Technological Breakthroughs in Sport

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We are currently witnessing an unprecedented era of digital transformation in sports, driven by the revolutions in Artificial Intelligence (AI), Virtual Reality (VR), Augmented Reality (AR), and Data Visualization (DV). These technologies hold the promise of redefining sports performance analysis, automating data collection, creating immersive training environments, and enhancing decision-making processes. Traditionally, performance analysis in sports relied on manual data collection, subjective observations, and standard statistical models. These methods, while effective, had limitations in terms of time and subjectivity.

sports technology performance analysis emerging technologies

1. Introduction

Effectively integrating these powerful resources into sports is an exciting challenge. Each tool offers unique solutions and applications to redefine the landscape of sports performance analysis [1][2][3][4][5]. Through these technologies, researchers can revolutionize performance analysis by automating data collection, processing vast datasets, interpreting performance, providing immersive training environments, offering real-time augmented feedback, and enhancing the decision-making process [1][6][7].

Performance analysis is a crucial element in sports science, playing a pivotal role in understanding, interpreting, and ultimately improving an athlete's performance [8][9][10][11]. It serves as an indispensable tool that assists athletes, coaches, and sports analysts in making informed strategic and tactical decisions that can significantly alter the outcome of competitive sports events [12][13].

Traditionally, the process of performance analysis has predominantly relied on manual data collection and/or input, subjective observational techniques, and standard statistical models [14]. Despite their proven efficacy, these methods often necessitate significant time and effort to implement, interpret, and apply [8][15]. Manual data collection involves meticulous documentation of numerous performance metrics, demanding not only extensive work hours but also a deep understanding of sport-specific parameters. Consequently, manual data collection is prone to observational biases and discrepancies that might arise due to the inherent subjectivity of human observation, leading to potential misinterpretation of performance data [4][9]. Similarly, while statistical models have been effectively used to decode patterns and inform strategies, they typically oversimplify the complex, dynamic nature of sports performance, often considering only limited variables and not adequately addressing the multifactorial aspects of sports performance [1][10][16]. These limitations are amplified when trying to analyze performance in real-time, where swift data processing and interpretation are essential [10][17][18][19]. However, technological advances in sports science have led to a transformative change in the field, bringing forth an era of enhanced, objective, and real-time performance analysis.

Recent AI tools captured the imagination of users and exponential adoption of the technology has exceeded any other innovation [20][21][22]. With AI's ability to streamline data collection, process massive datasets quickly and accurately, synthesize information, predict outcomes, and create new knowledge, it will revolutionize work and play environments. Infinite possibilities exist for using AI with future outcomes that were previously inaccessible through traditional human analysis [23][24]. AI—a general term for many different technologies, such as neural networks, large language model transformers, and diffusion grids, which have been instrumental in finding previously unknown relationships in datasets and making predictions with astonishing accuracy—boasts the capability to automate data collection processes, reduce human error, and drastically decrease the time taken to gather information [6][25].

VR introduces the capability to create highly realistic, immersive training environments. These environments are not simple simulations; they are commonly understood as platforms that mimic the exact conditions of a real-world game or training scenario. Hence, VR is recognized as an immersive environment that goes beyond mere emulation [26][27][28]. The advancement beyond emulation and into near-reality provides athletes with a unique opportunity to train and refine their skills and gain a comprehensive understanding of their performance in a controlled setting [4].

Complementing the immersive experiences offered by VR, AR presents another technological advancement that blurs the line between the physical and digital worlds [29][30][31][32][33][34]. AR can overlay digital information onto the real-world sports environment, effectively creating an interactive platform that provides real-time performance analysis [30][32][33][34]. This technology can be used to analyze and provide instant feedback on an athlete's technique, positioning, and movements, enabling immediate adjustments and refinements [30][32][33][34]. Such instant feedback mechanisms facilitate quicker learning and correction of errors, ultimately leading to improved performance. AR also holds promise in tactical planning. Coaches can overlay digital graphics onto the field of play to explain complex tactics and formations to players. This visual representation can enhance players' understanding and implementation of strategies [35][36][37].

Complementing the abilities of AI, VR, and AR, dynamic and interactive DV techniques bring forth an entirely new dimension of performance analysis. By converting complex data into easily understandable visual representations, this technology allows coaches, athletes, and analysts to easily interpret and act upon performance metrics [38]. This enhanced communication of information leads to a more effective understanding of performance patterns, trends, and areas of improvement, thereby facilitating more informed decision-making processes [39][40].

2. Artificial Intelligence (AI) in Sports Performance Analysis

2.1. Definition and History

AI is a branch of computer science that is focused on developing systems that can execute tasks mirroring human intelligence [20]. These tasks include learning from experiences, comprehending natural language, video analysis, recognizing patterns, solving problems, and decision-making. Although the AI boom of today sees a plethora of new models being developed daily for a wide array of tasks, the concept of AI is not new. The theoretical groundwork for a "thinking" machine can be traced back to the 1940s and 1950s. Inspired by biological neurons, Pitts and McCulloch [41] proposed the McCulloch–Pitts neuron, a computational model that simplifies the function of a biological neuron into multiple inputs and a single output. In the 1950s, pioneering computer scientist Alan Turing posited the concept of a machine capable of imitating human intelligence [42], marking a significant milestone in the development of AI. This was further advanced by McCarthy et al. [43], who theorized that every aspect of learning or intelligence could be defined so precisely that a machine could simulate it, which is considered the birth of AI as a field. Subsequently, Rosenblatt [44] proposed the Perceptron, which stands as the earliest form of a neural network capable of learning from its inputs.

Despite these early ground-breaking evolution benchmarks, the progress in developing modern neural networks was slow. This was largely due to computational limitations and data scarcity, leading to periods known as "AI winter", characterized by reduced funding and interest in AI research [45][46]. The tide turned in the 1980s and 1990s with the introduction of backpropagation by Geoffrey Hinton and then the emergence of deep learning in the 2000s and 2010s. These developments have culminated in the creation of powerful neural networks, bringing an end to the 'AI winter' and propelling AI research to the forefront of technological innovation. Within the context of machine learning, modern AI systems can process vast amounts of data, identify intricate patterns, and enhance system performance without the need for explicit programming [47]. Deep learning, a subset of machine learning, deploys artificial neural networks designed to emulate the function of the human brain. Finally, in the 2020s, the proliferation of high-capacity models, such as the Generative Pretrained Transformer (GPT)—the engine that gives life to ChatGPT—heralded a new era in the AI landscape [48][49][50]. These large-scale models demonstrate an unprecedented capacity to generate human-like text, making AI technology more accessible and usable to the public and not just computer scientists. The success of these models has stirred a competitive environment among leading tech companies, each vying to develop and deploy the most advanced AI technologies. This competition not only spurs technological advancement but also contributes to the popularization of AI applications in everyday life.

2.2. How AI Can Contribute to Sports Performance Analysis

AI has brought about profound changes across various sectors, including healthcare, automotive, retail, finance, and entertainment [21][22]. Unsurprisingly, sports performance analysis has also been profoundly impacted [2][6][14][23][24][51].

The applications of AI in sports performance analysis are vast and diverse, transforming traditional methodologies in data collection, analysis, and interpretation. AI-powered technologies offer an efficient shift from manual, bias-prone methods to precise data collection on a large scale. However, AI's value extends well beyond data collection. Another strength lies in data processing and interpretation [25]. Modern data collection techniques often generate enormous volumes of data, beyond human capabilities to handle and digest. AI addresses this challenge by automating data analysis, akin to data mining, identifying patterns and trends that might be overlooked [47]. This analytical process not only reduces data volume but also can uncover hidden patterns, providing valuable insights for performance enhancement and strategy planning. Furthermore, AI's learning capacity from past data significantly bolsters its predictive abilities, yielding increasingly insightful interpretations over time.

AI applications have the potential to enhance traditional sports performance analysis methodologies. It has enabled video analysis to become faster, more precise, and comprehensive, supplanting time-consuming and potentially biased manual reviews [52]. Through machine learning algorithms, computer vision can detect and track players and objects, analyze movements, and extract real-time information [53]. These techniques offer a detailed understanding of player movements, team formations, and tactics, significantly enriching strategic planning. These algorithms can also discern patterns in an opposing team's play, providing valuable insights for competitive strategy planning which traditional methods, reliant on subjective human analysis, may not capture. AI also can be used for the recognition of specific sports movements [14], which can be used for implementing semi-automatic and automatic systems. Furthermore, computer vision's capabilities extend into injury prevention and rehabilitation, analyzing player movement biomechanics, identifying potentially harmful patterns, and suggesting technique modifications or training regimen adjustments [54][55]. AI-powered computer vision techniques considerably expand the scope and depth of performance analysis in sports, promoting precise strategic planning, enhancing player safety, and improving overall team performance.

AI holds impressive potential to streamline notational analysis, enhancing both its efficiency and accuracy by automating the intricate process of recognizing and annotating discrete events. For instance, machine learning and computer vision algorithms can accurately detect and note instances of specific actions [56][57], such as assists in soccer, basketball throws, or swimming techniques [58][59][60]. Furthermore, AI can handle and scrutinize vast quantities of data, offering comprehensive insights into the effectiveness of tactics, strategies, and player actions. For example, AI could analyze thousands of hours of game footage to determine the success rate of a particular strategy or tactic [61]. Similarly, AI has the potential to revolutionize time-motion analysis, making it more efficient and predictive, thereby becoming a far more effective tool for evaluating players' physical performance. AI algorithms can analyze athletes' movements during a game, provide real-time insights into their energy expenditure, and predict fatigue levels, leading to better player substitution strategies. Finally, the role of AI in analyzing data from wearable devices has been transformative, offering real-time, predictive, and personalized sports performance analysis. For example, wearable devices coupled with AI can track an athlete's heart rate, speed, and oxygen levels in real time, predict potential health risks based on past data, and suggest personalized training programs to optimize performance and recovery [62]. In this way, AI offers an unprecedented leap forward in the field of sports science.

AI's insights are not merely theoretical; they have practical applications in real-world scenarios, influencing field strategies and becoming a transformative force in the sports sector [63]. AI's predictive capabilities play a pivotal role in injury prevention, with algorithms assessing data from wearable devices to predict potential injury risks and recommend appropriate training modifications [54].

3. Virtual Reality (VR) and Augmented Reality (AR) in Sports Performance Analysis

3.1. Definition and History

VR is a technology that immerses users in computer-generated environments, transcending the boundaries of physical reality and enhancing users' experiences and engagement, including visual, auditory, and tactile cues [28][64]. It encompasses various system categories, including Non-Immersive, Semi-Immersive Projection, and Fully Immersive systems [64]. On the other hand, AR can be defined as a dynamic fusion of the virtual and real, seamlessly integrating virtual entities within real-world environments in real time, enabling users to interact with both domains [29][65][66].

The concept of VR has its origins dating back to the 1960s when Morton Heilig, an American cinematographer, created the Sensorama—a mechanical device aimed at providing a multisensory experience through stereoscopic 3D images, sounds, smells, and even vibrations [67]. In the late 1960s and early 1970s, Ivan Sutherland developed what is often considered the first true head-mounted display (HMD) system, called the "Sword of Damocles" [68]. However, it was not until the 1980s and 1990s that VR technology began to take a more concrete shape with advancements in computer graphics, display technology, and interaction devices. In fact, the term "virtual reality" was only coined in the 1990s by Jaron Lanier [69]. Also, in the 1990s, the Computer Automatic Virtual Environment (CAVE) systems were introduced, offering a fully immersive environment [70]. This technology enables users to fully experience and interact with 3D computer-generated environments within a spacious cube formed by multiple display screens. As users physically enter this projection cube, they become fully enveloped by the virtual environment and a more natural and realistic sense of being [34].

Similarly, the AR concept dates back to the 1950s, with the term being coined by Tim Caudell and David Mizell in 1990 [64][71]. AR systems can be head-mounted see-through and monitor-based video systems [64][65]. While there are some conceptual differences between VR and AR, both technologies share a common goal: enhancing user experiences by extending possibilities beyond the physical world through seamless and harmonious interactions [29][64]. In fact, some argue that both should be enclosed by the same comprehensive framework under the term 'XR', where X works as a placeholder for any reality [33][64].

It is evident that the development of both VR and AR relies on an inherent relationship with emerging technologies. As a result, the extensive utilization of these technologies hinges on the commercial availability of the associated devices. In recent decades, significant progress has been made in the VR and AR landscape, leading to the creation of a variety of devices catering to different levels of immersion and functionality (**Table 1**). From the pioneering attempts of SEGA VR and Google Glass, to the more recent Microsoft HoloLens and Meta Quest 2 & 3, and the recently introduced Apple Vision Pro, these devices have the power to transform how we perceive and interact with both the virtual and real worlds, paving the way for innovative applications in fields such as medicine and physiotherapy [72][73][74][75][76], manufacturing [31][77], entertainment [31][78], exercise [79][80], and education [78][81][82][83].

Table 1. Commercially widely available VR and AR devices across recent years.

Augmented Reality (AR)		Virtual Reality (VR)	
Google Glass (2013)	• Wearable AR device with head-mounted display • Hands-free access to digital information • Interaction with virtual elements in real world	Google Cardboard (2014)	• Low-cost VR viewer made from cardboard • Designed for use with smartphones
Microsoft HoloLens (2016)	• Overlays interactive holographic images • Enhances productivity and collaboration	Zeiss VR One (2014)	• VR headsets designed for different applications • Quality optics and ergonomic design
Magic Leap One (2018)	• AR system superimposing virtual objects • Improved field of view and interaction	Samsung Gear VR (2015)	• VR headset developed in collaboration with Oculus • Designed for Samsung smartphones
Microsoft HoloLens 2 (2019)	• Upgraded version with improved features • Catering to enterprise and creative applications	Oculus Rift (2016)	• VR headset offering immersive experiences • Tracks head and hand movements • Focus mainly on gaming
Apple Vison PRO (2023)	• Mix of AR and VR • Purely hand-tracking	HTC Vive (2016)	• High-quality immersion with motion tracking • Motion-sensing controllers for interaction

Augmented Reality (AR)		Virtual Reality (VR)	
		PlayStation VR (2016)	• VR headset for PlayStation gaming consoles • Bringing VR to a broader gaming audience
		Oculus Quest (2019)	• Standalone VR headset • No need for external sensors or PC
		Valve Index (2019)	• High-end VR system with precise tracking • Finger-tracking controllers and quality visuals
		Meta Quest 2 (2020)	• Standalone VR headset • No need for external sensors or PC • Upgrade from the Oculus Quest
		Apple Vison PRO (2023)	• Mix of AR and VR • Purely hand-tracking

R and AR, nce [30][32][33][34].

3.2. How VR and AR Can Contribute to Sports Performance Analysis

VR and AR technologies hold immense promise for revolutionizing sports coaching, training, and performance analysis. These technologies are reshaping traditional methodologies [26][27][28][84][85], with a primary focus on coaching, training, and skill enhancement [30][32][33][34].

By harnessing VR and AR, sports professionals can create immersive environments that optimize athlete performance in various ways [35][36][37]. These include improving team dynamics, refining individual skills, and minimizing injury risks through preventive and rehabilitative models [86]. These technologies serve as invaluable training tools, allowing for strategy refinement, tactic development, and real-time response practice within meticulously controlled environments [30][87][88][89].

In fact, VR can recreate environments to challenge training by manipulating constraints in complex and dynamic situations, thus creating specific repeatable scenarios [33][36]. On the other hand, AR can provide real-time information for athletes, acting as an assistant coach. It also offers benefits to coaches and players alike [90][91][92]. Athletes benefit by receiving real-time feedback and performance data displayed directly in their field of vision, empowering them to make on-the-fly adjustments during training sessions. Coaches, meanwhile, leverage AR's capabilities to dissect game strategies, visualizing virtual markers and lines that offer insights into positioning and tactics. Even for spectators, AR enriches the viewing experience by overlaying live broadcasts with dynamic graphics and statistics, providing deeper insights into the game [90][93][94].

Both VR and AR can provide immersive experiences, transporting athletes to meticulously crafted simulated settings, such as virtual arenas or controlled training configurations. This can be achieved using different levels and setups, ranging from the use of 360-degree VR, real-world video footage of a particular environment that has been pre-recorded, to animated VR, computer-rendered images that change in accordance with users' actions [86][89][95][96]. In the latter, environments can intricately replicate sensory inputs and physical sensations, allowing athletes to fine-tune their abilities and decision-making processes in a manner that provides instantaneous feedback and promotes skill refinement [36][97].

This dynamic interaction between the world of sports and the virtual realm brings forth an unprecedented avenue for learning and advancement [86]. However, the effectiveness of VR technology in sports is influenced by a myriad of factors that determine its applicability in real-world scenarios. These factors, ranging from reaction time and anticipation to expertise level and environmental context, must be methodically measured and comprehended to maximize the potential of virtual training. The interplay of these variables plays a pivotal role in shaping how athletes respond to the diverse events presented within virtual scenarios.

While promising, it is important to point out that VR training is not useful or practical for training in all sports; for example, water sports such as swimming cannot be trained in virtual environments. The current state of technology also makes it challenging to simulate training for skills relying on highly accurate haptic feedback and multiplayer interactions. The technical limitations and the costs associated with the creation of virtual training environments pose a significant barrier to uptake in VR sports training [30]. Moreover, the acceptance of the technology by coaches seems to be the biggest barrier [98][99]. Furthermore, the skill transfer from the virtual to the real world is still under debate [30], and a small evidence base supports its use in enhancing athletic performance [32]. However, the debate on using VR in rehabilitation settings has grown substantially recently [72][100][101][102], suggesting that virtual environments can be useful from this perspective.

When considering the potential of AR in sports, an intriguing avenue emerges [91][103]. While VR often transports athletes to entirely virtual environments, AR enhances the real world by overlaying digital information onto the physical surroundings [65]. This technology can be harnessed to provide real-time data, statistics, and visual cues directly into an athlete's field of view. Imagine a soccer player receiving instant tactical insights while on the field or a cyclist having crucial performance metrics displayed on their glasses. AR holds the potential to offer athletes immediate access to valuable information, enhancing decision-making and overall performance.

While the applications of VR and AR in sports have predominantly focused on physical training [104][105][106][107], a vast uncharted domain with substantial potential lies in harnessing these technologies to cultivate cognitive awareness and psychological readiness. By visualizing performance data and creating simulated scenarios, athletes can enhance their cognitive grasp of the sport, hone their decision-making skills, and develop mental fortitude for high-pressure situations. This unexplored territory represents a promising frontier for technology-enabled athlete development, bridging the gap between physical prowess and mental acuity.

Below researchers have listed the main points where VR and AR can transform current sport performance analysis:

- **Creating Immersive Coaching and Training Environments:** VR and AR technologies immerse athletes in realistic training scenarios, providing real-time coaching feedback.
- **Skill and Strategy Development:** These technologies offer interactive, repeatable scenarios that challenge and refine athletes' skills. Also, to visualize game scenarios, positioning, and tactics in a comprehensive and interactive manner.
- **Delivering Tactical Insights:** AR overlays digital information onto the physical environment, assisting athletes in making strategic decisions during gameplay.
- **Providing Real-time Athlete Feedback:** Athletes receive immediate feedback and performance data in their field of vision, allowing adjustments during training.
- **Facilitating Data-Driven Decision-Making:** Coaches and athletes can make informed decisions by accessing comprehensive performance metrics and tactical insights.
- **Supporting Rehabilitation:** VR and AR can be used for aiding in injury prevention and rehabilitation.
- **Bridging the Gap Between Physical and Mental Preparedness**: VR and AR develop cognitive awareness and psychological readiness, complementing physical training for high-pressure situations.
- **Visualizing Performance Data:** VR and AR help athletes better understand performance data, enhancing their decision-making and mental acuity.
- **Enriching Spectator Experiences:** AR enhances the viewing experience for spectators by overlaying live broadcasts with dynamic graphics and statistics, providing deeper insights into the game.

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