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The Application of Digital Sports in Sports Biomechanics

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Abstract: *Digital sports are profoundly reshaping the research paradigms and application paths of sports biomechanics. This article systematically explores how digital technologies such as wearable sensing, motion capture, artificial intelligence and virtual reality can empower sports biomechanics, breaking through the limitations of traditional laboratories in terms of time and space, cost and ecological validity. The article focuses on elaborating its innovative applications in areas such as refined analysis of sports technology, precise monitoring of internal and external loads, active early warning and rehabilitation assessment of sports injuries, generation of personalized training plans, and real-time biofeedback. It also points out that VR/AR technology has opened up a new dimension for immersive training. Meanwhile, the paper also examines the current challenges, including issues such as data accuracy, the lack of multi-source fusion standards, privacy ethics risks, and uneven technology popularization. Research shows that the deep integration of digital sports and sports biomechanics not only significantly enhances competitive performance and scientific training levels, but also provides strong support for public health promotion and sports injury prevention and control. In the future, it is necessary to strengthen technical standardization, cross-disciplinary collaboration and ethical norms construction to achieve sustainable and high-quality development.*

Keywords: *Digital Sports; Sports Biomechanics; Digital Technologies*

1. Introduction

With the rapid development of information technology, the sports field is undergoing a profound digital transformation. "Digital sports", as an emerging paradigm integrating cutting-edge technologies such as the Internet of Things, big data, artificial intelligence, and virtual reality, is reshaping the ecosystem of competitive training, mass fitness, and sports science research. Sports biomechanics, as a core discipline that reveals the inherent laws of human movement, optimizes technical movements, enhances sports performance and prevents sports injuries, has long relied on equipment such as high-speed cameras, optical motion capture systems and force measurement platforms in laboratory environments. Although such traditional methods can provide high-precision data, they generally have limitations such as high cost, complex operation, environmental constraints, and difficulty in real-time feedback, which makes it difficult for research results to be effectively transformed into front-line training practices[1].

The rise of digital sports provides a brand-new path to break through the above-mentioned bottlenecks. Through technologies such as wearable sensors (like IMUs, electromyography, and smart insoles), portable motion capture, wireless transmission, and edge computing, the collection of sports biomechanical data is no longer confined to laboratories but has extended to real training grounds, competition sites, and even daily life. It has achieved a fundamental transformation from "offline analysis" to "online monitoring", from "group averaging" to "individual precision", and from "post-event assessment" to "real-time intervention". This transformation not only greatly enhances the ecological validity and application value of data, but also promotes the evolution of sports science towards a more intelligent, dynamic and personalized direction[2].

Against this backdrop, systematically sorting out the specific application scenarios, technical advantages, practical achievements and existing challenges of digital sports technology in sports biomechanics holds significant theoretical and practical significance. This article aims to comprehensively explore how digital sports can empower the research and application of sports

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biomechanics, with a focus on analyzing its innovative practices in areas such as technical diagnosis, load monitoring, injury prevention, personalized training, and immersive interaction. At the same time, it examines issues such as data reliability, ethical privacy, and popularization fairness, and looks forward to future development trends. This research promotes the high-quality development of digital sports.

2. Sports and Sports Biomechanics: Concepts and Technical Foundations

Digital sports is a new form of sports that is supported by new-generation information technology and realizes the perception, analysis, decision-making and optimization of the entire process of sports activities through digital means. Its technical system can be divided into four layers: the perception layer, which includes an inertial measurement unit (IMU), surface electromyography (sEMG), smart insoles, optical/depth cameras, force platforms and wearable physiological monitoring devices, is used to collect multimodal data during movement in a non-intrusive or minimally invasive manner; The transport layer relies on wireless communication such as Bluetooth, Wi-Fi, 5G and the Internet of Things (IoT) architecture to achieve real-time and stable data transmission. The processing layer utilizes cloud computing and edge computing platforms to clean, integrate and efficiently compute massive heterogeneous data. The application layer converts the analysis results into actionable training guidance or scientific decision support through artificial intelligence algorithms, visual interfaces, mobile apps and VR/AR systems.

The core of sports biomechanics lies in applying mechanical principles to analyze human movement, focusing on kinematic (such as joint angles, angular velocities, and displacements) and dynamic (such as ground reaction forces, joint moments, and power) parameters. By constructing multi-rigid body or musculoskeletal models, it reveals movement efficiency, load distribution, and injury mechanisms. Traditional research is highly dependent on controlled laboratory environments and is difficult to reflect the complex dynamics in real scenarios.

The integration of digital sports and sports biomechanics is essentially a supplement and upgrade of "data-driven" to "model-driven". The former provides high-dimensional, continuous and ecologically valid real-world data, while the latter offers a mechanical interpretation framework and predictive capabilities. By embedding digital technology throughout the entire process of biomechanical research, not only has a paradigm leap from "offline, static, and fragmented" to "online, dynamic, and full-cycle" been achieved, but also biomechanical analysis has moved out of the laboratory and integrated into daily training and health management, laying a solid technical and theoretical foundation for precise and intelligent sports science practice[3].

3. Key Application Areas of Digital Sports in Sports Biomechanics

Digital sports technology is permeating all aspects of sports biomechanics with unprecedented breadth and depth, enabling full-chain innovation from data collection and analysis to intervention feedback. This has significantly expanded research boundaries and application scenarios.

3.1 Sports Technique Analysis and Optimization

Sports technique analysis, a traditional core of sports biomechanics, aims to reveal the inherent laws of movements, identify technical bottlenecks, and optimize movement patterns to enhance efficiency and performance. Traditional methods relied on laboratory-based high-speed cameras and optical motion capture systems (e.g., Vicon, OptiTrack). While precise, these systems are limited by fixed venues, cumbersome marker attachment, high costs, and difficulty capturing dynamic performance in real competitions or under psychological pressure[4].

Digital sports technology, particularly wearable systems based on Micro Inertial Measurement Units (IMUs), has revolutionized this field. These lightweight sensors—typically integrating accelerometers, gyroscopes, and magnetometers—can be directly attached to body segments or embedded in sports equipment, enabling markerless, cable-free 3D kinematic data collection. For example, in track and field, IMUs on sprinters precisely measure joint angular velocities, body posture angles, ground contact time, and flight time. They quantify force transmission efficiency during starting pushes, coordination between stride frequency and length in acceleration phases, and swing leg folding/forward swing techniques in mid-run. Coaches can determine whether athletes are "stride frequency-oriented" or "stride length-oriented" and adjust training accordingly.

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In skill-dominated sports like gymnastics and diving, IMUs capture critical parameters such as aerial rotation speed and axial stability, helping athletes control movements precisely. In ball sports, technical analysis has become more sophisticated. Golfers' swings are recorded via sensors in club grips or on the body, documenting swing plane, clubhead trajectory, speed, lag (release timing), and face angle at impact to generate detailed "swing profiles." By comparing with world-class athletes' "golden data" or personal bests, systems pinpoint issues (e.g., early release, plane deviation) and provide intuitive improvement suggestions. Similarly, biomechanical analysis of tennis serves and table tennis strokes has become real-time and efficient due to digital technology. This shift from "qualitative observation" to "quantitative diagnosis" makes technical guidance more objective, precise, and personalized.

3.2 Sports Performance Evaluation and Monitoring

For team sports (e.g., football, basketball, rugby) and cyclic endurance events (e.g., long-distance running, cycling), scientifically evaluating and monitoring athletes' performance and load status is critical for preventing overtraining, avoiding injuries, and achieving supercompensation. Digital sports provide unprecedented tools to construct athletes' "load panoramas."

External Load refers to the physical workload endured by athletes. The integration of Global Positioning Systems (GPS) with high-sampling-rate (e.g., 100Hz) triaxial accelerometers has become standard for team sports load monitoring. Systems precisely record total distance covered, high-speed running (HSR) distance, sprint counts, maximum speed, acceleration/deceleration events (representing directional changes and sudden stops), and metabolic power during matches or training sessions, comprehensively depicting exercise intensity and patterns. Coaching teams use this data to assess fitness reserves, competition engagement, and adjust rotation strategies[5].

Internal Load reflects physiological and psychological responses to external workloads. Heart rate monitoring is fundamental, with heart rate variability (HRV) used to evaluate autonomic nervous system recovery. Advanced technologies like Near-Infrared Spectroscopy (NIRS) devices (e.g., Moxy Monitor) non-invasively monitor muscle oxygenated and deoxygenated hemoglobin concentrations, reflecting real-time oxygen supply-demand balance and fatigue. Surface electromyography (sEMG) analyzes activation levels, discharge frequencies, and fatigue characteristics of specific muscle groups[6]..

By correlating external load (e.g., high-speed running distance) with internal load (e.g., heart rate, muscle oxygen saturation decline), coaches gain deeper insights into individual differences—why two players covering the same distance exhibit vastly different physiological responses. This integrated monitoring provides a solid data foundation for developing highly personalized training plans, precisely regulating weekly/monthly training volumes, and achieving closed-loop management of "training-recovery-regeneration."

3.3 Sports Injury Prevention and Rehabilitation

Sports injuries are a core issue restricting athletes' careers and public fitness participation. Digital sports technology is driving a paradigm shift from "post-injury treatment" to "pre-injury prevention" and "precision rehabilitation."

Numerous studies confirm strong correlations between many non-contact injuries (e.g., ACL tears, Achilles tendinitis) and specific biomechanical risk factors, such as knee valgus collapse during landing/cutting, hip adduction, trunk lateral tilt, excessive ground reaction force (GRF) peaks, or rapid loading rates. Digital sports enable large-scale screening of these risks during regular training[7].

Portable IMU systems or computer vision-based depth cameras (e.g., Kinect, DARI) can real-time calculate and quantify these high-risk biomechanical indicators during squats, jumps, landings, and sudden direction changes. Systems automatically flag "high-risk" movements and generate risk assessment reports. Coaches can then implement targeted neuromuscular training for high-risk individuals—e.g., strengthening gluteus medius to improve hip-knee alignment or correcting landing posture through feedback training—to proactively reduce injury rates.

Digital technology also plays a crucial role in the rehabilitation stage. Traditional rehabilitation relies on therapists' subjective observations and periodic testing. Digital sports provide objective, continuous quantification tools. Wearable sensors or smart rehabilitation devices monitor movement patterns during gait training and strength exercises, ensuring adherence to correct biomechanical pathways and avoiding compensatory movements. For example, stroke patients or post-ACL surgery patients using smart insoles or lower limb IMUs receive real-time feedback on gait symmetry, affected limb weight-bearing ratios,

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and joint range of motion, ensuring safe, efficient rehabilitation. Doctors and physical therapists can remotely monitor data to dynamically adjust rehabilitation plans, enabling precision rehabilitation.

3.4 Personalized Training Design and Real-Time Feedback

Every athlete is unique, with significant differences in biomechanical characteristics (e.g., gait patterns, force generation habits, flexibility, muscle strength ratios). A core advantage of digital sports is enabling true "personalization."

By continuously collecting and analyzing athletes' long-term biomechanical data, systems establish unique "digital baselines" and "movement fingerprints." Artificial intelligence algorithms can then transcend "one-size-fits-all" training models to design optimal personalized programs. For example, for runners with poor running economy, long-term data analysis might reveal an optimal stride frequency range of 180-185 steps/minute, compared to their current 170 steps/minute. The system can then design interval training focused on "stride frequency improvement."

For strength training, combining motion capture and force plate data, systems analyze knee-ankle torque distribution during squats. If excessive knee loading is detected, recommendations might include adjusting stance width, center of gravity, or adding auxiliary exercises for specific muscle groups.

Furthermore, digital sports enable real-time biofeedback. During training, athletes receive immediate correction prompts via wearables (e.g., smart bracelets/belts with vibration alerts), AR glasses, or mobile apps. For instance, golfers receive vibration patterns when swing plane errors occur; basketball players see highlighted error zones in AR glasses when knee valgus angles exceed safe limits during landing. This immediate, intuitive feedback accelerates motor skill acquisition and consolidation, effectively correcting faulty movement patterns[8].

3.5 Virtual Reality (VR) and Augmented Reality (AR)

As cutting-edge digital sports technologies, VR and AR have opened new research and application dimensions for sports biomechanics.

VR creates highly immersive, fully controllable virtual environments. Athletes wearing VR headsets can practice techniques, simulate tactics, or conduct psychological stress training in virtual stadiums, tracks, or complex terrains. Critically, their biomechanical movements (tracked via IMUs in headsets or on the body) are synchronized with virtual performance. This allows researchers to study how psychosocial factors—environmental stress, crowd noise, time pressure—influence biomechanical performance (e.g., technical deformation, decision speed) under safe, repeatable conditions, which is difficult to simulate in traditional laboratories[9].

AR focuses on "virtual-real integration," overlaying digital information (e.g., virtual force arrows, movement trajectories, real-time biomechanical parameter readouts) onto athletes' real-world view. For example, in gymnastics training halls, AR systems project "ideal" somersault trajectories for athletes to mimic; in weight rooms, smart mirrors display real-time knee angles during squats, with color warnings when exceeding safe ranges. This "what-you-see-is-what-you-get" guidance significantly enhances training intuitiveness, engagement, and efficiency, forming a core component of future smart training facilities[10].

4. Challenges and Issues

While digital sports show promising applications in sports biomechanics, their in-depth development faces severe technical, application, and ethical challenges requiring urgent resolution.

4.1 Technical Challenges

Data quality and reliability represent core bottlenecks. Despite wearable sensors and portable systems enabling sideline monitoring, data accuracy is vulnerable to multiple interference factors in complex real-world training or competition environments. For example, IMUs suffer from integration drift, causing accumulated attitude angle errors during prolonged use; optical motion capture systems degrade significantly under strong outdoor light or multi-person occlusion; sEMG signals are highly susceptible to skin impedance, sweat, and motion artifacts[11].

Furthermore, data from different brands/models (e.g., varying GPS sampling rates, accelerometer ranges) lack unified standards and calibration protocols, creating severe "data silos" that hinder cross-study/team comparisons and integration. Constructing high-fidelity personalized biomechanical models (e.g., musculoskeletal models) requires substantial computational resources, while applying these complex models to real-time feedback scenarios demands exceptional edge computing capabilities. Most critically, currently widespread machine learning and AI algorithms,though capable of processing massive datasets, often operate as "black boxes" lacking sufficient interpretability. This makes coaches and athletes hesitant to fully trust AI-based diagnoses or recommendations, limiting their use in critical decision-making.

4.2 Application Challenges

High-precision motion capture systems, advanced wearable devices and their corresponding analysis software are expensive, and the maintenance and operation costs are also relatively high. This makes them unaffordable for many grassroots sports schools, amateur clubs, and individual athletes, creating a significant "technical divide" that may exacerbate competitive sports resource inequality and unfair competition[12].

Even for elite teams, extracting truly valuable, actionable insights from massive multi-dimensional data streams—rather than succumbing to "data overload"—poses enormous challenges for coaching staff. A more profound risk is "over-reliance" on technology: when coaches overly depend on screen metrics, they may neglect athletes' subjective experiences (e.g., fatigue, pain), in the game state, and non-quantifiable emotional intelligence/tactical wisdom. Similarly, athletes relying long-term on real-time feedback for movement correction may weaken their proprioception and autonomous error-correction abilities, hindering the development of stable, internalized motor skills.

4.3 Ethical and Social Challenges

Data privacy and security present major dilemmas. Athletes' physiological data (heart rate, EMG, sleep quality), biometric information (gait, movement patterns), and location trajectories constitute highly sensitive personal health information. Breach, misuse, or unauthorized exploitation (e.g., commercial development, insurance assessment, discriminatory selection) would severely violate athletes' privacy and dignity.

Currently, global regulations and ethical norms regarding data ownership (athlete, club, or service provider?), usage rights, storage duration, and cross-border transmission remain unclear and fragmented. Additionally, algorithm-based risk prediction models (e.g., injury risk scores) with flawed design or biased data may discriminate against specific groups,Raising questions about fairness.

5. Prospects and Suggestions

In the future, the integration of digital sports and sports biomechanics will develop in a more intelligent, precise, and inclusive direction. Sensors will tend to be miniaturized, flexible, and unobtrusive, enabling long-term comfortable wearing. Artificial intelligence will be deeply integrated into biomechanical analysis, constructing adaptive prediction models to realize injury risk early warning and dynamic optimization of training programs. Edge computing will enhance real-time processing capabilities to support instant feedback. Digital twin technology is expected to create virtual avatars for each athlete for simulation, prediction, and personalized intervention. Applications will expand from elite athletics to mass fitness, elderly health, and rehabilitation medicine. At the same time, it is necessary to accelerate the establishment of data standards, safety norms, and ethical frameworks, promote interdisciplinary cooperation, cultivate compound talents, and ensure the healthy and sustainable development of the technology.

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