

System Dynamics of Quadruple Helix Collaboration for AI-Integrated University Physical Education: Evolution Mechanisms and Optimization Strategies

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Abstract: *Based on the quadruple helix theory, this study employs literature review and logical analysis to construct a collaborative innovation framework for university sports involving government, technology companies, sports colleges, and the public. It systematically analyzes the role positioning and functional coupling relationships of the quadruple helix's stakeholders and explores the dynamic evolution mechanism and optimization path of multiple stakeholders supported by artificial intelligence technology. The study reveals multi-dimensional challenges faced in the quadruple helix collaboration process, including differences in technology access, misaligned educational philosophies, imbalanced talent resources, and hierarchical institutional barriers. Furthermore, it proposes four paths—technology integration, concept integration, talent aggregation, and institutional innovation—to promote intelligent, systematic, diversified, and efficient development, providing theoretical and practical references for AI-enabled collaborative innovation in university sports.*

Keywords: AI, University physical education, Quadruple helix theory, Collaborative innovation.

1. Introduction

Against the backdrop of the digital wave sweeping the globe, artificial intelligence technology is reshaping the ecological landscape of the education sector. Physical education, as an important component of the school education system, is also facing profound changes and innovative opportunities. The "Outline of the Construction Plan for a Strong Educational Nation (2024 - 2035)" proposes to formulate and improve the digital literacy standards for teachers and students, deepen the promotion of teacher team building through artificial intelligence, and create a large model for artificial intelligence education [1]. The development of artificial intelligence has triggered structural changes in the educational environment, resources, and evaluation, refreshing the field of education [2]. The widespread application of artificial intelligence accelerates the innovation of educational technology and shortens the distance between various entities.

The quad-helix innovation theory emphasizes the collaborative construction of an innovation ecosystem by the government, industry, universities, and the public [3], evolving from the basis of triple-helix theory and dual triple-helix theory. The integration of AI technology into university physical education helps form a dynamic, open, and continuously optimized teaching innovation system. However, current academic research on sports teaching scenarios driven by AI mostly focuses on the implementation of smart physical education teaching promoted by artificial intelligence [4], and the evaluation of physical education empowered by artificial intelligence [5], with insufficient in-depth study on the dynamic evolution mechanism of collaborative innovation in physical education.

Based on this, this study takes "AI-driven quad-helix collaborative innovation" as the entry point to deeply explore the dynamic evolution mechanism and path optimization of collaborative innovation in physical education teaching,

providing theoretical support and practical reference for the reform of physical education teaching in the new era, promoting the modernization process of physical education.

2. The Subject Deconstruction of Quad-helix Collaborative Innovation in AI-driven University Physical Education

2.1 Subject Role Positioning

2.1.1 Government Departments

The role of government departments is mainly as policy makers and resource coordinators, providing policy support for physical education in colleges and universities, strengthening special investment in digitalization of physical education teaching, improving the infrastructure construction of colleges and universities, realizing cross-departmental coordination mechanisms, and providing a solid driving force for the development of physical education teaching in colleges and universities. (1) Policy maker. The "Opinions of the Ministry of Education and Other Nine Departments on Accelerating the Promotion of Educational Digitalization" pointed out that we should adhere to reform and innovation, proactively follow the development trend of new technologies such as artificial intelligence, and improve the institutional system adapted to digital development. Adhere to overall planning, pilot first, strengthen departmental collaboration, central-local linkage, regional coordination, and encourage social participation [6]. The proposal of the "Opinion" provides a solid guarantee for accelerating the application of artificial intelligence technology in the field of physical education. (2) Resource coordinator. The government promotes the integrated development of educational technology talents through policy, planning, financial and other resource allocation tools and administrative means. Educational technology talents closely cooperate with

industries, connect and promote the transformation of scientific and technological achievements, promote the connection between education and industry to improve talent supply capacity and level, and cultivate talents according to industrial requirements [7]. The government uses relevant data to optimize educational administrative functions, can also provide quality services for the further development of school education, and promote schools to use data value to enhance their own educational governance capabilities [8]. Reasonable allocation of resources has an important impact on the development of all walks of life.

2.1.2 Sports Colleges

Sports universities assume multi-dimensional roles in collaborative innovation. Universities are the main venues for talent incubation, possess strong scientific research and development capabilities, and act as crucial connection points between the government, enterprises, and the public. The dissemination of university sports culture holds significant importance for the development of societal culture. (1) Talent incubator. University sports education focuses on correctly implementing the "health first" educational philosophy, adhering to the logic and functions of sports and education, fully leveraging the value of nurturing individuals through sports, and cultivating more high-quality, versatile sports talents for our country [9]. (2) Technology breakthrough facilitator. Amidst the deep reform of education and digital transformation era development, AI standardization will reconstruct the school sports ecosystem, promoting intelligent transformation in teaching, training, competition, and other scenarios [10]. (3) Resource connector. Universities play a key role in cross-disciplinary, cross-field knowledge production networks. Through close collaboration with industries, they create industry-academia collaborative innovation platforms, becoming core bases for cultivating technological talents [11]. Universities can effectively leverage their disciplinary and research advantages to attract more high-tech enterprises to participate in collaborations, jointly build complete knowledge structures, production clusters, and technology R&D networks with enterprises, achieving academic implementation and technical execution. (4) Cultural communicator. University sports education can effectively build campus sports culture and promote sports culture; university sports events are crucial for the development of sports culture and significantly contribute to the dissemination of sports culture.

2.1.3 Technology Enterprises

Technology enterprises are developers of technology and iterators of products; they are important drivers for pushing technology implementation and product development. (1) Developers of technology. Technology enterprises are vital sources for achieving technological innovation. The R&D and implementation of artificial intelligence technology require not only talent support from universities but also substantial capital investment and front-end development that necessitate technology enterprises to accurately analyze market demands and integrate innovation into enterprise development, establishing stable R&D, production, and achievement transformation chains [12]. (2) Iterators of products. Technology enterprises establish cooperative models with

universities, closely aligning with the diverse needs of university sports education and continuously iterating intelligent sports teaching products. Technology enterprises can establish product 预留 open interfaces, enabling universities to conduct specialized sports courses, meet students' special needs, and provide personalized customization, thereby driving continuous iteration and updates of intelligent sports teaching products.

2.1.4 Public

The public mainly refers to the user groups, which include roles such as teachers and students in college physical education. The public has transformed from traditional passive recipients to multi-dimensional demand drivers, data contributors, and social supervisors. (1) Active participants. Innovation in college physical education requires the collaborative progress of multiple entities. Students' feedback is an important indicator for measuring teaching quality, and the application of artificial intelligence technology can effectively promote the construction and dissemination of sports culture, create a high-quality sports environment, and stimulate students' enthusiasm for active participation in physical education. (2) Demand drivers. The high-quality development of physical education is an inevitable requirement of the modern sports teaching system. The diversified innovation of current sports teaching processes, models, and scenarios has become a common demand for both teachers and students. (3) Data contributors. Data serves as an effective evaluation basis in teaching. The application of AI technology in daily teaching can effectively generate data from various aspects, thereby assisting teachers in evaluating teaching quality and helping students understand learning outcomes. (4) Social supervisors. As the end-users, the public are deep experiencers of AI technology and intuitive perceivers of physical education, capable of providing the most direct evaluations of both and promptly identifying existing issues. Public concerns and feedback can drive continuous innovation and improvement in college physical education.

2.2 Functional Coupling

In the context of college physical education scenarios under the AI-driven quadruple helix collaborative innovation framework, the functions of the four main entities — government, technology enterprises, colleges, and the public — are closely interconnected. These four entities form an organic whole through "demand transmission—resource flow — value feedback." The government, as the policymaker and resource allocator, plays a key role in guidance and assurance. By implementing industrial policies that include the development of higher education, public venture capital investments, and platform strategies, the government achieves high-level collaborative innovation among the three [13].

The goal of enterprises is to leverage talent and resources from all parties to acquire new technologies, reduce R&D and other costs, and maximize production and economic benefits [14]. Technology companies, as technology developers and product innovators, are a key force in meeting public needs and driving the dynamic evolution of collaborative innovation in physical education. By leveraging technological

advantages to develop intelligent physical education products and widely applying these smart sports products in college teaching while continuously optimizing technology and products based on ongoing public feedback, they promote the development of physical education towards intelligence and personalization.

As the implementers of physical education and important forces for scientific research innovation, universities are the core bridges connecting public demand with technological enterprise conversion, and key points for implementing government educational strategies. Universities and research institutes collaborate with businesses and industry organizations on project research aimed at solving practical industry issues, promoting scientific discoveries and technological inventions [15]. Universities can feedback the actual situation of physical education and public needs to technology companies, introduce new technologies and products from these companies into physical education practice, carry out innovative activities in physical education, and provide practical references for the formulation of new national policies.

As the source of demand and co-creators of value, the public's requirements are the starting point of the entire collaborative innovation. Students, teachers, and parents express personalized, intelligent, and efficient demands for physical education, pushing university physical education towards a direction of multi-party collaborative education, prompting the current centralized school management model and regulatory forms to shift towards decentralized and service-oriented models [16]. Public demand drives collaboration between universities and technology enterprises, while government policy and resource support promote deeper cooperation, achieving value co-creation.

3. Dynamic Evolution Mechanism of Quadruple Helix Collaborative Innovation in AI-driven University Physical Education

The quadruple helix collaborative innovation model focuses on the core entities of "government - technology enterprises - sports universities - public" and promotes the deep integration of AI technology and physical education through multi-dimensional interactions of policy guidance, technology development, teaching practice, and social needs.

3.1 Government: Dynamic Adaptation of Policy Supply and Institutional Efficiency Collaboration

As the top-level designer and resource allocator, the government relies on policies, regulations, financial support, and cross-departmental collaboration to provide multiple guarantees for integrating AI technology into physical education. First, adjust policy directions based on technological iterations and societal needs, introducing relevant policies targeting data privacy risks when AI is applied in university physical education. The "Opinion by the Ministry of Education and Nine Other Departments on Accelerating the Advancement of Educational Digitization" emphasizes strengthening data integration, linking up the whole chain management information systems of schools, students, and teachers, gradually realizing "one number one

source," exploring the rich mine of educational data, and building a new system for big data-enabled educational governance [17]. Second, build collaborative innovation platforms to promote resource exchange among the quadruple helix entities. The government collaborates with universities and enterprises to develop AI motion monitoring systems; for instance, Beijing Sport University and iFlytek have jointly constructed an intelligent exercise evaluation system, promoting smart sports development [18]. Led by the government, this influences the participation depth of other entities and continuously optimizes the innovative development of physical education.

3.2 Technology Enterprises: The Dual-Drive of Technology R&D and Market Transformation

Technology enterprises are the core force in AI technology supply. By identifying market demands, these enterprises invest in technology R&D and rapidly obtain data feedback, achieving continuous product iteration and upgrades. First, enterprises need to develop customized products based on the teaching needs of sports universities. The teaching requirements of sports universities are also part of market demand, and universities connect the market with users. The application of AI technology in universities is crucial for providing feedback on enterprise technology updates and upgrades. Second, public demands for sports safety and enjoyment drive technological upgrades. With the diversification of sports forms and scenarios constantly evolving, user needs are continually changing, and so are the requirements for technology. Through university-enterprise cooperation, the feasibility of technology can be verified, and a social feedback optimization algorithm model can be constructed.

3.3 Sports Universities: The Symbiotic Mechanism of Teaching Innovation and Research Feedback

As a comprehensive social venue linking talent with society, technology with products, and research with industry, universities are the most productive platforms [19]. Universities are both important scenes for technological breakthroughs and gathering places for high-quality researchers, while also undertaking teaching tasks. Technology R&D can be directly applied to teaching verification, overcoming difficulties during the technology application process to form a complete knowledge system. At the research level, interdisciplinary teams at universities use AI technology to solve technical problems, closely integrating their knowledge innovation achievements with practical applications. Universities can leverage big data and artificial intelligence technologies to conduct in-depth research on exercise physiology, sports psychology, and other aspects, enhancing research standards and promoting the transformation of scientific and technological achievements [20]. At the teaching level, AI technology revolutionizes the physical education system in universities. With the function of "knowledge feedback," universities output patented technologies to enterprises while popularizing technical knowledge to the public. Based on technological development and educational needs, universities dynamically adjust their disciplinary structures, cultivate interdisciplinary talents, and promote the synchronous evolution of technology R&D and

education.

3.4 The Public: The Mutual Balance Between Demand Feedback and Ethical Constraints

The most important role characteristic of the public is that, as end-users, they are the source of demand. Public feedback has a crucial impact on technology application, teaching quality, and product iteration, effectively driving continuous optimization and innovation in the educational ecosystem. First, demand drives technological optimization. Public needs and expectations are the fundamental drivers of technological development. Increasing public demands push for technological upgrades. Second, the public, as participating entities, influences the spiral process. Only through public participation in technology application and the teaching process can data be effectively generated. The volume of public data is a precondition for algorithm learning and optimization, which can effectively propel technological innovation to higher levels. Lastly, ethical constraints are a key part reflecting the value of public feedback. As public awareness of data security increases, so does their consciousness about protecting their own data. The public will conduct real-time supervision and feedback on AI technology development and teaching innovation, preventing deviations in AI technology and teaching progress. At the same time, the public's demand orientation significantly affects data ethics, and data ethics also feed back into user needs, creating a balance between the two.

4. Realistic Dilemmas of Quadruple Helix Collaborative Innovation in AI-Driven University Physical Education

4.1 Technological Access Disparities Restrict Collaborative Innovation in University Physical Education

Technological access disparities have become a key bottleneck restricting collaborative innovation in university physical education. From the government level, there is regional inequality in the allocation of educational resources. While artificial intelligence can promote fairness in physical education, the lack of relevant infrastructure exacerbates inequities in physical education, and this outcome will worsen with the iteration of artificial intelligence, forming a "Matthew Effect" [21]. During the process of technology research and promotion, tech companies often prefer to collaborate with universities that have substantial funding and solid research foundations, further widening the technological access gap between universities. Universities specializing in physical education themselves face difficulties such as financial shortages and inadequate support resources when promoting AI infrastructure construction in the field of physical education [22], resulting in uneven capabilities in technology absorption and transformation. At the public level, varying degrees of awareness and acceptance of emerging sports technologies among students and parents from different regions affect the comprehensive promotion and application of technology in physical education.

4.2 Disparities in Educational Philosophy Restrict the Evolution of Innovation in University Physical Education

The traditional training concept of colleges and universities restricts the innovative development of sports teaching. There are significant differences in the positioning of colleges and universities and the development of regional economies. Government policy formulation will have a certain bias, which also leads to relative backwardness in some areas. When technology companies develop sports education-related products, there is a serious market-oriented phenomenon. Due to the different differences existing in colleges and universities, corporate research is not deep enough, and product application efficiency is not high. Inside sports colleges and universities, there is a conflict between traditional and modern training concepts. Faced with the new phenomenon of intelligent sports education, most physical education teachers lack a clear understanding of the basic issues such as the connotation, characteristics, value, role orientation, and implementation methods of intelligent education, and thus cannot form a correct concept of intelligent education [23]. The public's expectations for college sports teaching and the existing training concepts of colleges also have gaps. The focus of students and parents changes with the development of the times. Some colleges cannot keep up with the pace of the times, and the quality of training cannot meet public needs.

4.3 The Imbalance of Talent Resources Hinders the Sustainable Development of College Physical Education

The imbalance of talent resources has become a serious obstacle to the sustainable development of college physical education. From the government's perspective, there are defects in sports education talent policies, with outstanding sports talents overly concentrated in developed areas and key universities, leading to a severe talent gap. In terms of technology enterprises, the mechanism for cultivating and delivering versatile talents is not well-established. Universities face numerous institutional barriers when bringing in corporate technical personnel to teach part-time, making it difficult to integrate cutting-edge technologies into physical education promptly, thus causing a disconnect between college physical education and technological advancements. The training model for physical education majors lags behind, with the curriculum failing to keep up with the demands of the AI era, resulting in graduates struggling to meet the practical needs of AI technology application in college physical education. At the public level, although there is an abundance of social sports talent, the channels for communication between universities and social sports talents are not smooth, preventing the effective integration of talent resources for use in college physical education.

4.4 The Limitations of Hierarchical Systems Impact the Collaborative Promotion of College Physical Education

The limitations of hierarchical systems have become apparent in the quadruple helix collaborative innovation of college physical education, adversely affecting its collaborative promotion. In the relationship between the government and universities, the autonomy of college physical education is restricted, with local governments using overly simplistic assessment indicators that overlook the long-term and

complex nature of innovation in physical education. Cooperation between technology enterprises and universities is constrained, making it difficult for advanced corporate technologies to quickly enter college physical education scenarios. Differences in intellectual property rights and profit distribution often lead to disagreements, affecting the stability and sustainability of cooperation. Internally, the complex hierarchy within sports universities results in teaching innovations that easily deviate from actual needs, with inefficient resource integration and coordination. Public participation in the collaborative innovation of college physical education is also limited, with inadequate upward feedback channels for students and parents' opinions on physical education, restricting the depth and breadth of their involvement in college physical education.

5. Optimization Pathways for Quadruple Helix Collaborative Innovation in College Physical Education Driven by AI

5.1 Technology Integration Promotes Collaboration in College Physical Education

First, the government actively promotes cooperation and exchange among universities, facilitates in-depth interdisciplinary integration, jointly implements interdisciplinary learning and research programs, realizes resource sharing of teachers, equipment, and research funds among different universities through regional resource optimization, fully utilizes the educational advantages within the region, and enhances the depth and breadth of interdisciplinary talent cultivation [24]. Secondly, technology companies should conduct in-depth research to understand the physical education needs and actual situations of different universities, provide customized technical applications and solutions for universities, continuously improve products and technical services based on teaching feedback from universities, offer comprehensive technical training for physical education teachers in universities, and enhance teachers' ability to use technology. Thirdly, sports universities should increase investment in technology access, build a complete AI technology governance system for sports teaching, improve the efficiency of AI technology equipment usage while simultaneously enhancing AI management levels, and comprehensively promote the implementation of public awareness campaigns. Finally, invite public participation to provide reference plans for the improvement of sports teaching technology in universities.

5.2 Conceptual Integration Promotes Systematization of University Physical Education

First, the government should strengthen macro-control over university physical education, issue relevant policies and regulations, guide universities to establish appropriate values for physical education, and at the same time establish a complete evaluation system for university physical education to ensure that the use of AI technology in university physical education complies with regulations. Secondly, when technology companies develop physical education products, they need to understand the teaching philosophy of universities and the needs of students. Establish university-enterprise alliances to jointly conduct market

research and demand analysis, address the actual needs and pain points in physical education, and continuously drive product upgrades. Thirdly, universities should adjust the evaluation model of physical education, formulate a diversified evaluation system, incorporate the effectiveness of learning evaluations after AI integration, pay attention to the actual communication between students and teachers, and prevent teaching from losing its naturalness. Finally, establish public feedback channels, use data analysis to evaluate different feedbacks, accurately distribute them to the government, enterprises, and universities, thus achieving top-down adjustments and ensuring that university physical education meets public requirements.

5.3 Talent Aggregation Ensures Diversification of University Physical Education

First, the government can build diverse communication platforms to promote the reasonable flow of talent between universities and enterprises, drive resource sharing, and introduce high-quality talent-related policies to assist enterprises and universities in recruiting talent. Technology companies should actively engage in interactive cooperation with universities, improve the talent delivery mechanism, form stable cooperative pathways with universities, and boost the advancement of cutting-edge technology research and development. Again, sports universities should proactively adjust their talent cultivation plans according to social needs and market development conditions. At the same time, they should enhance operational training for physical education teachers in artificial intelligence applications, encourage teachers to participate in various AI-related educational and popular science activities, and strengthen the awareness and skills of in-service physical education teachers in AI applications [25]. Finally, encourage public participation in technology research and experimentation, establishing product-service-oriented R&D guidance.

5.4 Institutional Innovation Boosts Efficiency in University Physical Education

First, the government should streamline administration and delegate power, offering preferential policies to enterprises and universities, providing the public with more feedback channels, and ensuring the practical application value of education is effectively implemented. Second, technology enterprises need to establish reasonable profit distribution mechanisms and rights protection mechanisms. Again, sports universities should optimize management systems, enhance decision-making efficiency and execution speed, improve their adaptability and adjustment capabilities, and make administrative system operation procedures transparent. Finally, guide the public to supervise improper behaviors of the government, enterprises, and universities, promoting transparency at all levels of operation.

6. Conclusion

AI-driven collaborative innovation in university physical education is an educational innovation with characteristics of a new era. It is an important driving force for building China's modern education system and promoting high-quality development of China's sports industry. Collaborative

innovation in university physical education is an essential path to constructing an educational innovation ecosystem and building an education powerhouse, having a crucial impact on the development of Chinese sports.

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