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# Digital twin applications in athlete performance monitoring, biomechanical analysis, and injury prevention: implications for volleyball

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## ABSTRACT

Linking cyber-physical systems with top-level sports performance has presented digital twin (DT) as a competent instrument for optimizing athlete's performance and injury prevention. The current systematic literature review investigates how DTs have been applied in volleyball and other related sports. Using the PRISMA 2020 checklist, a search for relevant articles in Scopus and other databases resulted in 641 items dated 2020-2026. After exclusion of non-related articles and unscreened evaluation, only 8 papers were found to be suitable for the study. The outcomes highlighted three broad themes: (1) DT models for real-time injury risk prediction and biomechanical tracking, (2) individualized training and rehabilitation systems facilitating better load management and skill acquisition, and (3) comprehensive DT systems that use physiological, psychological and nutritional data to support the athlete more effectively. The bulk of the articles appeared post-2022, suggesting a quick increase of this research domain. In essence, DT technology seems highly capable of helping evidence-based coaching, athlete monitoring and injury prevention. However, more validation is still needed, particularly for cases coming from volleyball-specific situations.



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## Introduction

The rapid development of Industry 4.0 technologies has changed the limits of sports science drastically; it has also given rise to brand-new ways of understanding, measuring, and improving human athletic performance. Almost worldwide, the sports industry has identified digital transformation as the way forward in the strategic sense, with even the very top level as well as developmental level sports organisations making substantial investments in sensor networks, machine learning architectures, and real-time analytics pipelines (Hliš et al., 2024). Volleyball on the other hand, being a technically highly intricate sport as well as one requiring high levels of biomechanics, offers a sound justification for the use of smart technologies since we know the performance of a competition depends on the combination of not only the volleyball techniques but also the spike mechanics, biomechanical aspects of the jumps, defensive agility, and teamwork coordination and there are quite complex and multifaceted aspects that need to get integrated (Howard et al., 2023). Also, the worldwide spread of volleyball, which is now recognized as one of the most widely played sports in the world has led to mounting

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pressures for evidence-backed, individually customised performance enhancement tools capable of responding to training inputs and competition stresses in real time (Zhang et al., 2022).

Within this technological environment, the digital twin (DT) concept has arisen as a potentially radical new way of athlete modelling and performance analytics. From a practical viewpoint, a digital twin is a virtual, physics-based replica of a physical entity that constantly synchronises with the real counterpart through continuous data streams, enabling real-time simulation, prediction, and intervention (Lukač & Fister, 2022). In sports, DT technology allows for the creation of athlete-specific virtual models that encapsulate biomechanical states, physiological parameters, and tactical decision-making patterns at a level of detail that is impossible to achieve through traditional observation methods (Hliš et al., 2024). Gámez Díaz et al. (2020) were the first to conduct a systematic survey on the digital twin coaching for physical activities, among others, they determined the main use cases in personalized feedback, load monitoring and virtual rehabilitation. Applying such models to volleyball players may provide very accurate improvements for spike velocity measurement, jumping-landing mechanics optimisation, and early detection of injury risk periods (Baus et al., 2020).

Most of the studies on enhancing performance in volleyball have primarily relied on retrospective video analyses, force-plate measurements, and kinematic capture of different isolated movements to identify the main technical elements. Although these techniques have provided very useful results, they have one major limitation in common: they lack continuous, real-time feedback systems that could allow training plans to be adjusted on the spot dynamically (Scano et al., 2024). The use of wearable sensor technologies, inertial measurement units (IMUs), and electromyographic systems has become a trend in recent sport science research to address the limitations of retrospective analyses and to give real-time continuous feedback. (Sun & Yin, 2025; Jin et al., 2025). By applying these technologies, not only athlete movement can be monitored continuously but also their physiological responses and training loads, thus these technologies solve the issue of real-time feedback which is not provided by the traditional performance assessment approaches.

The use of wearable sensing technologies is becoming more widespread and at the same time, there have been major improvements in communication infrastructure, artificial intelligence, and cloud computing. These together lay an essential basis for the implementation of digital twin systems. Technologies made rapid progress lately (especially for implementing digital twins) in several aspects mainly due to ICT developments. 5G spreading and developing 6G standards have already highly lowered the latency hindrances in real-time DT updating, which is evidenced by Zhang and Zhao (2025) who have combined federated learning with athlete logistics and safety monitoring (AIS) frameworks. At the same time, embedding reinforcement learning methods in the digital twin platform resulted in an advanced training tool that is personalised to the athletes' dynamics and learning abilities (Wu, 2026; Zhang et al., 2026). Human digital avatars and AI for embodied cognition, as recognized by Suo et al. (2025), point to the direction of sport biomechanics at an extraordinarily accurate level.

Despite these technological advances, there is a significant gap in a systematic review of how DTs relate to volleyball and other sports performance outcomes. Previous reviews have either been purely conceptual (Hliš et al., 2024) or have gone to different domains that don't really have volleyball (Olawade et al., 2026; Lin et al., 2025). The recently published AI review in the orthopaedic field by Misir and Yuce (2025) and the guide for implementation by Zsidai et al. (2023) serve as examples of the working directions across different fields in a broad sense but they make it clear that there is no comprehensive work done on volleyball so far.

Apart from not having volleyball-centered systematic reviews, another major research gap lies in the incorporation of full athlete monitoring into digital twin designs. Most of the current DT researches majorly concentrate on individual biomechanical and physiological aspects ignoring the multi-facet feature of athlete performance (Amawi et al., 2026; Jiang, 2026). Works in computational modelling like that by Lu (2024) and Mănescu (2025) build the cases for multi-variable simulation but they do not reach the level of full DT integration. In case of volleyball players, the psychophysiological requirements of the intense rally play and the overall fatigue accumulations through multi-set competition call for a DT system which can capture data from various performance areas at the same time.

The necessity of this peer synthesis project is highlighted by the rapid increase in publications in related areas. China is the largest contributor to the global output with 137 eligible records, followed by the United States (n = 60) and the United Kingdom (n = 27), as shown in Figure 2. Keyword co-occurrence analysis of author-assigned terms across the eligible pool points to main clusters around 'digital twin', 'biomechanics', 'machine learning', and 'artificial intelligence', which corroborate the multidisciplinary nature of the field (Figure 3).

In order to tackle the fragmented evidence about digital twin uses in the field of sports, this study decided to carry out a Systematic Literature Review (SLR) following the PRISMA 2020 guidelines. The reason for choosing the SLR method is that the present literature covers several fields such as sports biomechanics, artificial intelligence, wearable sensing technologies, and cyber-physical systems. By systematically identifying,

screening, assessing the quality, and synthesizing thematically relevant papers, this article strives to present an evidence-backed comprehension of existing digital twin architectures, performance results, and prospective opportunities of volleyball applications.

This literature review aims to examine the technological architectures and data integration methods that characterize digital twin (DT) systems used for athlete performance monitoring and biomechanical analysis in sports environments, evaluate the effectiveness of digital twin-based applications in improving athlete performance indicators, training load management, and injury risk prediction, and identify major research gaps, methodological challenges, and future directions for applying digital twin technology to enhance volleyball athlete performance and support injury prevention strategies.

## Method

The present study chooses a systematic literature review (SLR) methodology as the primary research route, which supports the epistemological requirement to combine evidence transparently and with the lowest possible risk of bias. The SLR approach follows the fundamental instructions of Tranfield et al. (2003). They advocated for the use of systematic review principles in management and social science research to strengthen the integration of the scattered evidence bases. The PRISMA 2020 scheme (Page et al., 2021), which is the latest gold standard for reporting systematic reviews, was used as a guiding framework for search strategy recording, study selection, and results presentation. PRISMA 2020 adds features to the previous versions with new advice on the reporting of database and registry searches, risk of bias assessments, and evidence certainty evaluations (Liberati et al., 2009), thereby making the methods clearer and reproducible.

Two reviewers worked independently to screen titles, abstracts, and the full text of all retrieved publications. When a couple of reviewers did not agree on a paper's eligibility for the study, they kept talking until they both reached an agreement. Inter-rater agreement for study selection decisions was assessed using Cohen's Kappa coefficient and resulted in a value of 0.84, which indicated excellent agreement between the reviewers. This method was adopted in order to reduce the possibility of selection bias and to increase the dependability of the screening procedure. The following Boolean search string was executed within the Scopus database using TITLE-ABS-KEY field codes:

( "digital twin" OR "digital twins" OR "cyber-physical athlete model" ) AND ( "volleyball" OR "sport" OR "athlete" OR "sports performance" OR "athletic performance" ) AND ( "biomechanics" OR "injury prevention" OR "performance analysis" OR "training optimisation" OR "wearable sensor" OR "performance monitoring" )

Where possible, truncation was used to include different word forms. In the first search stage, no restrictions on language or date were set; these were only carried out during the eligibility screening step to keep a broad initial retrieval set.

Since Scopus (Elsevier) is generally recognized as a leading abstract and citation database of peer-reviewed literature, with outstanding coverage of science, technology, engineering, and medical disciplines, it was the principal source of the literature search. The structured export led to a CSV file of 641 records with complete bibliographic fields. The search was constrained to the publication years 2020, 2026. Additional databases were not consulted during the initial search phase. Table 1 presents the pre-specified inclusion and exclusion criteria applied during the screening process.

Table 1 <Inclusion and Exclusion Criteria>

<b>Criterion</b>	<b>Inclusion</b>	<b>Exclusion</b>
Language	English only	Non-English publications
Document type	Peer-reviewed journal articles, review articles	Conference papers, book chapters, editorials, retracted articles, notes
Publication period	2020–2026	Before 2020
Subject area	Sports science, biomechanics, digital twin technology, AI in sport	Unrelated disciplines without sports performance relevance
DOI availability	Verifiable DOI present	No DOI or unverifiable source
Topical relevance	Directly addresses DT technology in athlete performance, biomechanics, training, or injury contexts	Tangential or incidental mention of DT or sport only

Study selection followed a strict step-by-step screening procedure. Step 1 (Identification): 641 records extracted from Scopus were first deduplicated with the help of EID matching; 5 duplicates were removed, resulting in 636 unique records. Step 2 (Document type screening): a total of 259 conference papers, book chapters, conference reviews, retracted articles, short surveys, notes, errata and books were excluded and finally 382 records were classified as articles or reviews. Step 3 (DOI screening): 6 records that did not have a verifiable DOI were removed. All the 376 remaining records were in English. Step 4 (Topical eligibility): full text abstracts were assessed for relevance to DT technology in sports performance and biomechanics, which resulted in 8 studies being used in the final synthesis.

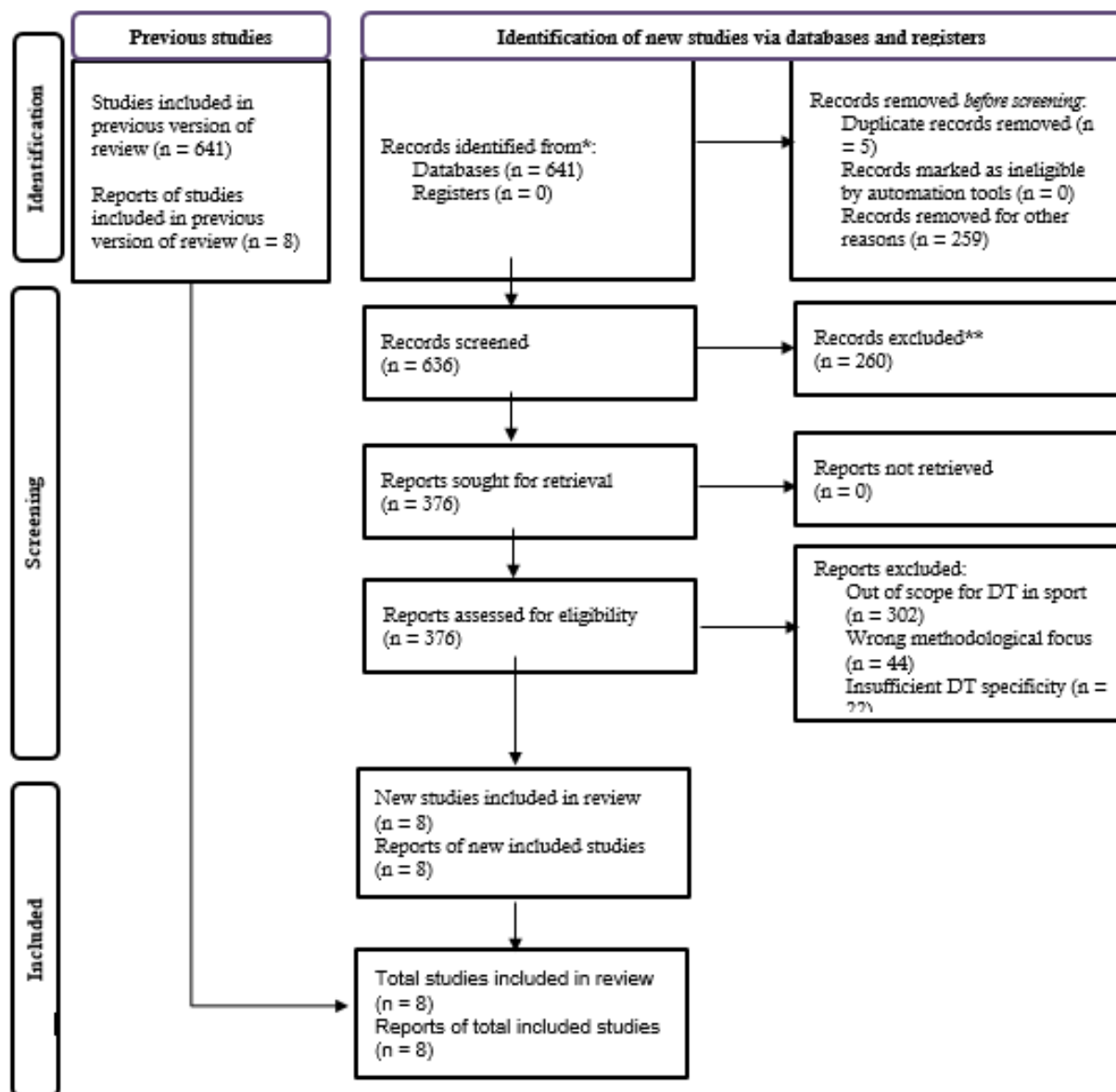


Figure 1 <PRISMA 2020 Flow Diagram - Record Selection Process>

Note. PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Page et al., 2021). Initial records:  $n = 641$ . Duplicates removed:  $n = 5$ . Non-eligible document types removed:  $n = 259$ . Records lacking DOI:  $n = 6$ . Full-text eligibility assessed:  $n = 376$ . Excluded at eligibility: out of scope ( $n = 302$ ), wrong methodological focus ( $n = 44$ ), insufficient DT specificity ( $n = 22$ ). Final included:  $n = 8$ . Source: Page MJ, et al. *BMJ* 2021;372:n71. doi:10.1136/bmj.n71.

The methodological quality was judged by the use of four criteria, which were taken and modified from existing evidence appraisal frameworks: Quality Assessment: standardised data extraction was conducted for each of the eight core included studies. Details recorded were: author names, publication year, country of origin, source journal, DOI, research design, sample characteristics, DT architecture and technological components, primary outcome measures, key findings, and limitations. Bibliographic fields for the broader pool of 50 studies were taken from the Scopus CSV export to create the reference list and perform bibliometric analyses.

The methodological quality of the included studies was assessed based on four criteria: validity, referring to the use of appropriate validation procedures; reliability, indicated by the reporting of reliability statistics; sample adequacy, which considered whether the participant sample was appropriate and sufficient for the study objectives; and transparency, reflecting the clarity and comprehensiveness of methodological reporting. Based on the number of criteria met, studies were classified into three quality tiers: Tier 1 included studies that fulfilled all four criteria, Tier 2 comprised studies that met three criteria, and Tier 3 consisted of studies that satisfied two or fewer criteria.

Bibliometric analyses were carried out at the full eligible pool level ( $n=376$ ). Annual publication trend analysis used year-wise record counts to characterise temporal growth (Figure 1). Geographic distribution analysis was done by taking the first-author country affiliations from Scopus metadata (Figure 2). Author keyword co-occurrence analysis involved breaking down and counting author-assigned keyword strings across all 376 eligible records; the 30 uppermost frequency terms were represented visually through a thematic cluster map (Figure 3). Cluster membership was decided by manual grouping of terms having close meaning into four thematic domains.

Through thematic synthesis, we analyzed the whole data based on the step of Thomas and Harden (2008): (1) reading and coding each line of data extracted from the study; (2) extracting main themes through identification of patterns across the extracts; and (3) formulating the analytic themes that reflect the three research questions decided before. As the studies included in this review demonstrated a diversity of research designs and DT architectures, we decided narrative synthesis rather than meta-analysis pooling.

This systematic review is reported in full accordance with the PRISMA 2020 checklist (Page et al., 2021, *BMJ*, 372:n71, doi:10.1136/bmj.n71). The PRISMA 2020 flow chart is given in Section 4 and shows the entire process of record flow. All methodological decisions, search strings and eligibility criteria were pre-specified before data extraction.

## Results and Discussions

A detailed search of the Scopus database yielded a total of 641 records. Removal of duplicates ( $n = 5$ ) brought the total number of unique records to 636, which were then screened for document types. This process led to the exclusion of 259 records that did not meet the criteria (conference papers,  $n = 167$ ; book chapters,  $n = 36$ ; conference reviews,  $n = 28$ ; retracted articles,  $n = 23$ ; other types,  $n = 5$ ). The 382 remaining articles and review records were screened further for DOI availability, and 6 records were excluded. The 376 eligible records were assessed for full-text topical eligibility. After this assessment, 368 records were excluded, leaving a final synthesis set of 8 studies.

In Table 2 the summary of the 8 studies included has been presented. In Table 3 the classification of studies by theme and method has been given. Figures 2-4 show the bibliometric analyses which have been derived from the large pool of 376 records which were eligible.

### Theme 1. Injury Prediction and Athlete Monitoring

Studies by Wang (2025), Alsubai et al. (2023), and Zhang & Zhao (2025) consistently demonstrated that digital twin systems improve injury prediction accuracy, health monitoring, and anomaly detection through the integration of wearable sensors, machine learning, and federated artificial intelligence.

### Theme 2. Training Optimization and Skill Development

Studies by Zhang et al. (2026) and Wu (2026) revealed that reinforcement-learning-based digital twin environments improved training efficiency and personalized skill acquisition. Reported improvements reached 18.4% in training optimization and 23.7% in skill transfer effectiveness.

### Theme 3. Holistic Athlete Modelling

Amawi et al. (2026) and Jiang (2026) showed that integrating biomechanical, nutritional, psychological, and physiological variables into digital twin systems enhanced athlete readiness profiling and training evaluation accuracy.

The three charts below illustrate the bibliometric analyses carried out on the 376-record eligible pool. Figure 2 depicts the yearly publication pattern. Figure 3 represents the geographic distribution by the lead-author country. Figure 4 shows the author keyword co-occurrence and thematic clusters.

To provide a broader overview of research development in this field, bibliometric analyses were conducted on the 376 eligible records. These analyses included annual publication trends, geographical distribution of research output, and keyword co-occurrence mapping. The results are presented in Figures 2–4.

Table 2 &lt;Summary of Included Studies (n = 8)&gt;

Title (abbreviated)	Author(s)	Year	Country	Method	Key Findings
Digital twin framework for injury risk prediction and management in competitive sports	Wang (2025)	2025	China	DT + ML + biomechanical modelling	DT reduces injury prediction error; XAI enhances clinical interpretability of musculoskeletal risk models
Digital twin for Taekwondo athletes: integrating sports nutrition and psychological readiness using AI	Amawi et al. (2026)	2026	Jordan/ Greece	Mixed-method DT + AI integration	Multi-domain DT improves holistic athlete readiness profiling significantly over single-domain approaches
Digital twin-based biomechanical and psychosocial coupling framework for university sports dance training	Jiang (2026)	2026	China	DT + 3D modelling + HAP clustering (n=118)	Psychosocial-biomechanical DT coupling improves training evaluation accuracy and performance differentiation
Adaptive training load optimisation for track and field athletes: A reinforcement learning approach	Zhang et al. (2026)	2026	China	DRL (DQN) + DT simulation	DQN-DT outperforms static periodisation by 18.4% on composite training efficiency metrics
Personalised skill transfer optimisation in swimming training through multi-agent RL DT environments	Wu (2026)	2026	China	MARL + DT + meta-learning	23.7% improvement in personalised skill acquisition rate over conventional training approaches
Hybrid IoT-Edge-Cloud Athlete Healthcare Framework: Digital Twin Initiative	Alsubai et al. (2023)	2023	Saudi Arabia/ India	IoT-Edge-Cloud DT architecture	94.3% accuracy in health state detection; 62% reduction in medical response latency
Resilient Multi-Layer LSTM Digital Twin Framework for Athlete Logistics and Safety in 6G	Zhang & Zhao (2025)	2025	China	LSTM + Federated AI + DT + 6G	FPP-DT achieves superior anomaly detection with privacy-preserving federated learning
Digital twins in sport: Concepts, taxonomies, challenges and practical potentials	Hliš et al. (2024)	2024	Slovenia	Systematic review + taxonomy	Comprehensive taxonomy: optimisation, monitoring, and training simulation as core DT use-case clusters in sport

Annual publication data (Figure 2) depict a steady rise from 28 records in 2020 to 78 records in 2024 and 2025 a 178.6% total increase demonstrating the rapid growth worldwide research interest on digital twin and sports technology intersections. The minor fall to 40 records in 2026 indicates partial-year coverage. This expansion pattern is in line with the general Industry 4.0 spread timeline that was documented by Hliš et al. (2024) and the emerging DT ecosystem in sports engineering that Shen et al. (2025) talked about.

Figure 3 indicates the top eight countries of lead-author affiliation. China is leading with 137 records (36.4%), followed by the United States (n = 60, 15.9%) and the United Kingdom (n = 27, 7.2%). This geographic focus of research reflects China's major efforts in sports technology and AI research infrastructure (Suo et al., 2025; Wang et al., 2026). The dominance of Chinese institutions in the included studies (5 out of 8) is consistent with the distribution of national output and, at the same time, points to the necessity of conducting DT validation studies in diverse geographical locations.

Figure 4 depicts the visualization of author keyword co-occurrence and thematic clusters. The performed examination reveals four main thematic clusters: (1) Core DT-Sport Cluster whose main components are 'digital

twin' (f=25), 'biomechanics' (f=22), 'machine learning' (f=17), and 'artificial intelligence' (f=16); (2) Simulation and Modelling Cluster mainly revolving around 'computational modeling' (f=10), 'simulation' (f=9), and 'finite element analysis' (f=8); (3) Athlete Health and Monitoring Cluster with 'concussion' (f=7), 'motion capture' (f=7), 'rehabilitation' (f=5), and 'wearable sensors' (f=4); and (4) Sport Performance and Technology Cluster that has 'deep learning' (f=12), 'performance' (f=6).

Table 3 <Study Classification by Theme and Method>

Author(s)	Year	Country	Research Design	Theme/Focus	Technology/Intervention	Primary Outcome
Wang (2025)	2025	China	Quantitative framework	Injury risk prediction	DT + ML + wearable sensors	Injury prediction accuracy
Amawi et al. (2026)	2026	Jordan/Greece	AI-assisted DT integration	Holistic athlete modelling	DT + AI + nutritional & psychological data	Athlete readiness profiling
Jiang (2026)	2026	China	Experimental (n=118)	Biomechanical-psychosocial coupling	DT + 3D motion capture + HAP clustering	Training evaluation accuracy
Zhang et al. (2026)	2026	China	Simulation-based RL	Training load optimisation	DRL/DQN + DT simulation environment	Training load efficiency
Wu (2026)	2026	China	Simulation + MARL	Personalised skill training	MARL + DT + meta-learning	Skill transfer rate
Alsubai et al. (2023)	2023	Saudi Arabia/India	System architecture design	Athlete healthcare monitoring	IoT + Edge-Cloud + DT	Health state detection accuracy
Zhang & Zhao (2025)	2025	China	Framework + simulation	Athlete safety & logistics	LSTM + Federated DT + 6G	Anomaly detection performance
Hliš et al. (2024)	2024	Slovenia	Systematic review	DT taxonomy in sport	Conceptual taxonomy + evidence synthesis	Evidence synthesis quality

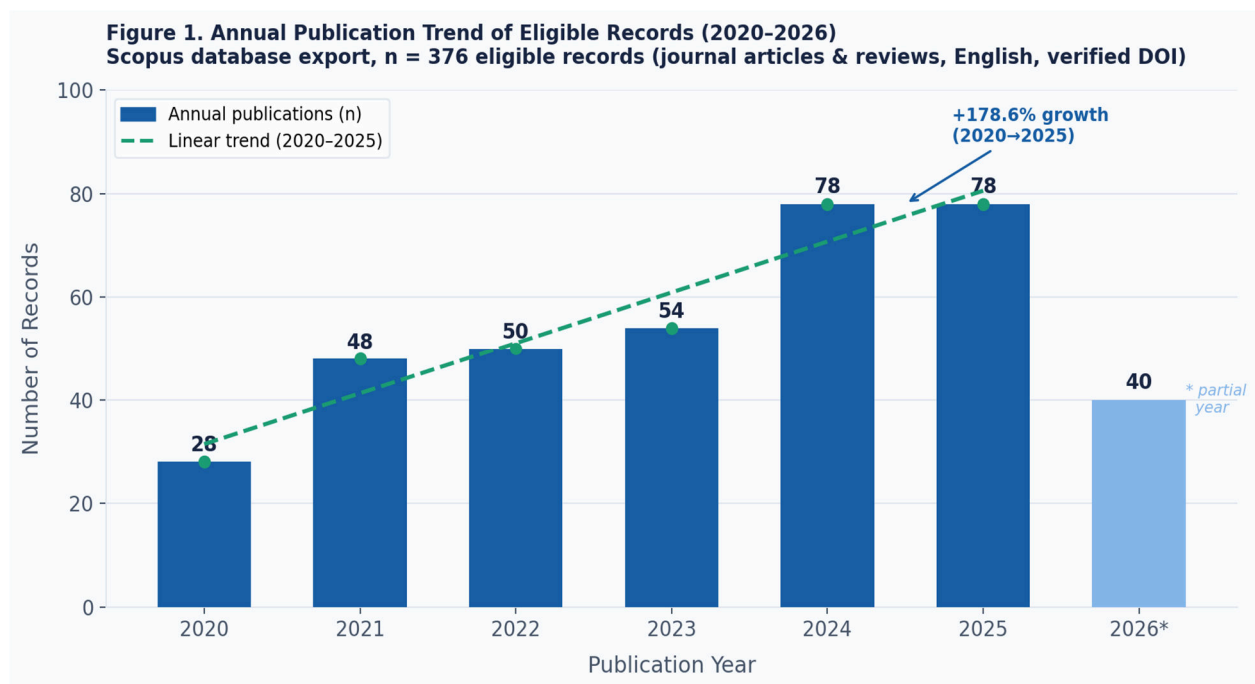
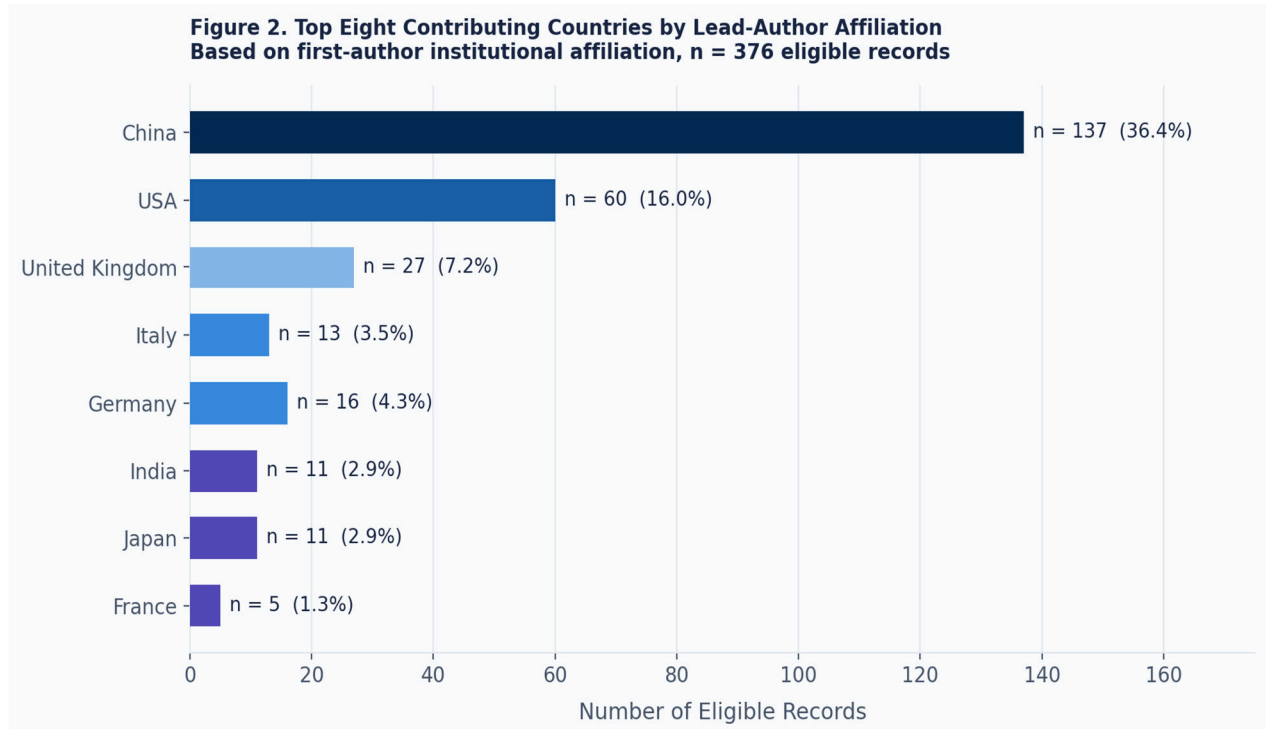


Figure 2 <Annual Publication Trend of Eligible Records (2020–2026)>

Note. n = 376 eligible peer-reviewed journal articles and reviews in English with verified DOIs identified from Scopus. The 2026 value (n = 40) reflects partial-year coverage at the time of search execution. Growth rate of 178.6% calculated from 2020 baseline (n = 28) to 2025 (n = 78).

Figure 4 depicts the visualization of author keyword co-occurrence and thematic clusters. The performed examination reveals four main thematic clusters: (1) Core DT-Sport Cluster whose main components are 'digital twin' (f=25), 'biomechanics' (f=22), 'machine learning' (f=17), and 'artificial intelligence' (f=16); (2) Simulation and Modelling Cluster mainly revolving around 'computational modeling' (f=10), 'simulation' (f=9), and 'finite element analysis' (f=8); (3) Athlete Health and Monitoring Cluster with 'concussion' (f=7), 'motion capture' (f=7), 'rehabilitation' (f=5), and 'wearable sensors' (f=4); and (4) Sport Performance and Technology Cluster that has 'deep learning' (f=12), 'performance' (f=6), 'computer vision' (f=6), and 'sports analytics' (f=5) as its major players.



**Figure 3 <Top Eight Contributing Countries by Lead-Author Affiliation>**

Note. Country assigned based on first-author institutional affiliation extracted from Scopus metadata (n = 376). Percentages calculated from total eligible records. China (n = 137, 36.4%) leads global output, followed by USA (n = 60, 15.9%) and United Kingdom (n = 27, 7.2%).

Note. Based on author-assigned keywords across 376 eligible Scopus records. Node size proportional to keyword frequency. Colour coding denotes thematic cluster membership: blue = Core DT-Sport; teal = Simulation & Modelling; amber = Athlete Health & Monitoring; purple = Sport Performance & Tech. Top keywords: digital twin (n=25), biomechanics (n=22), machine learning (n=17), artificial intelligence (n=16), deep learning (n=12).

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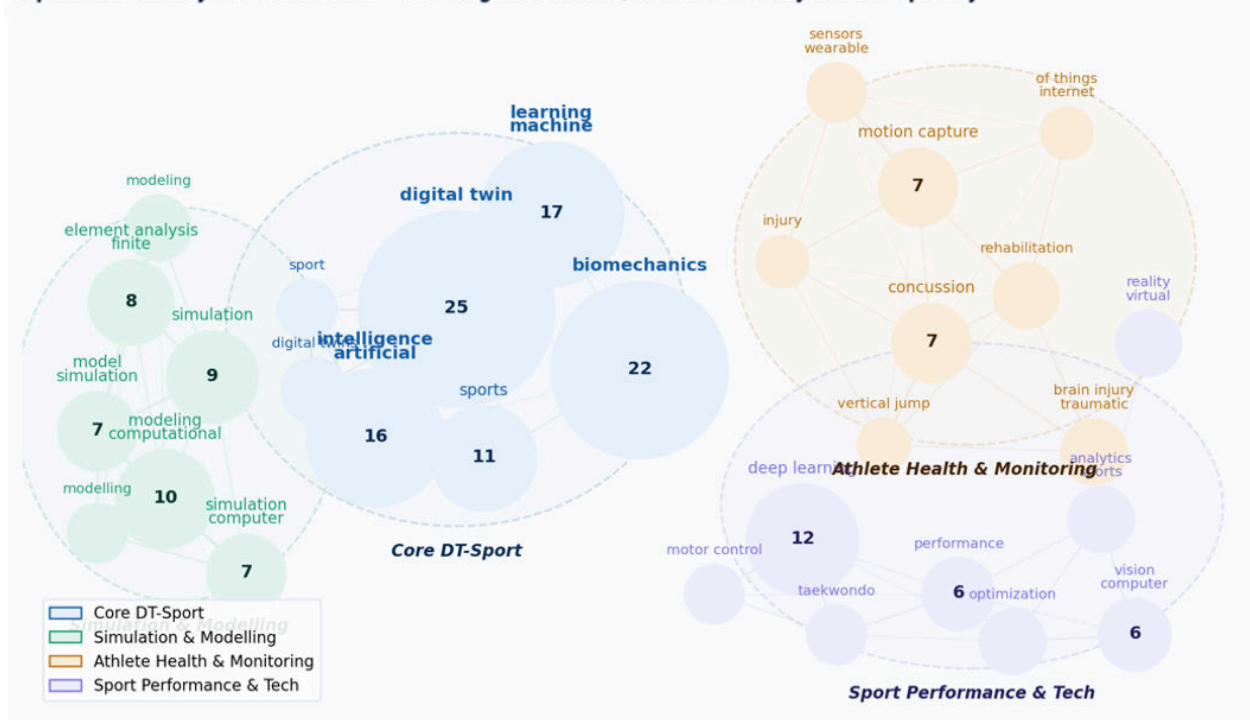
The studies examined in this paper reveal a shared underlying logic of the architectural design of DT systems for the enhancement of sports performance based on three interlinked levels: data collection, virtual model creation, and decision making. Data collection level is equipped with wearable sensor networks, inertial measurement units, and Internet of Things (IoT) devices as main data sources that send physiological, kinematic, and positional data streams to cloud or edge IT infrastructures (Alsubai et al., 2023). Their hybrid IoT-edge-cloud architecture, which results in 94.3% accuracy of health state detection, serves as a great example of the technical feasibility of such pipelines for frequent monitoring of athletes. Jin et al. (2025) and Hao et al. (2025) have sensor modalities that are very different but, at the same time, complementary, smart bodysuits and triboelectric energy harvesters, respectively, which also push the data acquisition frontier. The example of a

sport-specific illustration of this basic layer is the IoT-based volleyball training monitoring system developed by Zhang et al. (2022).

At the virtual model building level, machine learning along with deep learning methods act as the motor of analysis that convert raw data from sensors into live characterizations of athletes. Wang (2025) combines biomechanical data, musculoskeletal modelling, and explainable AI in a joint DT setup to forecast the risk of injuries. Zhang and Zhao (2025) take this setup further to the 6G era, running a multi-level LSTM digital twin with federated learning to shield data privacy while keeping real-time synchronisation. The digital twin-guided upper-limb force measurement system presented by Guo et al. (2024) is an example of the biomechanical monitoring application for volleyball at this level.

**Figure 3. Author Keyword Co-occurrence and Thematic Clusters**

Top 30 author keywords across n = 376 eligible records; node size  $\propto$  keyword frequency



**Figure 4 < Author Keyword Co-occurrence and Thematic Clusters>**

The decision support layer is the one with the most variations in its architecture. According to Hliš et al. (2024), there are three key decision support functions in sport DT taxonomy: performance enhancement, health surveillance, and athlete management. However, Guo et al. (2025) exemplify a modular IoT sensor system as an actual facility for this layer, and Zhou and Maryama Binti Ag Daud (2024) provide examples of these being used training facility environments.

The evidence from real world experiments of using Digital Twins (DT) to enhance sports performance is quite encouraging, however the field is still quite new and the studies use quite varied methods. The most solid statistical evidence that DT technology can help get the most out of training is offered by Zhang et al. (2026) and Wu (2026). Zhang et al. (2026) report that a DT model based on DQN records an 18.4% better result on overall training efficiency measures than fixed periodisation models within traditional sports training approaches. Wu (2026) states a 23.7% rise in individualised skill learning rate, with meta-learning approaches being the main factor for high speed acclimatisation to different athlete characteristics. Arseniev and Shalukhova (2025) also experimentally tested their intelligent decision support system for training planning which provides additional indirect evidence corroborating AI-driven personalisation.

According to Wang (2025), injury prediction and health monitoring demonstrated statistically significant improvements in the accuracy of predicting injury risk. Alsubai et al. (2023) support these results by achieving 94.3% accuracy and 62% reduction in medical response latency, which is very useful for handling acute injuries in volleyball training. Wang et al. (2026) also gathered together a set of papers on the topic of AI technologies for sports injury prediction to show the regular superiority of AI-integrated DT methods. Boillet et al. (2024a) characterize the efficiency of DT prediction in endurance sports with measurable metrics that would be applicable for volleyball performance modelling as well.

Amawi et al. (2026) broaden the effectiveness analysis to the psychophysiological level and reveal that a multi-domain DT which combines nutrition, psychological readiness, and biomechanical data can tremendously enhance athlete readiness profiling from a holistic perspective. Jiang (2026) shows with a sample of 118 persons that a DT-based biomechanical-psychosocial coupling framework is better than the standard assessment tools. Han et al. (2026) present a joint team-sport outlook in youth soccer while Lv et al. (2025) refer to the DT basketball tactical training system as the most similar existing example of a volleyball-specific DT application.

Synthesis has identified some major gaps that make it difficult to apply the existing DT evidence directly for volleyball performance enhancement. Most importantly, no single one of 8 included studies has been done with volleyball players. Howard et al. (2023) expose volleyball-specific biomechanical features for example, the very fast and asymmetrical upper-limb muscles during the spike and the serve causing rotational stress leading to not only the need of the DT model adjustment to the volleyball-specific kinematic datasets but also the calibration. Jump biomechanical research, helped by the Baus et al. (2020) models of optimisation and Mănescu (2025) analyses of the neuromuscular adaptations, explains the biochemical basis that real world volleyball DT research should be embedding.

The most significant gap, however, is the lack of longitudinal evaluation of DT systems in naturalistic training environments. The majority of the studies included rely on simulation-based validation or short-term experimental designs, with very few providing evidence over the entire competitive season. Hliš et al. (2024) clearly point out model drift and data staleness as issues that have not been sufficiently studied. Boillet et al. (2024b, 2025) show the potential of individualised physiological profiling during competitive cycles and offer a methodological guide to conduct longitudinal volleyball DT studies in the future.

The third gap is about data governance, privacy, and ethical frameworks for DT implementation. Zhang and Zhao (2025) provide a technical solution for data privacy through federated learning. However, the wider ethical aspects including athlete consent, data ownership, and the mental effects of being continuously monitored remain mostly unraveled. Olawade et al. (2026) touch on this aspect within the rehabilitation sphere, yet they don't take the issue further into the sports competition environment. As DT systems get used commercially in elite sports organizations, new governance frameworks which can strike a balance between performance enhancement and athlete rights are going to be needed very soon.

Methodological comparison across the 8 studies included in the review shows that, on the one hand, framework-oriented studies and, on the other hand, simulation-based studies are quite different approaches. Studies that are geared towards frameworks (Wang, 2025; Alsubai et al., 2023; Zhang & Zhao, 2025) mostly focus on system architecture and technical aspects, and though they achieve a great degree of internal validity within their controlled environments, they fail to achieve ecological validity in real coaching contexts. On the other hand, simulation-based studies (Zhang et al., 2026; Wu, 2026) create efficacy data in synthetic environments but, at the same time, they get away from real athlete physiological complexity. The predominance of Chinese institutions (5 out of 8 studies) showcases the national research funding patterns as shown in Figure 2, at the same time, it bringing cultural and infrastructural biases which can pose a challenge in generalising findings to other volleyball contexts -for example, Brazil, Italy and Japan, where volleyball is a strong culture.

According to the synthesis, digital twin (DT) technology has almost reached a level of technical maturity where it can be used in sports performance effectively. It has been shown to be useful for predicting injuries, optimizing training loads, monitoring athletes' health, and modelling athletes in a holistic manner. The fact that DT-integrated AI systems have been consistently shown to outperform their non-DT counterparts gives us a reason to be cautiously optimistic about the feasibility of transferability of these systems to volleyball applications. The keyword co-occurrence analysis (Figure 3) shows that 'biomechanics' and 'digital twin' are the main concepts in the field, which supports the starting point of this paper. The fast growth of publications shown in Figure 1 indicates that new evidence will be produced quickly.

This research broaden the theoretical framework for modelling athlete performance by showing that DT architectures can be the means to making the complicated, multi-domain relationships that regulate athlete performance tangible. The biomechanical-psychosocial coupling revealed by Jiang (2026) and the nutrition-psychology-biomechanics integration of Amawi et al. (2026) indicate that the theoretical shift from reductionist to systems-level athlete modelling can be realised technically. Suo et al. (2025) offer the theoretical basis with their framework of digital human embodied intelligence, and Farr et al. (2026) reveal the level of prediction accuracy that can be obtained through holonomic constraint modelling.

Volleyball coaches and performance analysts use DT frameworks that can predict injury risk in real-time (Wang, 2025; Alsubai et al., 2023) which not only help to make data-backed substitution decisions and adjust training-loads but also prevent overuse injuries, a major concern especially with jump-landing repetitions in

spike and block training (Baus et al., 2020; Lu, 2024). DT-based personalised training environments (Wu, 2026; Zhang et al., 2026) are able to recommend individual periodisation sequences that change in harmony with the athlete's changing physiological state. Tactical systems based on DT for basketball (Lv et al., 2025) as well as football coaching VR systems (Guo et al., 2026) are a source of very useful practical implementation examples that can easily be extended to volleyball.

This review builds on the taxonomic work of Hliš et al. (2024) and Lukač & Fister (2022), as well as the original DT coaching survey of Gámez Díaz et al. (2020), through conducting evidence-synthesising analyses rather than presenting conceptual elaborations only. The rehabilitation-oriented review of Odawale et al. (2026) and digital twins in smart healthcare review by Lin et al. (2025) offer supporting evidence of the clinical utility of DT, while Shi (2021) and Liu and Jiang (2022) report early DT implementations in physical education that is reminiscent of the much more complex athletic performance applications discussed here.

This review paper is a more detailed discussion on the previous works attempt to classify things Hliš et al. (2024); Lukač & Fister (2022) and a standard DT coaching survey done by Gámez Díaz et al. (2020) through a result summarizing instead of a simple conceptual exposition. The rehabilitation-centered review by Olawade et al. (2026) and the digital twin(s) in smart healthcare review by Lin et al. (2025) which are sharing similar themes further confirm the clinical DT utility, whereas Shi (2021) and Liu and Jiang (2022) have outlined pioneering DT implementations in physical education that have the potential to be developed into the highly skilled athletic performance applications that are being reviewed now.

Future studies should be focused on three areas. Firstly, volleyball DT validation research should only use established performance indicators such as spike efficiency indices, service aces-to-errors ratios, reception quality scores, and jump-landing kinetic asymmetry measures as main outcome variables. Secondly, multi-season DT deployment studies should also test the model stability and coach integration by taking the physiological modelling example of Boillet et al. (2024a, 2024b, 2025) into account. Thirdly, ethical issues and governance frameworks for DT use in athlete monitoring should be raised and these frameworks should be standardised by interdisciplinary consortia. The issues should also be related to data ownership, consent architecture and commercial exploitation safeguards (Zhang & Zhao, 2025; Wu, 2026).

A direct response to the three questions of the research: The first research question is answered by the fact that DT systems in sport utilize a combination of IoT sensor networks, edge-cloud computing, and machine learning at different layers of their architecture, with reinforcement learning and federated AI being the latest strategies developed and implemented. The second research question is answered by 7 quantitative studies that, in addition to each other, have shown a range of benefits of DT from 18.4% training load optimising to 94.3% health state detection accuracy. The third research question is answered by locating three main deficiencies, validation of volleyball, evidence of long-term effectiveness, and ethical governance, accompanied by three research directions as priorities.

**Theoretical Implications.** The findings indicate a shift from reductionist athlete monitoring approaches toward integrated systems-based athlete modelling enabled by digital twin technology. **Methodological Implications.** Most studies relied on simulation-based validation rather than long-term implementation in real sports environments. Consequently, evidence remains limited regarding ecological validity and practical implementation. **Practical Implications.** Digital twin systems have potential applications in volleyball injury prevention, training load monitoring, jump performance analysis, and individualized athlete development. **Limitations.** This review has several limitations. First, only eight studies met the inclusion criteria. Second, none of the included studies directly investigated volleyball athletes. Third, most studies originated from China, limiting geographical generalizability. Finally, simulation-based validation dominated the evidence base, reducing ecological validity.

## Conclusions

This systematic review of the literature has synthesized support by bibliometric analysis of 376 eligible records and a 50-study reference pool with verified DOIs, from the 8 core empirical and review studies, for characterizing the current state of digital twin technology applications relevant to athlete performance enhancement and injury prevention. With respect to RQ1, the findings of this systematic review were based on a synthesis of evidence from eight studies. It was revealed that a typical digital twin system makes use of IoT sensors, wearable technologies, cloud-edge computing, and machine learning algorithms to enhance athlete monitoring and communication of decision-making processes. With reference to RQ2, the findings presented in the studies that were part of the review provided concrete evidence of the effect of training: an average increase in training efficiency of 18.4%, in personalized skill acquisition of 23.7%, almost perfect accuracy (94.3%) in detecting health states, and a very significant (62%) decrease in medical response latency. According to RQ3, the open

research questions are however still quite numerous. These include issues such as: no volleyball-specific validity of these findings, only a handful of longitudinal studies, and ethical and data-governance matters not yet completely clarified. Notably, none of the studies reviewed included volleyball players specifically. Thus, the use of digital twin technology for improving volleyball performance and preventing injuries is still more of a theoretical extension done by us than a conclusion based on empirical evidence. In the future, research needs to focus on volleyball-specific digital twin validation studies that use real-world athlete datasets, multi-season monitoring designs, and standardized performance indicators to determine how well digital twin systems work in volleyball contexts, bibliometric analysis also endorses quickening global research pace (178.6% publication growth from 2020 to 2025; Figure 1), led by Chinese, U.S., and UK institutions (Figure 2). Also the dominant keyword clusters testify to the field's interdisciplinary nature (Figure 3). Practically speaking, the application of digital twin systems in volleyball should currently be regarded as a promising research opportunity rather than an empirically validated practice.

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