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Review

The Future of Technology at Mega Sports Events

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Abstract

Mega sporting events, such as the World Cup and the Olympics, are international events where the host country and city change. Technological developments at these events are used in various fields, including wearable devices, line technologies, and advanced analytical applications. These developments improve athlete performance, fan participation, and managerial efficiency. This study examined the technologies used in mega sporting events from historical and contemporary perspectives, as well as made predictions about future technologies. The study was conducted as a review. First, the technologies used in mega sporting events were examined within the scope of the research. Information was collected by reviewing academic publications, event reports, company websites, news sites, and event videos. The study concluded that the technologies used in mega sports events fall into five main categories: athlete performance and health technologies; refereeing and decision support systems; fan experience and interaction technologies; organizational and infrastructure technologies; and education, preparation, and analysis technologies. It is believed that this categorization can be used in future research.

Keywords: Future, Mega Events, Sports, Technology

Mega Spor Etkinliklerinde Teknolojinin Geleceği

Öz

Mega spor organizasyonları, katılımın uluslararası seviyede olduğu fakat organizasyonun düzenlendiği ülke ve şehirlerin değiştiği Dünya Kupası veya Olimpiyatlar gibi organizasyonlardır. Bu organizasyonlarda yaşanan teknolojik gelişmeler sporcu performansı, taraftar katılımı ve yönetimsel verimliliğin arttırılmasının yanında giyilebilir cihazlar, çizgi teknolojileri, gelişmiş analitik uygulamalar gibi farklı alanlarda kullanılmaktadır. Bu araştırma, mega spor organizasyonlarında kullanılan teknolojilerin geçmiş ve bugün perspektifinden inceleyerek gelecekte kullanılabilecek teknolojilere yönelik tahminler oluşturmak amacıyla gerçekleştirilmiştir. Araştırma derleme makale türünde gerçekleştirilmiştir. Araştırma kapsamında ilk olarak mega spor organizasyonlarında kullanılan teknolojiler incelenmiştir. Bu teknolojiler incelenirken öncelikle yayınlanmış akademik yayınlar, ardından organizasyon raporları, web siteleri, teknolojileri üreten firmanın web siteleri haber siteleri ve organizasyonlara ait videolar incelenerek bilgiler derlenmiştir. Araştırma sonucunda mega spor organizasyonlarında kullanılan teknolojiler; sporcu performans ve sağlık teknolojileri, hakemlik ve karar destek sistemleri, taraftar deneyimi ve etkileşim teknolojileri, organizasyonel ve alt yapı teknolojileri ve eğitim, hazırlık ve analiz teknolojileri olmak üzere beş başlık altıda sınıflandırılabileceği ve bu şekliyle gelecek araştırmalarda kullanılabileceği düşünülmektedir.

Anahtar Kelimeler: Gelecek, Mega Etkinlikler, Spor, Teknoloji

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INTRODUCTION

The sports industry, which has seen significant developments over the past century, has become not only a source of entertainment but also a powerful economic force. Historically, sports, which were initially limited to local events, became global with the advent of television (Holden et al., 2019; Mencarini et al., 2022; Wang et al., 2022). Over time, the rise of cable television, sports networks, and the increasing use of the internet have further fueled this growth. Technological developments around the world have been integrated into the sports industry, improving athlete performance, fan participation, and managerial efficiency, as well as taking many different forms, from wearable devices and line technologies to advanced analytical applications (Ramkumar et al., 2021). Finally, with the integration of artificial intelligence, one of the greatest technological developments of the 21st century, the sports industry has entered a major transformation process. With the use of artificial intelligence, machine learning has enabled significant improvements in athlete performance, injury prevention, and game strategy (Dindorf et al., 2022).

The rapid advancement of technology has brought about significant changes in the sports industry. As a result of these changes, GPS systems, wearable technologies, video analysis software, and AI-powered applications have provided athletes, coaches, managers, and fans with different experiences. These technologies enable the real-time tracking of athletes' movements and the use of the data obtained to create training programmes, game strategies, and detailed analyses of performance and injuries (Carling et al., 2012; Franks, 2004; Hughes and Şimşek and Devecioğlu, 2019).

All developments in the sports sector are of utmost importance in terms of contributing to the development of mega sports events, finding application areas, and introducing them to large audiences. In this regard, the technologies used in sports events show various innovations with each new event, both for coaches, media workers, and spectators in the sports venues and for spectators watching from their screens (Şimşek and Devecioğlu, 2019).

Mega sports events are events such as the World Cup or the Olympics, where participation is at an international level but the country and city hosting the event change. While these events cover a specific short time frame, they have long-term effects on the country and city hosting the event (Preuss, 2009).

According to Müller (2015), it is possible to examine a sporting event as a mega-event from two different perspectives. From the first perspective, the duration and scale of the event are important in terms of its internal characteristics. The internal characteristics in question include the total spectator capacity of sports facilities, the number of employees and volunteers working for the event, the sports disciplines, the number of facilities to be built, renovated, or expanded for the event, and the number of athletes, coaches, administrators, and spectators participating in the event. The second perspective focuses on the external characteristics contributed by the country or city hosting the event. From this perspective, the external characteristics include the number of countries and broadcasters that will broadcast the sporting events live, sponsorship opportunities and numbers, investments in infrastructure such as transportation, accommodation, and communication, sports heritage plans and strategies, and the impact on the host country and city.

As a result of all the evaluations made, mega sports organizations are defined as limited-term, one-time, or repeatable events that showcase the vision, culture, and strategies of cities and countries through their candidacy and that leave a lasting impact on the country or city through planned sports heritage strategies, with investments made in various areas for the purpose of promoting the country and city through sustainable finance and financial programmes (Gold and Gold, 2011; Hiller, 2000; Mills and Rosentraub, 2013; Müller, 2015; Roche, 2000). Countries hosting mega sports events have different motivations. The most important motivational

factors include economic, political, social, and cultural reasons (Baum and Lockstone, 2007).

This article aims to examine fast-developing technologies such as artificial intelligence, biometric systems, digital twins and immersive audience interaction platforms for future technologies for mega sports organizations. By analysing the current trends and examining the systems applied in mega sports organizations in the past and present, it creates predictions for future applications and brings them to the attention of organisation managers, academicians, rule makers and technology developers. A literature review was first conducted for the research data. First, published articles were examined, followed by reports on mega sporting events (PubMed, ScienceDirect, Human Kinetics, Google Akademik, Web of Science), websites of brands related to the events' Technologies, and news site publications. The literature review for the scope of the research was conducted between 1 November 2024 and 1 May 2025. Finally, the authors evaluated and interpreted the findings in terms of future perspectives. Furthermore, this research is significant because it contributes to the existing literature and future research in this field.

Sports Technologies Used in Mega Sports Events

This section of the study examines the technologies used in mega sporting events, from past events to those in the present day. These technologies are categorised and explained with examples.

Wearable technologies

Wearable technologies allow athletes to simultaneously monitor various data, such as heart rate, pulse, sleep, and body temperature. Examining wearable technologies from this perspective reveals that the process began with the invention of eyeglasses in the 13th century and has undergone major evolution, leading to the augmented reality (AR) and virtual reality (VR) glasses used today. Wearable technologies come in various forms, including smart bracelets, shoes, glasses, watches, clothing, head-mounted displays, and virtual reality glasses. At major sports events, Intel Curie Module technology was used at the 2016 Rio and 2020 Tokyo Olympics to analyse athletes' movements, enhance performance analysis, and improve the viewer experience. Electronic Performance and Tracking Systems (EPTS) were used at the 2018 and 2022 Fédération Internationale de Football Association (FIFA) World Cups (Mannai, 2025; Pan et al., 2024). At the 2024 Paris Olympics, smartwatches, biometric sensor-equipped clothing, and wristbands were used to collect data on heart rate, sleep quality, exercise load, and stress levels. These data were then analysed using artificial intelligence (Mooney, 2024).

Artificial intelligence supported performance analyses

AI-supported performance analysis is the process of predicting athletes' fatigue, injury risk and performance values by using big data analysis and artificial intelligence algorithms. At the Tokyo 2020 Olympics, Intel 3D Athlete Tracking (AI + Image Processing) technology was used in the movement analysis of sprinters and gymnasts and was used for technical analysis and referee support systems in the organisation (International Olympic Committee [IOC], 2019). At the FIFA 2022 Qatar World Cup, Connected Ball and AI Video Analytics technology were used for offside detection and analysing passing lanes, tracking players and the ball, and tactical analysis (Federation Internationale de Football Association [FIFA], 2022).

Video analysis and ımage recognition systems

Video analysis and image recognition systems enable the automatic analysis of athletes' positions, movements and performance through video images. The Hawk-Eye system is an image recognition technology used especially in sports such as tennis, cricket and soccer. This technology is used to track the movement of the ball on the field. It is used in many different sports organizations such as the FIFA World Cup, Wimbledon and World

Cricket Championship. 3D video analysis systems are technologies used to analyse player movements, strategic changes and in-match data in a 3D environment. These technologies are used as an effective analysis tool in players' training. These technologies are used in organizations such as the Olympics, FIFA World Cup, NBA (National Basketball Association) and Formula 1 (Iguma et al., 2020; Sheppard, 2006). Object recognition systems are used to identify moving objects. These technologies are especially used in sports such as football and basketball to track the movements of the ball and players, as well as to analyse different angles of matches. These technologies are used in organizations such as the Olympics, FIFA World Cup, NBA, tennis, hockey and Formula 1. Ball tracking systems are a technology used especially in tracking the movements of the ball. With this technology, it is used to accurately determine the speed, path and location of the ball in sports such as soccer, tennis and cricket (Kamble, 2019).

Biomechanical and physiological test systems

Biomechanical and Physiological Testing Systems are used to optimize the performance of athletes, reduce the risk of injury and perform training in scientific ways. Using these systems, it is effective to analyze the movement mechanics and physiological capacities of athletes. 3D motion analysis systems were used by the United Kingdom Institute of Sport at the 2012 London Olympics to evaluate the performance of athletes before the games. Examples of these technologies include Electronic Performance and Monitoring Systems (EPES) and Semi-Automated Offside Technology (Moeslund et al., 2006). Accelerometers and Gyroscopes are among the wearable sports technologies that are increasingly used in developing sports technologies. Using these sensors, it is possible to analyze athletes' movement speed, direction, acceleration, rotational movements and posture in real time. These systems are used for athlete performance and load monitoring, technical analysis and injury prevention. Examples of these technologies are the IMU (Inertial Measurement Unit) sensors developed by Catapult and STATSports, which include accelerometers, gyroscopes and magnetometers (Chambers and Gabbett, 2009).

Video analysis software is a technology that enables major changes in both individual and team sports. Thanks to these software, technical and tactical performances of athletes or teams are analyzed through images. In the Olympics, programs such as Dartfish, SportsCode and SiliconCoach were used in branches such as gymnastics, diving, swimming and athletics, and software such as NAC Sport, Dartfish and Longomatch were used in tactical analysis especially in team sports. In the World Cups, SAP and Dartfish were used to analyze rival teams, Technical Study Group (TSG), FIFA officially Enhanced Football Intelligence (EFI), FIFA Player App and FIFA Insight System provided video-supported analysis during and after the match (Carling et al., 2012). Pressure Analysis Systems are used to measure athletes' sole pressure, balance, ground contact time and load distribution. Using these systems, it is an important area in the performance development of athletes, injury prevention, rehabilitation follow-up and technical corrections. Devices such as Bosu platforms and Pedar Pressure Plate have been used to analyze the pressure points and balance of athletes on the ground, and platforms of Kistler and Tekscan brands have been used to measure parameters such as gait analysis and pressure distribution analysis, step pressure, foot contact with the ground and balance shifts in runners and track and field branches (Razak et al., 2012).

Physiological testing systems are highly advanced and comprehensive technologies used to reduce the risk of injury in athletes and to ensure maximum efficiency. Maximal oxygen consumption (VO2 max) test systems are used to measure the maximal oxygen consumption capacity of athletes and are important in determining the levels of endurance sports (Holder, 2024). Heart rate monitors and HRV (heart rate variability) analysis are technologies used to monitor athletes' training levels, fatigue and recovery processes. Monitoring the performance of athletes with these technologies is important

for the management of training and the development of recovery processes. These technologies were first used at the 2012 London Olympics. In the 2022 Qatar FIFA World Cup, these technologies went one step further and were used to monitor the stress levels and recovery of athletes before, during and after the match (IOC, 2013). Body composition analysis is an important tool used in the examination of values such as fat ratio, muscle mass, water ratio and bone density of athletes and in the optimization of their physical and performance. Along with this analysis, it is used to determine the endurance, strength and performance of athletes. These systems have been used in the Olympics, World Cups and Olympic preparation camps (Ackland et al., 2012; Silva et al., 2013).

Heat and perspiration analysis are technological methods used to analyze athletes' body temperature, hydration levels, electrolyte loss and heat-induced performance degradation. It plays an important role in optimizing both heat-related health problems and performance of athletes in mega sports organizations held in hot and humid climates (Plakias, 2024). Blood gas and respiration analysis are used to measure physiological parameters such as oxygen utilization, carbon dioxide excretion, acid-base balance, blood pH and muscle metabolism and metabolic efficiency levels of athletes. These analyses allow athletes to obtain important information on aerobic capacity, lactate threshold, hypoxia tolerance, training adaptation and performance optimization (Migliaccio et al., 2023).

Athlete health and rehabilitation technologies

Athlete health and rehabilitation technologies are advanced technological tools and methods used to improve athletes' performance and injury and post-injury processes. Injury prevention and risk analysis technologies are technological systems used to protect athletes' health, improve their performance and reduce injuries. In the 2020 Tokyo Olympics, one of the first Olympics where these technological analyses were used, movement analysis of athletes was performed using artificial intelligence and machine learning, data such as muscle activity, balance, and stress levels of athletes were monitored using wearable sensors, and high-speed cameras and motion analysis systems were used to analyse risky movements in gymnastics and track and field branches (Soligard et al., 2023). Performance and health tracking systems are technological systems that enable athletes to maximise their performance while at the same time protecting their health. Using the Electronic Performance and Tracking System, players on the field were constantly monitored with three cameras, and instant data was accessed on tablets. Values such as respiration, heart rate and body temperature of athletes were obtained using smart jerseys, and fatigue score calculations were performed (The Government of Japan [GOJ], 2021). Orthopaedic and supportive technologies consist of technological products and systems such as orthoses, compression products, bionic supports, special insole systems and 3D-printed prosthesis solutions used to minimise the performance and injury risks of athletes. In the 2022 Qatar World Cup, carbon fibre protectors such as rib protection, wrist splints and knee braces for players with fragile bone structures and personal orthoses were used with 3D printers. Insoles with pressure sensors were used, and data such as muscle tension, joint angle and humidity/temperature were obtained with smart support bandages. Sprain-proof support technologies were used with advanced protection systems that provide special structures such as athletes' wrists inverted. Psychological health and neuro-rehabilitation technologies are technological systems used in athletes' performance, endurance, stress management and injury recovery phases, both in physical development and mental recovery and endurance (Mira et al., 2022). For example, at the 2020 Tokyo Olympics, athletes' mental levels, such as stress, anxiety, focus, etc., were analysed with neurofeedback systems, and training sessions were created for competition stress, lack of self-confidence and mental rehearsals with virtual reality therapies (IOC, 2021).

Video assistant referee (VAR) system

The video assistant referee (VAR) system is used in sports such as soccer to review referees' decisions and correct incorrect decisions. Replaying a position ensures that critical decisions such as goals, penalties, and red cards are made correctly. Referees review their decisions using feedback from assistant referees in the VAR room. The system uses footage from multiple cameras to identify and correct potential incorrect decisions (International Football Association Board [IFAB], 2025; FIFA, 2023a). The VAR system was first used at the 2018 World Cup in Russia (FIFA, 2023) and was integrated with semi-automatic offside technology at the 2022 World Cup in Qatar (FIFA, 2023a).

Rapid video review

The Rapid Video Review (RVR) system is a technology that allows referees and officials to replay key moments and review decisions quickly during a game. It is used in sports such as football, basketball, and tennis to evaluate athlete or team objections. It enables referees to verify their decisions during the game. The system was first used as part of the Video Assistant Referee (VAR) system during the 2018 FIFA World Cup in Russia. In the 2022 FIFA World Cup in Qatar, the semi-automatic offside system was used in combination with VAR and goal-line technology (Teixeira da Silva et al., 2024).

Goal detection

It is a technological system consisting of components such as sensors, cameras, lasers or radars that allow the location of a target, such as an arrow, bullet or ball, on a target board, field or line to be determined millimetrically. At the 2004 Athens Olympics, the system started to be used, especially in shooting and archery branches, and was standardised after the 2008 Beijing Olympics. At the 2012 London Olympics, the Hawk-Eye System was used for the first time in tennis (Uzor et al., 2023).

Artificial intelligence and machine learning

In order to improve referees' decisions, machine learning algorithms use data from past matches to help referees improve their decision-making processes. In the 2018 Russia World Cup, artificial intelligence (AI) and video analytics along with VAR, and in the 2022 Qatar World Cup, semi-automated offside technology and advanced AI-based video analytics were used (Rathi, 2020).

Simulation based referee training systems

Training systems created to improve the decision-making abilities of referees are systems that create simulations from data obtained from past matches and teach referees their decisions in such situations (van Beimen et al., 2023). Virtual training applications were used in the taekwondo discipline at the 2020 Tokyo Olympics (World Taekwondo Federation [WTF], 2020). For the 2024 Paris Olympics, an AI-based training program has been added that is personalised for referees IOC, 2024).

In-stadium experience technologies

These are technological solutions used with in-stadium experience technologies to ensure attendee satisfaction, increase revenues and digitalise the event. Smart ticketing and contactless entry systems enable participants to enter securely and contactlessly by using QR (quick-response), NFC (Near Field Communication) and facial recognition systems, etc. For example, face recognition entry systems and mobile ticketing were used in the 2022 Qatar World Cup. The experiences of the fans are enhanced by providing content, ordering, live statistics, etc., tailored to the seat numbers of the participants by personalising with mobile applications. For the 2020 European Cup, the UEFA (Union of European Football Associations) Euro 2020 App, which provides special content for fans, was used to enhance the user experience. With augmented reality and virtual reality technologies, participants can see player statistics, etc., with the glasses they use and have the opportunity to experience the match from different angles. At the 2020 Tokyo Olympics, a virtual

reality-supported match experience was offered. Thanks to uninterrupted internet such as Wi-Fi and 5G infrastructure in the stadium, social media sharing, live broadcasts and fast data consumption become possible. At the 2020 Tokyo Olympics, the use of 5G networks started, and AR and VR were used in broadcast technologies with 5G-supported remote monitoring systems due to the fact that the games were played without spectators. At the 2022 Beijing Winter Olympics, unmanned logistics robots and facial recognition systems supported by 5G took place. In the experience areas, interaction areas were created for fans, such as shooting simulations, photo booths and meeting athletes with hologram technology. By using smart seats and screens, fans can access options such as touch screens, charging areas and live broadcasts from their seats. At the 2022 Beijing Olympics, some special areas had heating, sensors, and adjustable seats, while the screens on the seats enabled multiple camera angles, information about athletes, scores, analysis, and food and beverage ordering (Glebova et al, 2023; Teal, 2024). Smart ticketing and NFC/RFID (Radio Frequency Identification) based access systems have sped up visitor traffic and are used to manage the exhibition area. Sensors integrated with the Internet of Things (IoT) system in the facilities have increased operational efficiency by monitoring environmental parameters, such as energy consumption, occupancy rates, and waste accumulation, in real time. Additionally, emergency evacuation plans have been simulated using digital twin models for early intervention planning (Andhale et al., 2020; Chowdhury et al., 2016).

Digital and virtual interaction technologies

Digital and virtual interaction technologies are among the technological solutions used to involve fans in activities in the digital world. Technologies such as augmented reality and virtual reality, virtual stadiums, social media integrations and finally, fan token and blockchain technologies are used. With augmented reality and virtual reality technologies, fans are used in areas such as viewing statistics from the stands, social media content production with augmented reality filters and virtual souvenir photo corners. It has also been used in games such as virtual stadium viewing with virtual reality glasses, virtual locker room tours and penalty kicks with augmented reality. In the UEFA 2020 European Cup, augmented reality glasses were used to view the information of the players from the stands. At the 2020 Tokyo Olympics, matches were watched 360 degrees with virtual reality glasses, and at the 2018 Russia World Cup, the BBC's VR application was used to watch the matches from different angles. With social media integrations, there are areas of use, such as Instagram filters of the teams that fans can apply, participating in live comments, voting, hashtag campaigns and live videos. In the 2022 Qatar World Cup, 5 billion social media interactions were recorded, and in the 2020 Tokyo Olympics, 3.5 billion people followed the games on digital platforms. Over forty augmented reality filters have been developed by Instagram. In addition, many hashtags (#WorldCupDance, #Tokyo2020, #Qatar2022) were used in mega organizations. Virtual stadium technologies include content such as 360-degree camera systems of matches, virtual stands created with 3D modelling, real-time statistics panels and individual experiences such as seat selections. At the 2020 Tokyo Olympics, some competitions could be watched virtually with augmented reality technologies. At the 2022 Beijing Olympics, a virtual Olympic city was established, and with the Virtual Fan Fest experience implemented at the 2022 Qatar World Cup, people were able to watch matches, dance and chat in a three-dimensional environment. Fan tokens and blockchain technologies, along with crypto-based assets, have been used to interact with clubs and participate in decisions such as participating in surveys, digital uniforms, collectibles, and player and goal music selections. In the 2020 European Championship, fan tokens were used for the first time in an international tournament with the partnership with Socios (Avcı et al., 2023; Goebert and Greenhalgh, 2020; Pickman, 2023; Union of European Football Associations [UEFA], 2025).

Data and personalization technologies

With data and personalisation technologies, artificial intelligence, wearable devices and real-time data systems are being used in mega sports organizations to enhance the performance of athletes and enrich fan experiences. The 2022 Qatar World Cup featured an AI-powered data analysis application that allows each player on the field to be tracked 50 times per second from 29 different points, the FIFA Player App, an AI offside system and personalised fan applications. At the 2020 Tokyo and 2024 Paris Olympics, technological processes such as facial recognition and biometric access systems for athletes and officials, offering special content by analysing the analysis of users' preferences through artificial intelligence-based personalisation, and instant broadcasting of athletes' performances using wearable devices (Dudek et al., 2025; Lloyd-Smith, 2024).

Gamification and interactive experiences

In order to increase the fan experience in mega sports organizations, gamification and interactive experiences are used to reach large audiences on both physical and digital platforms by ensuring the active participation of the audience in the events. At the 2022 Qatar World Cup, the Hayya Fan App application was used to enrich the fan experience, enabling them to participate by earning points through virtual quizzes, score predictions and daily tasks. With the Fantasy game organized in the UEFA Champions League, fans were included in the event, allowing users to create virtual teams and collect points based on real match performance (UEFA, 2024).

Digital management systems

These are the technological systems used in the planning of mega sports organizations, audience experience, etc., to make the organizations more efficient, safe and interactive. With organisation and logistics management, the human and material resources that participate in mega sports organizations are brought together in a coordinated manner, and outputs are obtained from them. In this way, a smooth process is tried to be created with the effective use of the organisation's resources (Glebova et al., 2023). At the 2024 Paris Olympics, centralised information and interaction were provided between athletes, coaches, commentators, fans and organisation partners. At the 2024 European Football Championships, the use of digital management systems ensured the smooth running of the organisation and enabled fans to participate more in the events and personalise their experience (IOC, 2024; UEFA, 2024a). In mega sports organizations, broadcasting and media management using digital management systems are used to deliver events to audiences all over the world. The 2020 Tokyo Olympics marked a turning point in terms of digital transformation in broadcasting. In this Olympics, the OBS Cloud platform was developed in cooperation with Olympic Broadcasting Services (OBS) and Alibaba Cloud, and the content production and distribution processes of broadcasters were realised on a cloud-based basis. In this way, broadcasters were able to access content remotely and set up their own content production systems on the platform. For the 2024 Paris Olympics, the third version of the OBS Cloud platform (OBS Cloud 3.0) was used. Thanks to this platform, broadcasters' content production and distribution processes have become more efficient with artificial intelligence-supported cloud technologies. In addition, with virtual production tools and remote access, publishing operations have become more flexible and effective (Alibaba Cloud, 2021; Laemle, 2024). Artificial intelligence and automation technologies are used to improve broadcast quality, ensure efficiency and further enrich the audience experience. At the 2024 Paris Olympics, the Olympic Broadcasting Services (OBS) produced more than 11,000 hours of content with the use of AI technologies. These technologies were used in processes such as real-time statistics, personalised advertisements and automatic display of key moments (IOC, 2024d). In addition, 360-degree replays with Alibaba, AI-supported data explanations with Omega and fast highlights with Intel were created through collaborations (Bevir, 2024).

Smart stadiums and facilities

Smart stadiums and facilities consist of high-speed internet connections, 4K and 360-degree camera broadcasting systems, virtual reality and augmented reality (Cha, 2020). At the 2020 Tokyo Olympics, the smart city concept was integrated into stadiums, where live statistics and replays were provided to spectators with 5G and high-speed connectivity, athletes and officials were transported by autonomous vehicles, and robots were used for food service and welcoming (IOC, 2022a). At the 2022 Beijing Olympics, the movements of athletes were analysed and detailed performance data were obtained with AI-powered performance analysis, and high-quality broadcasting and data transmission were achieved with 5G and Internet of Things integration in the stadiums (IOC, 2022; Sampedro, 2023). At the 2024 Paris Olympics, crowd movements were monitored instantaneously with artificial intelligence-supported crowd management systems, and security was ensured through predictive analysis. It also supported crowd guidance systems with sensors placed in the stadiums and was built with energy efficiency using innovative recycled materials, such as Adidas Arena (IOC, 2024b). Paris 2024 has gone down in history as the first Olympics to broadcast live in 8K resolution. In collaboration with OBS and Intel, global live broadcasts were made with 50 Mbps bandwidth and an average delay of 400 ms (Olympic Broadcasting Services [OBS], 2024).

Energy management systems

These are technological systems that enable the effective use of renewable energy resources with fixed and mobile energy storage systems in order to optimise energy consumption and reduce carbon footprint in mega sports organizations. At the 2020 Tokyo Olympics, ISO 20121 certification standards have been set. Some of the energy needs were met through the use of renewable resources such as solar energy and biomass, and efficiency was achieved through smart meters and Internet of Things technologies. At the 2022 Beijing Olympics, with the carbon neutrality target, all facilities were operated with 100% renewable electricity, 800 hydrogen-fuelled vehicles were used for transportation and ISO 20121 standards were adopted (IOC, 2020). At the 2024 Paris Olympics, similar systems were used to reduce the carbon footprint by 54.6% compared to previous Olympics (IOC, 2024a). Prior to the 2022 Qatar World Cup, it activated the first large-scale solar power plant with a capacity of 800 MW, directed the air produced by large solar-powered absorption chillers into the stadium, and achieved high standards in environmental sustainability by obtaining Global Sustainability Assessment System (GSAS) certification (Méndez and Biçer, 2020; FIFA, 2022a).

Security systems

Advanced security systems are used in mega sports organizations to ensure the safety of participants and spectators. Along with these systems, technologies such as facial recognition, drone surveillance, smart access control systems and crowd management are significantly effective in the smooth management of these organizations. At the 2020 Tokyo Olympics, security was increased by speeding up identity verification processes using facial recognition technologies in all event areas, autonomous security robots were used, and approximately 450 million cyber attacks were prevented (Government Technology, 2021). At the 2022 Beijing Olympics, integrated surveillance systems were used in the event venues, ensuring border security and high levels of electronic surveillance (Ji et al., 2022). At the 2024 Paris Olympics, approximately 300 AI-powered security cameras were used to detect potential threats between spectators and athletes, and cybersecurity measures were strengthened and training was provided (Laanstra-Corn and Sewell, 2024; Popek, 2024). Facial recognition systems were not used in Paris 2024. Instead, AI-powered, algorithmic video analysis systems were used to monitor for behavioral anomalies (crowd movement, abandoned items, suspicious behavior, etc.) and generate alarms. These systems were tested with approximately 480 cameras in

accordance with France's “Loi JO 2024” law, which was passed in 2023 (Garzon Valenzuela, 2024;).

Training technologies

Educational technologies help participants learn their tasks and gain hands-on experience by using online training platforms and virtual simulations to ensure the best preparation of athletes, coaches, referees, organisational staff and volunteers. Training technologies include virtual and augmented reality as well as wearable technologies. At the 2020 Tokyo Olympics, the Yoi Don! training programme was used to increase students' interest in the Olympics, and Intel VR training systems were used to train managers who will take part in the competitions (Association of National Olympic Committees [ANOC], 2017). At the 2024 Paris Olympics, AI-supported training tools aimed to enable volunteers to fulfil their tasks more effectively (IOC, 2024e).

Preparation technologies

Using preparation technologies, athletes used digital tools and software in processes such as event planning, logistics management and time management. In addition, with the use of virtual and augmented reality technologies, it has enabled the event areas to be experienced beforehand and possible problems to be simulated. In this respect, it is effective in increasing organisational efficiency and preventing possible disruptions. At the 2018 PyeongChang Olympics, Samsung used clothes equipped with sensors that transmit body position data for Dutch speed skaters to determine the appropriate posture positions of the athletes. In addition, VR systems developed by STRIVR for US skiers allowed them to virtually experience the race tracks (Avcı, 2023; Cossich, 2023; Pickman, 2023; Zhao, 2023). At the 2020 Tokyo Olympics, the 3DAT technology developed by Intel was used to analyse performance with artificial intelligence and computers (Centre for European Studies of Technology [CEST], 2024; IOC, 2019).

Analysis technologies

Analysis technologies are used to monitor and analyse the performance of athletes before and during organizations. These systems are used to analyze competitions in depth and to identify details that may be overlooked during the game. At the same time, it is often used to identify the mistakes or positive aspects of athletes in training and competition. One of these technologies, artificial intelligence and machine learning, is used to make important evaluations in terms of injury predictions, performance and skill levels of athletes. These previously mentioned technologies were used in the 2022 Qatar World Cup and the 2024 Paris Olympics. Big data and sports analytics technologies will be used to analyse and improve the performance of athletes; they are used to monitor their physical condition, training efficiency and fatigue levels, while coaches are used to create appropriate training programmes and to analyse the tactics of teams and opponents during matches. It was first used at the 2012 London Olympics (FIFA, 2022). At the 2022 Qatar World Cup, AI-powered video surveillance systems were used for analysis, and at the 2024 Paris Olympics, organisers used data analytics for game planning and optimising operations. With the use of wearable technologies, it has been frequently preferred to monitor athletes' physical performances simultaneously. Smart watches, one of these technologies, have been used to determine heart rate, sleep hours and stress levels. The data obtained from these devices are directly related to athletes' injuries, health data monitoring and performance analytics (Laursen, 2024). At the 2014 World Cup, smartwatches were integrated into the GoalControl system used to verify referees' goal decisions. At the 2020 Tokyo Olympics, multi-sensor wearables were used to determine athletes' heart rate, body temperature and muscle activity (Avcı et al., 2023). In the 2024 Paris Olympics, GPS vests were used to collect data such as speed, distance and direction of players in sports such as football, volleyball and basketball, and smart glasses and sensor clothing were used to evaluate the technical performances of athletes in sports such as swimming and to determine technical errors (IOC, 2024c).

Future Sports Technologies in Mega Sports Events

The ideas put forward for the technologies to be used in mega sports organizations in the future will be based primarily on the technologies used today, as well as the ideas of some companies producing products and services for sports technologies and the technologies planned to be used in organizations.

In the future, research is being conducted to predetermine the characteristics of athletes, such as endurance, strength and injury susceptibility. Its use for training or performance prediction in research for this process has only recently begun. It is thought that these applications will come to an important point in the future in detecting musculoskeletal injuries of athletes and personalising training programmes. With the development of robotic exoskeletons and treatment devices, robotic rehabilitation technologies have been shown to provide rapid improvements in muscle strength, balance and endurance in clinical trials, and these technologies are expected to develop further. With virtual reality training, athletes' tactical decision-making, reflex and stress management skills will be further improved by simulating realistic scenarios in a safe environment.

In terms of performance monitoring and analysis, wearable sensors will be distributed to all athletes in the future, and training programmes can be personalised by obtaining simultaneous data on heartbeat, GPS, muscle activity and artificial intelligence-based analysis. Biometric scans and AI systems can be used for health monitoring and injury prevention. Advanced therapy centres can take part in the rehabilitation and rapid recovery processes of athletes. Athletes' hospital stays can be reduced with robotic walking devices, hyperbaric oxygen therapy and customised physical therapy programmes. In the future, health screening can be done even underwater using artificial intelligence in water sports. Considering that developments in athlete performance and health technologies are becoming more widespread every day, it is thought that technological developments such as wearable sensors, artificial intelligence and augmented and virtual reality systems will be used much more in mega sports organizations in areas such as protection of athlete health, prevention of injuries and performance enhancement.

It is thought that artificial intelligence-supported fully automatic decision systems will be used in football in the future. With the developed ball sensors, it can be used to automatically draw offensive and penalty area lines in the future. With artificial intelligence, positions can be detected by video analysis, and images and statistics can be delivered to referees using devices such as referee glasses or augmented reality. In athletics, with the use of fully automated systems and artificial intelligence, positions can be analysed and rule violations can be identified. Augmented reality glasses can be used to provide referees with information such as instant pace information, differences between athletes and shooting statistics. Injustices can be reduced by instantly displaying the distance of the shot with data sensors. With the further development of sensors located in the starting blocks in water sports, the body weight distribution of athletes can be monitored so that violations such as getting up early or pulling a helper by hand can be detected. With augmented reality technologies, decision support with virtual lines placed on the field, match statistics, rule summaries, and instant synchronised and telescopic views of the referee with glasses can be provided. In the future, the rules can be tracked with sensors placed in balls, rackets or sneakers. A transparent and secure process can be ensured with the use of blockchain technologies in recording referee decisions. Robotic or fully automated referee applications can be used in mega sports organizations in the future.

It seems likely that there will be some changes in terms of fan experience and interaction technologies in the future. The use of wearable devices to measure fans' biometric data in real time and include them in events, and the inclusion of the obtained data in social media posts and stadium shows, may be important in terms of strengthening fan loyalty. In addition, with the use of

systems such as facial recognition, it is thought that the usage areas of developments such as stadium entrances and contactless payments will increase. By using artificial intelligence, big data and algorithms, special content can be offered for fans. It is also thought that the use of chatbots will increase. Metaverse and virtual stadium experiences will improve the processes of watching the match from different angles and with friends in different parts of the world. 360-degree virtual stadium interactions will develop using augmented and virtual reality lenses. In the distant future, using Neuralink-like systems, the match can be watched mentally, and even mental activities such as camera angle, data display and goal warning can be performed using mental commands. Special artificial intelligence avatars can be defined for fans. Fans' pulse, sweating and excitement can be analysed using smartwatches or implants. Special camera angles, sound effects and personalised music can be used in moments of high emotional intensity. With quantum internet technologies, streaming delays can be reduced to near zero. By using holographic replicas, processes that can be played in stadiums in different parts of the world will develop. Hybrid Olympics could emerge. By using emotional simulations, sounds such as wind, stadium sounds, etc., can be physically felt, and the feeling of being there at that moment can be experienced. With the use of holographic projection systems, matches can be watched as 3D holograms.

In terms of event management and logistics, artificial intelligence-supported systems can be used in material procurement and transportation processes, and the tracking of materials can be done further through sensors with Internet of Things technology. In the future, smart wristbands or facial recognition systems can be used for everyone attending mega sports organizations, and biometric doors are expected to become widespread for access to VIP areas. Wireless sensors will increase in stadiums and facilities, and robotic security dogs and patrol drone systems will be integrated with camera systems. Artificial intelligence-supported content production, multi-channel broadcasting and user control technologies will be implemented.

Green energy solutions, environmentally friendly building designs and circular economy principles will be further developed in organizations. The modular design and construction of new stadiums and facilities and their relocation to other regions after the event, the use of foldable stands, disassembled renewable energy panels and water recycling systems will increase and even become standardised. 6G networks planned for use after 2030 will enable worldwide satellite connectivity and holographic communication.

Image processing and machine learning will increase automated processes in referee decisions. In addition, it is thought that AI-supported assistant coaches who can give strategic suggestions during the match will become widespread. Artificial intelligence-supported sensors and bioelectronic applications can be used to monitor the health and performance data of athletes, and new types of eyewear devices can be used to allow the audience to see the data of the athlete they are looking at.

With the development of artificial intelligence, in the future, deep learning-based video analysis will reach higher resolutions, player and ball tracking can be done more accurately, customised training for athletes with health data, and artificial intelligence coaches can be used by processing data in training and matches with cloud and 5G technologies. In the future, it is thought that devices that can track values such as blood sugar or lactate, as well as detect hydration and fatigue levels by measuring sweat analysis, electrolyte and metabolite levels by using online sensors and biotextile products in blood in biometric analyses, will become widespread. In the future, hybrid trainings can be realised with the development of the concept of mixed reality (XR) and the process of users experiencing the virtual and real worlds uninterruptedly. With virtual and augmented reality applications, it is thought that training can be shared live from anywhere in the world, virtual gyms can be collaborated in, and distance learning and even virtual competitions can be organised through metaverse-based simulations. Using 5G and Wi-Fi 6 connections, the data obtained with

video and sensors during training sessions will be processed instantly and made universally accessible using cloud-based services. In the future, it is thought that data-based individual performance management will be at the forefront in training, preparation and analysis technologies for mega sports organizations. The creation of digital twins of athletes can be used to test training scenarios of these twins in a virtual environment and to create the most efficient training strategies. The increase in the computational capabilities of artificial intelligence technologies will enable technologies such as automated coaching assistants and biomechanical analysis robots to assist in training and in matches.

DISCUSSION and CONCLUSION

This research evaluated the technologies that will be used at future mega sports events. First, the technologies used in mega sports events were examined within the scope of the research. Information was collected by reviewing news sites, event websites, technology company websites, event reports, and event videos. This study evaluated mega sports events from the perspectives of their past, present, and future and observed that changes have occurred in parallel with technological development in these events. All processes carried out before, during, and after mega sports events were examined, as well as the technologies involved from the perspectives of all stakeholders, including participants, sponsors, and fans. These were examined under five main headings. It is undeniable that these technologies significantly impact record-breaking, experience enhancement, and error minimisation in sports.

The research conducted has resulted in the classification of the technologies used in mega sporting events. According to this classification, they fall into one of the following five categories: Athlete Performance and Health Technologies; Refereeing and Decision Support Systems; Fan Experience and Interaction Technologies; Organisational and Infrastructure Technologies and Training, Preparation and Analysis Technologies.

Examining athlete performance and health technologies reveals significant developments, including the use of the LZR swimsuit at the 2008 Beijing Olympics. Athlete information tracking systems were used at the 2016 Rio Olympics. The 2020 Tokyo Olympics featured 3D systems, athlete tracking systems, and some artificial intelligence applications. At the 2024 Paris Olympics, artificial intelligence-supported performance and injury tracking using wearable sensors began to be used. Each Olympics has taken a step forward from the previous one, with an increase in the scope of technological applications. These technological advances in monitoring athletes' performance and health make it possible to prevent injuries and guide the physical and mental rehabilitation of athletes in adverse situations. These technologies will prevent athletes from experiencing irreversible health problems in the future.

Examining referee decisions and support systems, for example, reveals that goal-line technology was first used in the 2012 World Cup in Japan, VAR was first used in the 2018 World Cup in Russia, and sensor-equipped balls and artificial intelligence–supported systems were first used alongside VAR in the 2022 World Cup in Qatar. Implemented to enhance referees' ability to make accurate and fair decisions, these systems have been further developed in each subsequent tournament. In the future, advancements in artificial intelligence within these systems will make it easier to detect rule violations and prevent referee errors.

In terms of fan experience, the 2004 Athens Olympics used cable TV, the 2016 Rio Olympics used 4K Ultra HD broadcasts, and the 2020 Tokyo Olympics used 8K broadcasting, AR glasses, interactive seats, smart screens, and real-time 5G data communication. Additionally, as mobile technologies and social media applications have developed, so have the entertainment tools fans use, such as apps. From this perspective, it is clear that fan experiences are becoming more diverse at every major event

to enhance the experience. The process began with television broadcasts, the first development to influence the growth and globalisation of mega sports events. Now, technological developments such as streaming broadcasts and 5G internet have taken over. In the future, processes such as holograms, quantum computers, and internet or mental match viewing will evolve. The rapid development of sports technologies and the resulting changes will increasingly emphasise their importance within the sports industry. Technological systems and changes aimed at enhancing fan experiences and interactions, whether at home or at physical events, will play a significant role in helping participants enjoy themselves and create memorable experiences.

Significant advances have been made in the areas of organisation and infrastructure, particularly with regard to the internet and mobile devices. Additionally, major technological developments have occurred in areas such as security and energy Management Systems and smart sports facilities. Technologies used in previous Olympics include the visual systems used in the 2000 Sydney Olympics; technological recycling; facial recognition technology; robot technology; autonomous vehicles; and recyclable cardboard beds in the 2020 Tokyo Olympics, as well as smart stadium technologies, interactive seats, smart screens, and 5G internet in the 2024 Paris Olympics. These technological developments facilitate the smooth running of mega sporting events before, during, and after the event. In the future, technological developments in organisation and infrastructure will enable significant strides in event management and increased security systems with artificial intelligence applications, as well as the implementation of carbon-neutral events.

Video analysis software, wearable technologies, augmented reality, GPS, virtual reality, and image processing systems are used to examine training, preparation, and analysis technologies for mega sporting events. Technological developments in this area began with stopwatches and progressed to video analysis systems and, later, real-time data analysis. Off-field wearable devices were developed for the first time in the 2004 Athens Olympics. Live measurements were provided on the field in the 2008 Beijing Olympics. Artificial intelligence and sensors were used in the 2020 Tokyo Olympics. In the 2024 Paris Olympics, artificial intelligence-supported analyses were used in conjunction with 3D motion analysis systems, GPS, and accelerometer systems. In the future, hybrid systems will be used to prepare athletes, coaches, referees, organisational staff, and volunteers in terms of education, preparation, and analysis technologies. Additionally, data obtained from analyses of athletes, referees, and coaches will frequently be used to determine training, performance, and technical errors.

Clearly, the organisation of mega sporting events transcends the digital age in terms of social, economic, environmental, and technological developments. Future technological developments will mirror the evolution of these events. Examining past mega sports events reveals that the sports technologies employed have developed in tandem with global technological advancements and been integrated into sports. This integration is anticipated to be applied in vastly different fields in the future, significantly contributing to the growth of the sports industry.

This research is a compilation study on technologies used in mega sporting events and those that may be used in the future. As a result of this research, future studies can examine the economic impacts of technologies used in mega sports events, the role of technological developments in terms of sustainability and sports heritage, the role of technology in social perception and participation, the transformation brought about by digital transformation in mega sports events, the impact of technology on Olympic values from the perspective of athletes, and finally, the role of technology in terms of climate change and environmental factors.

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