economy has become the mainstay of China's national economic development [4]. With the continuous evolution of the technological revolution and the deepening of industrial change, the sports industry, as the future pillar of China's economy, will usher in a new round of structural adjustment and technological upgrading. The digital economy, based on data as the core production factor and digital information technology such as artificial intelligence technology, will provide an efficient development path for the sports industry [5], and at the same time, its role in enhancing the production efficiency of the sports industry and promoting consumption is becoming more and more obvious, which brings new opportunities for China's sports industry to achieve high-quality development [6]. More importantly, Artificial intelligence technology has a special advantage in the digital age, which can use big data, deep learning, and sensing devices to effectively monitor and accurately predict carbon emissions, thus optimizing the carbon emission reduction decision-making of the government and enterprises [7]. At the same time, the digital economy can not only promote high-quality energy development but also promote energy green transition and just transition [8], to a certain extent, to enhance the degree of intelligence and energy efficiency of environmental management, while reducing the degree of damage to the environment and improving the ecological potential [9]. It can also improve the environment and reduce carbon emissions to a certain extent by improving resource mismatch, and enhancing technological innovation capacity and social intelligence [10]. Under the requirement that "carbon reduction" has become the key strategic direction of China's ecological civilization construction, the digital economy centered on AI technology can further promote the green low-carbon transformation and high-quality development of the sports industry [11].

Although relevant studies have proposed that the digital economy and artificial intelligence have a positive contribution to the development of the sports industry, what is the relationship between the digital economy, artificial intelligence, and the sports industry? What is the mechanism of action between the three? Does the change in the relationship between the digital economy and artificial intelligence impact the development of the sports industry? At the same time, the economic system is always in the process of change, the digital economy, artificial intelligence, and the development of the sports industry are present in addition to the constantly changing trend, whether there is a time lag or instability in the interaction between the three? These issues have not yet been explored in depth by scholars. Due to the endogenous nature of these three variables, there is a dynamic mechanism of mutual influence, that can not be analyzed using the traditional panel regression, scholars mostly from the two-two relationship to start the study, has not yet been the dynamic interaction between the three in-depth investigations. Given this, this paper constructs a panel vector autoregressive model (PVAR) model based on the panel data of 15 provinces in China, which has the unique advantage of not needing to distinguish the exogenous and endogenous nature of variables in advance. Further analysis of the interactive relationship and mechanism between the digital economy, artificial intelligence, and sports industry development is of practical significance for transforming the development mode of China's sports industry, optimizing the sports industry institutions, and helping to achieve the goal of "double-carbon", and also provides a reference for promoting the coordinated development of the sports industry and the construction of ecological civilization in the new stage.

2. Literature review

2.1. 1Digital economy and AI

In 1997, the concept of digital economy was first proposed by Don Tapscott [12], an American economist. The following year, the report *Emerging Digital Economy* released by the US Department of Commerce officially opened the prelude to the development of the digital economy. The concept of digital economy is still controversial in academic circles. The more authoritative definition comes from the *G20 Digital Economy Development and Cooperation Initiative* issued by the G20 Hangzhou Summit in 2016, which proposes that the digital economy is a series of production activities that take digital knowledge and information content as important production factors, modern network information as important media, and rational use of information and communication technology as the main driving force to optimize the efficiency of economic structure. Artificial intelligence(AI), as a discipline developed based on computer science, cybernetics, and other disciplines, can simulate, extend, and expand human intelligence [13], and can continuously improve the level of survival and development. It is a technical ability to use human knowledge to discover problems, understand the world, and transform the world [14].

The rapid development of the digital economy has created a high-quality economic and technological environment for the whole AI industry [15]. In the industrial development pattern characterized by digital technology, data, a core factor of production, is required to be empowered with more details through more comprehensive and efficient technical means [16]. With the accumulation and

support of massive data, the digital economy provides a broad application platform for the development of AI technology. As the production means of the AI model running, data resources run through the whole life cycle of the birth, development, adjustment, and abandonment of the AI model. The accumulation of big data in the digital economy, the innovation of theoretical algorithms, and the evolution of network facilities drive the continuous innovation of AI technology and enter a new stage of development [17]. Simultaneously, the digital economy improves the effective supply capacity among the four major sectors of the national economy (non-financial enterprise sector, financial institution sector, government department, and household sector) through the direct role, substitution effect, and penetration of digital communication technology represented by AI, which provides support for accurate decision-making. In a market environment where digital marketing backed by artificial intelligence technology allows for the full flow of all information, which can solve the problems of limited updating and mismatch of the original product information and enhance the operational efficiency of the supply chain, thus realizing the maximum benefits of the transformation and enhancement of the marketing system and ultimately improving the operational performance [18]. Moreover, it improves the core competitiveness of enterprises and obtains a relative competitive advantage in the market environment by reducing production costs, optimizing the product structure, improving management efficiency, etc. [19]. In addition, the basic layer resources such as algorithm development platform, AIDC computing resources, and data basic services on which the development of the digital economy depends can improve the release of the value of artificial intelligence technology through multiple links, which solves the problem of scarcity of artificial intelligence productivity on the demand side in various segments of industrial development [20].

On the other hand, With the rapid development of Internet information technology, a new round of technological revolution and industrial change is in full swing. At this critical moment of historical change and convergence, artificial intelligence technologies that integrate data into systems, algorithms, and computational capabilities are evolving globally [21]. The combination of Artificial Intelligence and Big Data Economy has led to the gradual evolution of the traditional statistical economy into an intelligent digital economy, making possible economic linkages and precise data sharing which can be used for accurate economic statistics and mathematical analyses [22]. Big data would be worthless without a tool to extract more insights from it [23]. Meanwhile, AI strongly supports the digital economy. In other words, AI optimizes the rational allocation of relevant production factors and provides realistic decision-making by extracting effective information from big data, to improve the development level of the digital economy [23]. Digital communication technology represented by AI technology has realized the transformation and upgrading of traditional industries by the digital economy through the penetration effect and substitution effect [24]. If computers and the Internet are considered to provide application tools and data platforms for the development of digital technology, then AI should be regarded as an important link in transforming the indirect productivity of digital technology into direct productivity [25]. After experiencing the period of information, consumer Internet, and industrial Internet, the digital economy has entered a new stage of intelligent economy with AI as the core driving force [26].

2.2. *Digital economy and sports industry*

The main links to promote industrial economic growth include labor, capital, and other factor inputs and total factor productivity, while the digital economy can affect the factor input structure of industry through substitution effect and penetration effect, and improve the efficiency of industrial economic growth by improving total factor productivity. With the continuous evolution of the scientific and technological revolution and the deepening of industrial reform, the sports industry, as the pillar of China's economy in the future, will usher in a new round of structural adjustment and technological upgrading. The digital economy system is an essential driving force that promotes the development of the sports industry, aligning with Sustainable Development Goals (SDGs), including Goal 9 (Industry, Innovation, and Infrastructure), Goal 8 (Decent Work and Economic Growth), and Goal 11 (Sustainable Cities and Communities) [27]. The digital economy, which takes data as the core factor of production and is based on digital information technology, will provide an efficient development path for the sports industry [28]. The role of the digital economy in improving production efficiency and promoting consumption of the sports industry is becoming more and more obvious, bringing new opportunities for the high-quality development of China's sports industry. The digital economy is mainly through the formation of platform economic effects to reduce industrial costs and improve industrial efficiency, supplemented by business model upgrading. Digital innovation empowerment plays a leading role in the sports industry [29]. For example, in the area of sports consumption, Changing trends in consumption patterns of sports products lead to increasing awareness of sports organizations and adapting to new ways of satisfying market needs. These organizations create a new digitized space for the consumption of sports products indirectly(for example through digital broadcasting rights) [30].

Furthermore, the development planning ability and layout efficiency of the digital economy directly affect practical problems such as the optimization of sports industry structure, the transformation of growth kinetic energy, and the transformation of operation mode [31]. The digital economy helps to improve the efficiency of government management and governance, promote the omnidirectional transformation and fine operation of the sports industry, and enhance the competitive consciousness and scene construction ability of sports enterprises [32]. Digital application in the sports industry is also beneficial to optimizing the allocation of sports resources, improving total factor productivity, promoting cross-border integration of the sports industry, giving birth to new business types and a new model, and enhancing the competitiveness of sports enterprises. Generally, the digital economy can improve the development quality of the sports industry from many aspects, such as development power change, development efficiency change, development quality change, governance ability change, etc. For example, it can enhance the digital ability of the sports industry through reasonable and efficient means, and finally promote the development of the sports industry in many dimensions in the aspects of optimizing industrial structure, promoting industrial integration, strengthening basic security, and innovative governance mode.

On the other hand, the sports industry gives play to economies of scale, economies of scope, and the long tail effect through factor

digitalization, process digitalization, and product digitalization, forming the internal mechanism of the integration of the digital economy and the sports industry [33]. While the sports industry is affected by internal and external factors in the process of development. The demand for the optimization of supply and demand structure, the demand for supply-side reform, the demand for the promotion of enterprise competitiveness and the demand for industrial efficiency have inversely promoted the development of digital economy and technology [34]. Also in the digital transformation in the sports industry,the creation and application of a consultation instrument on digitalization is the first and necessary step to carry out relevant, in-depth, valid and replicable research, which allows information to be gathered on the digitalization needs of sports organizations to design their digital transformation roadmap and that the aids for digital transformation are distributed efficiently [35]. For example, the efficiency improvement of sporting goods enterprises has promoted the development of digital industry platforms, and the customer precision marketing of the sporting goods service industry has also promoted the construction of big data platforms. In China, Fujian is a major sporting goods manufacturing province, The government timely proposed to carry forward the "Jinjiang Experience" [36] and speed up the development of digital transformation. Jinjiang has the advantage of a sporting goods manufacturing cluster. In recent years, the Jinjiang Municipal Government has made great efforts to develop the construction of digital Internet platforms, such as "Yipinjia", "Xiechaungyun", "Yongyiku", etc., and has established cloud incubation centers with leading digital enterprises to improve the digital supply network, thus achieving a complementary win-win situation with the development of the sports industry while improving the level of regional digital technology.

2.3. AI and sports industry

At present, the technological development of AI is continuously improving by attracting many academic and industry researchers to extend its application in different walks of life effectively [37,38].In the field of sports, the hotspots of AI research involve "physical health promotion", "sports injury prevention and control" and "sports ability enhancement" in the direction of national fitness and sports events [39].In 2019, The State Council of China issued the *Outline for Building a Leading Sports Nation*, which clearly pointed out that it is necessary to accelerate the innovation of production mode, service mode, and business model of the sports industry through AI, to promote the development of sports industry and improve quality and efficiency [40].

AI is regarded as the core technology to activate the upgrading of the sports industry from digital to intelligent. The wide application of AI technology will affect total factor productivity, thus promoting sustained economic growth [41]. Customers' demand for data products and services including machine learning technology is becoming increasingly exuberant, which indirectly and effectively promotes the great-leap-forward development of the AI industry. As a key technology gradually integrated into enterprise business applications, AI technology plays an important role in the landing of many digital solutions and scene applications, in which different means and ways such as building data warehouses and data platforms are helping enterprise users to realize the business and strategic development concept of "digital + AI" [42]. Furthermore, AI can transform data and other production factors from the third industrial revolution to the fourth industrial revolution, so it will further promote the reform and upgrading of key production factors in the sports industry. At this stage, AI technology has not only completed the excavation and creation of the value of the sports industry using a large number of data resources but also accelerated the process of the rapid development of data resources into the core

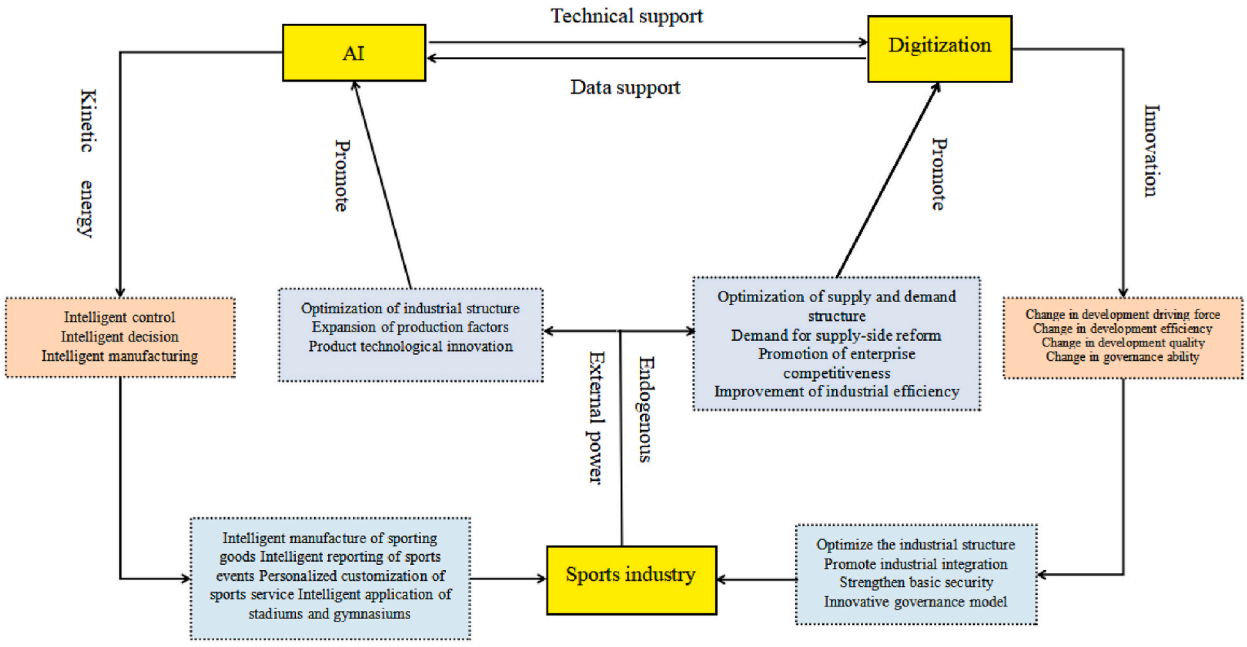

Fig. 1. The interactive mechanism of development of digital economy, ai and sports industry.

elements of the development of the sports industry [25]. AI finally improves the development quality of the sports industry through the fields of intelligent manufacturing of sporting goods, intelligent reporting of sports events, personalized customization of sports services, and intelligent application of stadiums and stadiums. At present, AI has built a "bridge" between science and application through its "deep learning" technology and has developed into the key technology of a new round of technological revolution [43]. At the same time, as a new generation of information technology, AI has the technical and economic characteristics of cooperation, accuracy, timeliness, predictability, openness, integrity, and standardization [44]. These characteristics in turn promote the high-quality development of the sports industry utilizing factor support, efficiency improvement, knowledge creation, etc. [45].

On the other hand, the optimization of industrial structure, the expansion of production factors, the improvement of management efficiency, and the demand for product technological innovation have further promoted the development of AI in the sports industry [26]. The intelligent upgrading of sporting goods production equipment and the birth of various new intelligent products are bound to bring a large number of data resources, which lays a good foundation for the unlimited supply of data resources, thus, providing an extremely sufficient guarantee for the value mining and creation of AI in the field of sports industry. For example, in order to achieve accurate marketing of products, prompting sports enterprises to develop marketing systems based on artificial intelligence technology through the collection of user big data on technology, driven by the enterprises to think about how to use digital channels to sell sports products and improve corporate performance [30]. Furthermore, to achieve accurate exercise and scientific fitness, AI robots and Intelligent wearable system was born in the field of sports fitness which can provide scientific guidance for sports enthusiasts or professional athletes [46–48]. In the aspect of news reporting of sports events, modern media technology promotes the promotion and application of AI writing robots [49].

The existing research tends to analyze the pairwise relationship among the three subjects through logical discrimination by presupposing the action mechanism among the digital economy, AI, and sports industry, but there is almost no empirical analysis based on relevant data, and. the cycle between the three and individual heterogeneity is even ignored. For this reason, the following two new perspectives are discussed: (1) A new analytical framework is built(Fig. 1). With the help of the PVAR model, the development level of the digital economy, the application level of AI and the development scale of sports industry (hereinafter referred to as "digital economy", "AI" and "development of sports industry") are placed within the same analytical framework, and all of them are regarded as endogenous variables, which depict the transmission mechanism of various shocks and the relative importance of observing random disturbances that affect variables. (2) the limitations of single-dimensional and static research have been broken through. In this work, the generalized method of moments, Granger causality test, dynamic impulse response analysis and analysis of variance are carried out on the relationship and mechanism of digital economy, AI and the development of the sports industry from a two-way and dynamic perspective, which clarifies the trend and influence degree of the short-term and long-term relationship among the three. In general, the interactive mechanism of the digital economy, AI and sports industry is shown in Fig. 1.

3. Research methods

3.1. PVAR method

The PVAR model can better describe the transmission mechanism between the variables and can satisfy the requirements of the theoretical model regarding the characterization of endogenous variables. It also has the characteristics of large cross section and short time sequence. In addition, it can effectively solve the problem of individual heterogeneity through panel data, taking full account of individual effects and time effects, and can reduce the length requirements of the VAR model for time series data. Therefore, with the help of the PVAR model, the relationship between the digital economy, artificial intelligence, and sports industry development can be analyzed more accurately, and the endogenous influence of the arrival of these three variables can be avoided in the process of analysis, to clearly portray the transmission mechanism of the formation of various shocks. In addition, from the perspective of bi-directionality and dynamics, through the generalized method of moments, Granger causality test, dynamic impulse response analysis, and analysis of variance in the PVAR model, it can clearly show the direction of the short-term and long-term relationship between the three and the degree of influence. Based on the PVAR estimation method, the following panel autoregressive model is constructed.

$$y_{it} = a_i + \eta_t + \beta_0 + \sum_{j=1}^{p} \beta_j y_{i,p-j} \varepsilon_{it} \tag{1}$$

Wherein, y_{it} represents the column vector containing three endogenous variables (DIG, AI, TYC), i represents the sample unit, t represents the year, p represents the lag order of the model, β_0 represents the intercept term vector, and β_j represents the parameter matrix of the lag variable, α_i represents the regional effect series vector, indicates the cross-section individual difference reflected in the form of fixed effect, η_t represents the time effect series vector, indicates the influence of time change on the cross-section individual, and ε_{it} represents the "white noise" disturbance term.

3.2. Data and variables

3.2.1. Measurement of level of digital economy publication

Concerning the research of Zhao et al. [50], the level of digital economy development is measured from the development level of Internet and digital finance. For the measurement of the development level of the Internet, the research of Huang et al. [51]has been used for reference. Specifically, four subdivided indicators are adopted: Internet penetration rate (Number of Internet Broadband

access users per 100), Internet-related employees (the proportion of employees in computer service and software industry in urban units), Internet-related output (total per capita telecom service) and number of mobile Internet users (Number of mobile phone users per 100). The above data come from the *China Statistical Yearbook*. For the measurement of the development level of digital finance, the China Digital Inclusive Finance Index was jointly compiled by the Digital Finance Research Center of Peking University and Ant Financial Services Group. The details of the indicators are shown in Table 1. In the selection of evaluation methods, the panel entropy method is selected to measure the digital economy comprehensive development index DIG.

3.2.2. Measurement of level of artificial intelligence application

At present, there is no unified and authoritative index to measure the level of AI application. Referring to the methods commonly used in authoritative literature [52], the processing methods in the classical literature written by Borland and Coelli are adopted, and the application level of AI is expressed by the ratio of fixed assets investment to GDP in information transmission, computer services, and software industry [53]. In addition, AI technology takes a period from input to impact, so the data of each year are processed with a lag period (one year) and then empirical analysis is carried out to get the provincial AI application degree measure AI. The data come from the National Bureau of Statistics.

3.2.3. Measurement of level of sports industry development

Currently, the indicators to measure the level of sports industry development are different, the commonly used indicators are the total scale of the sports industry, the added value of the sports industry, and the number of employees in the sports industry, etc. To accurately evaluate the development scale of China's sports industry, the General Administration of Sports and the National Bureau of Statistics of China adopted the index of "added value of sports industry" to evaluate the development of the sports industry. Therefore, this work chooses "sports industry value added (TYC)" as a measure of the development scale of the sports industry, in 10 billion. This index refers to the final results of sports industry production activities carried out by all resident units in a country (region) within a certain period. However, it is impossible to obtain complete local data because the statistical work of sports industry data in some provinces in China is not perfect. As a result, the added value of the sports industry from 2014 to 2020 in 15 provinces (cities) of Guangdong, Shanghai, Jiangsu, Zhejiang, Henan, Hebei, Fujian, Liaoning, Chongqing, Sichuan, Hunan, Guizhou, Anhui, Jiangxi and Shanxi was selected as the research object according to the availability, accuracy and completeness of the data. The data come from the websites of provincial (municipal) sports bureaus, provincial (municipal) sports industry work reports, and authoritative media news reports. The few missing data are filled in by interpolation. The summary of measurements for each variable is shown in Table 2. The final descriptive statistical results of digital economy, AI and sports industry indicators are shown in Table 3.

4. Empirical results and analyses

This study conducts empirical analysis by constructing the PVAR model. Before modeling, the stability of the panel data collected in the study shall be checked to prevent false regression and ensure the accuracy of the model; Secondly, the Granger causality test is used to determine whether there is a significant impact relationship between digital economy, artificial intelligence and sports industry development; Then, using the regression results of the system GMM estimation variables, the impulse response function is used to analyze the impact of endogenous variables on unit change; Finally, variance decomposition is used to study the contribution rate of endogenous variable changes.

4.1. Stationarity test and selection of optimal lag order

If there are unsteady variables in the PVAR model, the results cannot accurately reflect the logistic interactions among the variables [54].In this paper, the same-root LLC test the different-root Fisher-ADF test, and the Fisher-PP test are used to test the unit root of the panel data at the same time, and the test results are shown in Table 4. It can be seen that the test results of the LLC test and Fisher- ADF, Fisher-PP test all reject the original hypothesis at a 10% significance level, indicating that the original series of the three variables is smooth. Therefore there is a long-term equilibrium relationship between digital economy, artificial intelligence, and sports industry development, and the PVAR model can be tested next.

Then the AIC, BIC, and HQIC information criteria are calculated and compared for the model at each order of magnitude and the optimal lag order of the model is obtained according to the minimum of AIC, BIC, and HQIC criteria to ensure the reliability and

Table 1
Evaluation index system of digital economy development level.

First-Level Index	Second-Level Index	Third-Level Index	Index Attribute
Development Level of Digital Economy	Internet penetration rate	Number of Internet Broadband access users per 100	+
	Internet-related employees	The proportion of employees in the computer Service and software industry in urban units	+
	Internet-related output	Total telecommunications services per capita	+
	Number of mobile Internet users	Number of mobile phone users per 100	+
	The development level of digital finance	China Digital Inclusive Financial Index	+

Table 2
Summary of measurements for each variable.

Symbolic	Connotation	Measurement methods	Data sources
DIG	Digital Economy	Development Level of Digital Economy ( ) Table 1	China Statistical Yearbook
AI	Level of Artificial Intelligence development	The ratio of fixed assets investment to GDP in information transmission, computer services, and software industry	The Website of the National Bureau of Statistics of China
TYC	Sports industry	Sports industry value added	The websites of provincial (municipal) sports bureaus, provincial (municipal) sports industry work reports and authoritative media news reports

Table 3
The descriptive statistical results of indicators.

Variable	Observed values	Mean	Standard Deviation	Min	Max
DIG	105	0.452	0.143	0.233	0.855
AI	105	0.007	0.003	0.001	0.016
TYC	105	1.212	0.951	−1.256	2.936

Note: DIG means Digitization, AI means Artificial Intelligence, TYC means Sports Industry.

Table 4
Stationarity test results.

Variables	LLC test	Fisher-PP test	Fisher- ADF test	Result
DIG	−42.975***	7.004***	60.069***	stable
AI	−290.416***	10.268***	32.814***	stable
TYC	−1.544*	124.319***	1.292 *	stable

Note: Note: DIG means Digitization, AI means Artificial Intelligence, and TYC means Sports Industry; *, * *, and * * indicate significance at the confidence level of 10%, 5%, and 1% respectively, the same as below; the figures in the table represent the corresponding statistics in LLC test, IPS test and Fisher- ADF test, respectively.

validity of the estimation results. The results are shown in Table 5, The optimal lag order of the PVAR model is 3 orders.

4.2. Generalized method of moments (GMM)

The generalized method of moments (GMM) is commonly used in parameter estimation of vector autoregressive models. It employs the sample moment condition to infer the unknown parameters of the population and determine the parameter estimators of the population. Arellano et al. [55]confirmed that GMM can improve the effectiveness of estimators. Therefore, the GMM estimation of the PVAR model for 15 provinces is carried out according to the selected optimal order 3, and the long-term interaction between variables is analyzed. The results are shown in Table 6. Before the estimation of the PVAR model, the forward mean difference method (Helmert process) is used to eliminate the individual effect, which ensures the orthogonality between the transformed variable and the delayed explanatory variable [56].

According to Table 6:(1)When the development level of the digital economy is selected as the explanatory variable, each one-unit increase in the level of the digital economy in the lagged period induces a 1.344-unit increase in the level of the digital economy in the current period at the 1 percent significance level, indicating that the digital economy has formed a self-driving ability, and the dividend brought by the digital economy technology promotes the society to increase the demand for the digital economy. On the contrary, the digital economy that lags behind the second phase is negatively correlated with the current level at a confidence level of 1%, each one-unit increase in the level of the digital economy in lag two can cause a 0.593-unit decrease in the level of the digital economy in the current period at the 1 percent significance level. This may be due to the self-inhibition of the development of the digital economy caused by the unbalanced development of the consumption-oriented digital economy and production-oriented digital economy, which

Table 5
The optimal lag order of PVAR model.

lag	AIC	BIC	HQIC
1	−4.927	−3.258	−4.261
2	−9.13989	−6.941	−8.279
3	−14.215*	−11.324*	−13.137*
4	19.151	22.934	20.361
5	21.629	25.877	21.584

Note: * denotes the optimal lag order chosen for the corresponding criterion.

Table 6
The results of GMM.

Variables	h_DIG		h_AI		h_TYC	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
L1.h_DIG	1.344***	0.305	0.008*	0.005	9.539***	2.931
L1.h_AI	1.419	3.275	0.982**	0.490	−150.590	237.866
L1.h_TYC	−0.001	0.003	0.001	0.001	0.540*	0.281
L2.h_DIG	−0.593***	0.059	−0.004	0.009	−8.809	4.873
L2.h_AI	−0.246	1.238	−0.188	0.184	30.036	90.087
L2.h_TYC	0.002	0.003	−0.001	0.001	−0.527**	0.266
L3.h_DIG	−0.004	0.032	−0.001	0.004	1.264	2.487
L3.h_AI	0.172	0.462	−0.022	0.092	48.403	41.507
L3.h_TYC	−0.001	0.002	0.001	0.001	0.403***	0.123

Note: DIG means Digitization, AI means Artificial Intelligence, and TYC means Sports Industry; *, * *, * * indicate significance at the confidence level of 10%, 5%, and 1%, respectively; h _ represents the form of eliminating fixed effect after Helmert transformation; L1, L2, and L3 indicate lag of one, two and three orders, respectively.

may be caused by the large-scale promotion of digital technology. The lagging items of AI and the sports industry have no significant impact on the development level of the digital economy.

(2) When the degree of AI application is selected as the explanatory variable, each 1-unit increase in the level of AI adoption in the lagged period causes a 0.982-unit increase in the level of AI adoption in the current period at the 5 percent significance level. This shows that AI technology is now fully penetrated across industries, with the production demand of higher precision products and the application demand of high-efficiency service, AI technology continues to promote its own technological innovation. In addition, each 1-unit increase in the level of the level of the digital economy in the lagged period induces a 0.008-unit increase in AI adoption in the current period at the 10 percent significance level. The innovation of theoretical algorithms and the evolution of network facilities in the digital economy provide a display platform for the development of AI in a short period, which in turn drives the continuous innovation and development of AI technology.
(3) When the added value of the sports industry is selected as the explanatory variable, each one-unit increase in the value added of the sports industry in the lagged period can cause a 0.54-unit increase in the value-added of the sports industry in the current period at the 10 percent significance level. With the expansion of the scale of the sports industry, the development of the lagging second phase of the sports industry has a self-restraining effect, but the lagging third phase of the development of the sports industry is positively related to its current level of confidence level of 1%. According to the analysis of the reasons, the diversified factors such as the promotion of national policy make the development of the sports industry usher in a bright prospect. However, it is worth noting that the lack of production and supply of the sports industry, the low service efficiency of the sports industry, insufficient innovation power of the sports industry, and other problems hinder the development of the sports industry. With the upgrading of the structure of the sports industry and the implementation of a series of regulation and control measures such as the rational allocation of production factors, the sports industry has gradually returned to a reasonable and efficient way of development. In addition, Each one-unit increase in the level of the digital economy in the lagged period induces a 9.539-unit increase in the value-added of the sports industry at the 1% significance level. In other words, the development of the digital economy has promoted the scale growth of the sports industry in the short term, and advanced digital production and management technology has improved the production and management efficiency of the sporting goods manufacturing industry and sports service industry. But in the long run, the differences in the scale and concept of sports-related enterprises lead to the imperfect construction of digital platforms, the lack of digital technical personnel, the low efficiency of management mode and application, etc. In general, the digital transformation of the sports industry has not yet achieved the desired results.

Table 7
Results of the Granger causality test.

Variables	null hypothesis	Chi-square	Conclusion
DIG	AI is not the Granger reason for DIG	3.986	Accepted
	TYC is not the Granger reason for DIG	0.628	Accepted
	Neither is the Granger cause for DIG	4.630	Accepted
AI	DIG is not the Granger reason for AI	7.699*	Rejected
	TYC is not the Granger reason for AI	4.832	Accepted
	Neither is the Granger cause of AI	13.635**	Rejected
TYC	DIG is not the Granger reason for TYC	15.428***	Rejected
	AI is not the Granger reason for TYC	2.278	Accepted
	Neither is the Granger cause of TYC	34.570***	Rejected

Note: DIG means Digitization, AI means Artificial Intelligence, and TYC means Sports Industry; *, * *, * * indicate significance at the confidence level of 10%, 5%, and 1%, respectively.

4.3. Granger causality test

Granger causality is an approach that uses predictability as opposed to correlation to identify causation between time series variables [57].In Granger causality, a cause shall precede its effect while the understanding of a cause will help to increase the accuracy to predict the effect [58].To further clarify the short-term dynamic effects and causality among variables, a Granger causality test with a lag of three periods was carried out based on the constructed PVAR model. The results are shown in Table 7. Obviously, the level of the digital economy is the one-way Granger reason for the application of AI, and the level of the digital economy is also the one-way Granger reason for the development of the sports industry, indicating that the level of digital economy has a positive impact on the application of AI and the development of sports industry.

4.4. Impulse response function analysis

In the PVAR model, the focus of the analysis is not only to analyze the impact of the change of a variable on another variable but also to analyze the dynamic response of the whole model system when a variable changes. The impulse response function (IRF) reflects the dynamic effect of a shock of one unit of standard deviation in the imposed variable on the other variables. Specifically, it is first to give the impact of a unit positive standard deviation to the error term and then observe the changes of endogenous variables in subsequent periods [59]. IRF directly reflects the dynamic interaction between endogenous variables and helps analyze the time delay effect between variables [60]。In this work, the impact period is set to 10 periods, and the impulse response analysis of the digital economy, AI, and sports industry is carried out through 500 Monte-carlo simulations. The results are shown in Fig. 2. The middle solid line is the impulse response function, and the solid lines on both sides represent a 95% confidence interval.

It is obvious that: (1) in Fig. 2(1a) and(2a), after the digital economy is impacted by the sports industry and AI, a 95% confidence interval contains 0 value, that is, the assumption that the impulse response coefficient of sports industry and AI to digital economy is zero can not be rejected at 5% confidence level, so sports industry and AI have no significant impact on digital economy, which is also

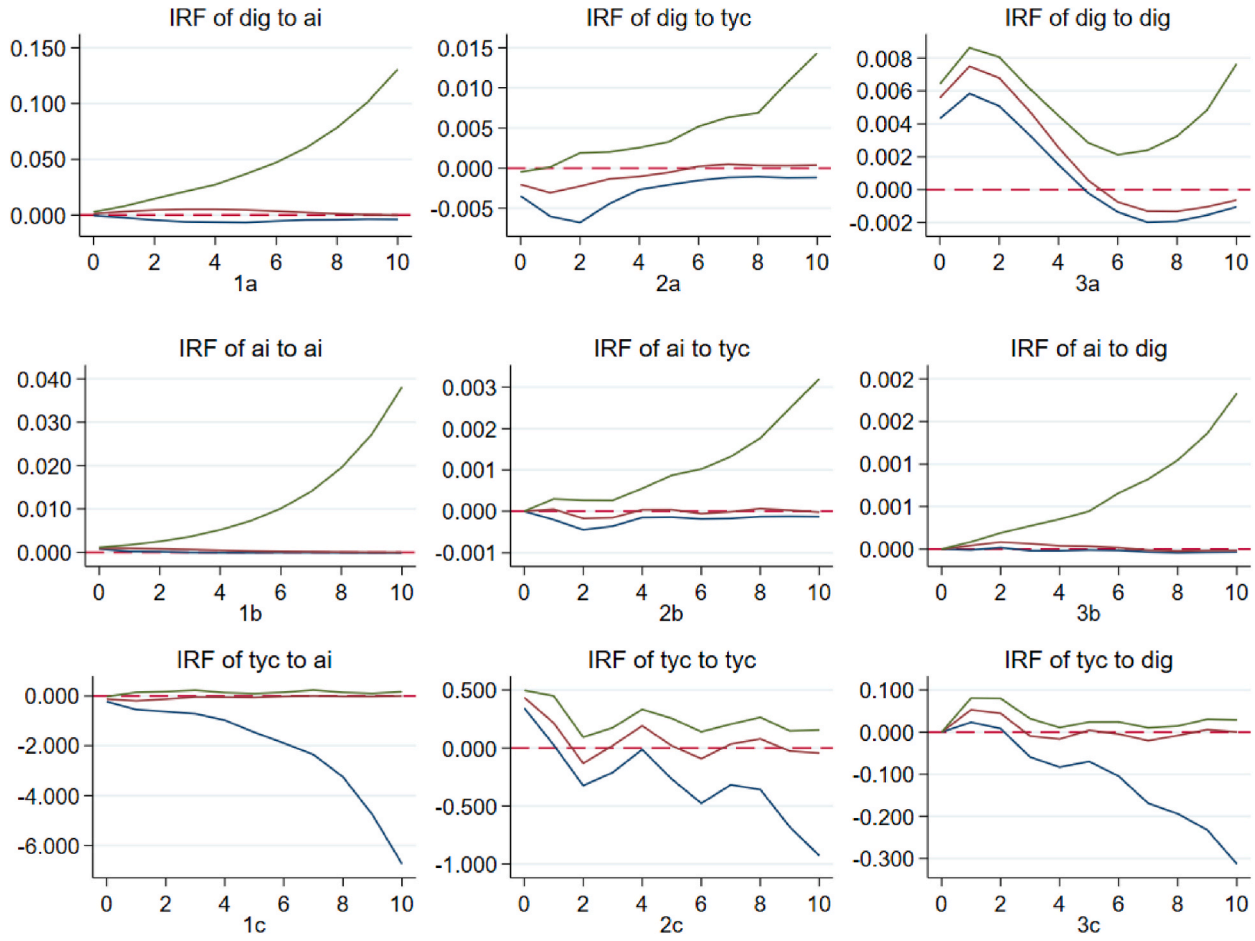

Fig. 2. The impulse response results
Note: DIG means Digitization, AI means Artificial Intelligence, TYC means Sports Industry.

consistent with the results of GMM estimation and Granger test. In Fig. 2(3a), the development of the digital economy will have a positive impact on its own impact, reaching its peak in the first phase, and then gradually weakening, and can not have a significant impact on itself since the fifth phase. (2) In Fig. 2(1b), AI will have a small positive impact when it is hit by itself, but then it gradually decreases and tends to stabilize. In Fig. 2(2b), AI is not significantly affected by the impact of the sports industry. In Fig. 2(3b), AI rises slightly in the short term and then decreases gradually after the shock of the digital economy, and has no significant impact after the third phase, indicating that the digital economy will promote the development of AI in the short term, which is also consistent with the above test results. (3) In Fig. 2(1c), the sports industry is not significantly affected by the impact of AI. In Fig. 2(2c), the development of sports property was positively affected by self-impact in the current period, then decreased rapidly, and could not have a significant impact in the second and third stages. In the fourth phase, the sports industry has a positive impact on itself, but the follow-up has no significant impact. In Fig. 2(3c), after the impact of the digital economy, the sports industry will have a positive impact in the first two periods, but in the long run, the impact is not significant, that is, the digital economy can promote the development of the sports industry in the short term, which is also consistent with the above research results.

4.5. Variance decomposition

Similar to the IRF, variance decomposition is another method for analyzing changes in the dynamics of the entire model system. The method involves analyzing the proportion of the mean square error that each variable bears in the overall model and using it to assess the relative importance of individual shocks to changes in the variables [61]. In this paper, the variance decomposition of the PVAR model is further carried out to examine the degree of interaction between the level of the digital economy, the degree of AI application, and the size of the sports industry. The results are shown in Table 8.

According to Table 8, the variance decomposition results of each variable in period 15 and period 20 are basically the same, indicating that the degree of explanation of each shock to the change of each variable has been basically stable after the 15th period. According to the analysis of the 15th issue as an example, the development of the digital economy, the application of AI, and the development of the sports industry are greatly influenced by themselves. From the results of variance decomposition, the contribution rate of digital economy to itself is 72.7%, while that of AI and sports industry to digital economy is 27.2% and 0.2% respectively, indicating that the digital economy is more affected by the development of AI than by the development of sports industry. Secondly, the contribution rate of digital economy shows a downward trend, while the contribution rate to AI and sports industry gradually increases, indicating that there is a lagging effect of the digital economy on the development of AI and sports industry. The fluctuation of AI is mainly influenced by itself, 91.5% of the fluctuation can be explained by itself, while only 7% and 1.5% of the contribution comes from the digital economy and sports industry. The contribution rate of the sports industry to itself reached 68.2%, and the contribution rates of digital economy and AI to sports industry were 12.3% and 19.6%, respectively. Compared with the digital economy and AI, the contribution rate of sports industry is the smallest, suggesting that it is more dependent on external factors, which are more affected by the development of AI than by the development of digital economy.

4.6. Robustness test

To verify the reliability and stability of the above research results, the variables of replacing the variables measuring the level of the digital economy and the degree of AI application are re-analyzed through the generalized distance estimation (GMM) in the PVAR model by drawing on the replacement. For the level of the digital economy, refer to the study of Fei Yue et al. [62], from the perspectives of digital foundation and a digital scale, the long-distance fiber-optic cable line lengths of the investigated provinces, telecommunication and communication service levels, the e-commerce logistics scale, and the total telecommunication service indicators, and re-measure the digital economy level of each provincial domain by entropy method, denoted as DIGr. Referring to Peng et al. [61], the number of AI patents in each province and region is used to represent the application level of AI technology, which is denoted as AIr. In addition, the total output of the sports industry, as the official data released at the same time as the value added of the sports industry, can also more accurately reflect the level of the sports industry in each region. reflect the development of the sports industry

Table 8
The Variance decomposition results.

Variables	Period	DIG	AI	TYC
DIG	5	0.826	0.173	0.001
DIG	10	0.727	0.271	0.001
DIG	15	0.727	0.272	0.002
DIG	20	0.727	0.272	0.002
AI	5	0.070	0.917	0.012
AI	10	0.070	0.916	0.014
AI	15	0.070	0.915	0.015
AI	20	0.070	0.915	0.015
TYC	5	0.121	0.196	0.683
TYC	10	0.122	0.198	0.680
TYC	15	0.123	0.196	0.682
TYC	20	0.123	0.195	0.682

Note: DIG means Digitization, AI means Artificial Intelligence, TYC means Sports Industry.

Table 9
The results of Robustness test.

Variables	h_DIGr		h_AIr		h_TYCr	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
L1.h_DIGr	0.682**	0.159	0.021***	0.023	6.892***	2.041
L1.h_AIr	0.816	1.946	0.662**	0.316	−77.152	117.629
L1.h_TYCr	−0.005	0.002	0.005	0.003	2.605***	3.383
L2.h_DIGr	−0.022**	0.012	0.002*	0.003	−2.412	1.690
L2.h_AIr	0.055	0.398	−0.305	0.192	65.005	146.937
L2.h_TYCr	−0.001	0.002	0.001	0.001	−3.146**	2.556
L3.h_DIGr	−0.001	0.011	−0.036	0.020	8.336	11.172
L3.h_AIr	−0.103	0.278	−0.180	0.279	90.645	83.063
L3.h_TYCr	0.009	0.015	0.002	0.001	2.552*	1.992

Note:*, * *, * * indicate significance at the confidence level of 10%, 5%, and 1%, respectively; h _ represents the form of eliminating fixed effect after Helmert transformation; L1, L2, and L3 indicate lag of one, two and three orders, respectively.

in each region, therefore, the total output of the sports industry is adopted as a proxy variable to measure the scale of the sports industry in tens of billions of dollars, denoted as TYCr. Table 9 shows the GMM results by replacing the relevant variables, and it can be seen that the direction and significance of the regression coefficients of the main variables are basically the same as those of the benchmark regression.

5. Conclusion and discussion

5.1. Conclusion

In the face of the current "low value-added, high energy consumption" and other characteristics of China's sports industry, the coordinated development of industrial-scale growth and ecological environment has become an important issue. Digital economy with artificial intelligence technology as an important driving engine can achieve industrial structural adjustment and transformation and upgrading of traditional industries through digital industrialization and industrial digitization, and can also effectively reduce information asymmetry through the use of data elements, promote the free flow of factors of production in the market, to realize the Pareto improvement in the allocation of factor inputs. In addition, digital technology, as an important hand for green and low-carbon development, can improve the resource utilization efficiency of the sports industry, regulate the factor structure in the labor market and capital market, promote the in-depth integration of different sports enterprises in the physical space and information space, reduce the carbon emission intensity of the sports industry, and contribute to the realization of the "Carbon Peak" and "Carbon Neutral" goals in China. This provides a possible path for China to achieve the goals of "carbon peak" and "carbon neutrality".Based on the panel data of 15 provinces in China from 2014 to 2020, the dynamic relationship between the digital economy, AI, and the development of the sports industry is analyzed by using PVAR model, and the following conclusions are drawn.

(1) According to the results of the Granger causality test, digital economy is the one-way Granger cause of AI, and digital economy is the one-way Granger cause of the development of sports industry, that is, digital economy has a "predictive ability" to the development of AI and sports industry. However, neither AI nor sports industry is the Granger cause of the other.
(2) The results of generalized moment estimation and impulse response analysis show that the development of digital economy, AI, and sports industry has a strengthening mechanism for themselves in the short term, but in the long term, it has a tendency to weaken gradually. Every 1 unit of the digital economy level in the lagged period can cause the level of AI application in the current period to increase by 0.008 units, i.e., the digital economy has a short-term and weak promotional effect on AI, with no significant effect in the long term. Every 1 unit increase in the level of digital economy in the lagging period can cause the value added of sports industry to increase by 9.539 units. That is, the digital economy has a short-term but strong promotion effect on the development of sports industry, but the long-term effect is not significant.
(3) The results of variance decomposition show that their own internal driving force mainly drives the development of digital economy and artificial intelligence, and the self-contribution rate is 72.7% and 91.5% respectively, compared with the weak self-driving force of sports industry. In addition, the contribution rate of artificial intelligence to the digital economy is much higher than that of the sports industry. The contribution rate of digital economy to AI is 5.5 percent higher than the contribution rate of sports industry to AI, which means that AI is more affected by digital economy than by sports industry. The contribution of artificial intelligence to the sports industry is 7 percent higher than the contribution of the digital economy to the sports industry, i.e. the sports industry is more affected by artificial intelligence than by the digital economy.

5.2. Discussion

5.2.1. Digital economy and sports industry

The digital economy promotes the development of sports industry in the short term, but there is no significant lasting effect, indicating that the current application of digital technology in China's sports industry is not fully efficient matching, and can not bring

long-term economic benefits. Therefore, the following ways may be used to improve the digital application level of the sports industry: (1) Strengthen the training of digital talents in the sports industry. The compound talents in the development of sports industry are of great significance to the digital development of sports industry. The relevant government departments are suggested to formulate a reasonable strategy for the introduction and development of technical compound talents based on fully investigating the market demand. The relevant sports enterprises should formulate the training plan and system of high-tech compound talents according to their own development plans, and explore the new employment relationship of sports enterprises under the digital economy strategy under the traditional role paradigm of enterprises and employees, so as to enhance the enthusiasm of staff development and creation. At the same time, we should actively create an open platform for employment and entrepreneurship, which will inevitably be conducive to the innovation of digital technology and the reasonable upgrading of factors of production. (2) Accelerate the improvement of enterprises' mastery and utilization efficiency of digital platforms. All kinds of sports enterprises are suggested to speed up the digital transformation of sports enterprises and the incubation of sports industry organizations through the link function of science and technology platforms to connect the resources of various elements in the sports industry and the characteristics of accelerators and incubators of science and technology platform. The relevant departments should, in conjunction with various digital technology enterprises, speed up the construction of the data-sharing platform for the sports industry, enhance the transparency of public sports data, widen the access channels, and further enrich the hierarchical connotation of "Internet + Sports". Moreover, the promotion of the digital mass entrepreneurship and innovation platform for the sports industry should be accelerated. (3) Strengthen the policy support and supervision of the government. Currently, the digital transformation of sports industry is facing diversified practical challenges, such as weak development foundation, high cost of technology acquisition, insufficient technology penetration, inadequate supervision, insufficient reserve of digital talents, etc. This implies that the digital transformation and upgrading of the sports industry are inseparable from the strong driving force of the government. In addition, the government may also use digital thinking to strengthen the management of the sports industry market, improve the construction of consumer complaint platforms, and supervise the implementation of digital technology in the sports industry market in real time. (4) promote the precision of multi-agent collaborative governance. Digital economy is a decentralized ecological control system composed of multiple subjects, in which collaborative governance is its core. In the post-pandemic era, the continuous updating of the format and mode of the digital transformation of the sports industry has led to the shaking of the position of the traditional main body of the sports market. Therefore, the co-governance of multiple subjects may be beneficial to further optimize and promote the digital transformation and development of the sports industry.

5.2.2. AI and sports industry

At present, the interaction mechanism between sports industry and AI is not clear. Specifically, AI technology can not provide sufficient momentum for the development of sports industry, and the development of sports industry can not promote the promotion of AI technology for the time being. However, AI technology has infiltrated into all fields of the development of sports industry. Some scholars agree that AI technology may be able to search the relevant data generated by enterprises and groups in the sports industry in the process of production and operation with the help of Internet thinking, and import it into the AI system, to promote a series of intelligent changes in production control and operation management of the sports industry. The sports industry-related data is not perfect, and the limitations of the application and promotion of AI systems are the important reasons why AI can not promote the development of sports industry. Therefore, the following suggestions are put forward: (1) Construct the platform carrier of AI to promote the development of sports industry. The first is to enhance the popularity of the sports industry Internet platform, and efficiently implement the real-time exchange and value exchange of all kinds of business and information among all kinds of sports industry-related enterprises. Secondly, the data mining ability of AI technology should be brought into full play based on all kinds of production data of sports industry platforms. Thirdly, it is necessary to create a comprehensive service platform for sports resources trading and make full use of the technical advantages of AI in perceptual activities, cognitive value, computing speed, and accuracy, to promote the integration and sharing of sports industry resources. The last part is to build a modern intelligent network platform to meet the coordination and sustainable development of the regional sports industry. (2) Strengthen the research and development of AI technology and standard-setting in sports industry. First of all, the special promotion plan for AI technology in the sports industry should be formulated, and the R&D team of universities and high-tech sports enterprises should be established with the help of policy and financial support. Secondly, it is necessary to improve and expand the transformation efficiency and application scope of AI technology in the sports industry. At the same time, the formulation and implementation of national standards and industry standards for the core technology of sports AI should be strengthened, to continuously expand the international influence of China's intelligent sports field. (3) Strengthen the training and introduction of high-end compound talents. First of all, expand the channels for talent training, create a talent training model of school-enterprise cooperation, enrich and improve the curriculum system structure, and improve the quality of curriculum teaching. Secondly, all regions are suggested to improve the introduction and training plan of high-end talents of AI technology in the field of sports industry in the light of the actual situation of the region, to effectively protect the living needs of high-end talents, strengthen scientific research subsidies, establish incentive and funding policies, and enhance the enthusiasm of research and development.

6. Limitations and further research direction

This paper explores the dynamic interaction between the level of digital economy, the degree of artificial intelligence application, and the scale of sports industry in 15 provinces in China, but there are still some shortcomings. Firstly, this paper is based on the provincial level and does not consider the spatial correlation between the development of digital economy and the application of AI

technology in each province. In the future, based on the spatial spillovers of the development of digital economy and AI, we can construct appropriate spatial econometric models to explore the spatial interactions between digital economy, AI and sports industry. Secondly, because the various regions of China have not adopted a unified standard for the openness of data related to the sports industry, resulting in the inability to collect data on the sports industry in some provinces, which causes limitations in the coverage of the research sample. In the subsequent study, we will further obtain as much provincial sports industry data as possible through field research, communication with government departments, and other means, to improve the accuracy and universality of the research results. Thirdly, this paper selects data from 15 provinces in mainland China for analysis, but the status quo of digital economy, AI, and sports industry in different provinces may vary, so in the future, specific provinces can be selected for in-depth analysis by combining case studies and empirical analyses. Finally, this paper only investigates the interrelationship between digital economy, artificial intelligence, and sports industry, and more relevant factors can be included in the study by combining theoretical analyses and realities, focusing on the impact of multiple factors on the development of the sports industry, in order to get a more comprehensive conclusion.

Ethical approval and consent to participate

The authors declare that they have no known competing financial interests or personal relationships that seem to affect the work reported in this article. We declare that we have no human participants, human data, or human tissues.

Additional information

No additional information is available for this paper.

Availability of data and materials

The data can be available on request.

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CRediT authorship contribution statement

Laibing Lu: Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Shaoxiong Yang:** Software, Resources, Project administration. **Qiuying Li:** Visualization, Supervision, Software, Resources, Project administration.

Declaration of competing interest

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