International Journal of
Digital Rehabilitation & Therapy
e-ISSN:
https://ndpapublishing.com/index.php/ijdrt

The Future of Artificial Intelligence and Sports Rehabilitation: A Digital Transformative Perspective

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Keywords
Artificial Intelligence
Sports Rehabilitation
Wearable Technologies
Machine Learning
Virtual Reality

ABSTRACT

Sports rehabilitation is a critical process for injured athletes to regain their physical and functional capacities. In recent years, the advancement of artificial intelligence (AI) technologies has led to revolutionary changes in sports rehabilitation. This article examines the integration of AI into sports rehabilitation and its potential transformative role in the future. AI algorithms analyze athletes' injury data to provide faster and more accurate diagnoses. Machine learning models combine imaging techniques (MRI, ultrasound) and biomechanical data to create personalized rehabilitation programs. Wearable technologies and IoT-based sensors track athletes' movements, muscle activity, and recovery process in real time. AI analyzes this data to offer optimized exercise recommendations to coaches and physiotherapists. Robotic support systems and virtual reality (VR) enable athletes to perform rehabilitation exercises in a controlled environment. AI, integrated with these technologies, accelerates motor learning and improves the accuracy of repetitive movements. By examining athletes' performance and health data, AI can predict potential injury risks in advance, allowing preventive interventions to reduce the likelihood of injuries. However, as AI becomes more widespread in sports rehabilitation, challenges such as data privacy, algorithmic biases, and ethical concerns arise. Therefore, transparent and secure AI systems must be developed. In conclusion, AI is shaping the future of sports rehabilitation by offering faster recovery, personalized treatments, and injury prevention strategies. However, a multidisciplinary approach is essential to ensure these technologies are used effectively and safely.

1. INTRODUCTION

Sports injuries are a significant issue that can profoundly impact the careers of both professional and amateur athletes. Traditional rehabilitation methods sometimes fall short due to lengthy recovery periods and non-personalized approaches. However, with the advancement of artificial intelligence (AI) technologies, a new era in sports rehabilitation has begun. This article explores the integration of AI into sports rehabilitation and its future potential, supported by literature. Today, AI technologies are leading revolutionary changes in the field of sports rehabilitation. The data analytics, machine learning, and computer vision capabilities offered by AI are surpassing the limitations of traditional methods, particularly in diagnosing sports injuries, personalizing treatment processes, and monitoring rehabilitation. AI-assisted systems stand out for their accuracy and efficiency in helping professional athletes regain their performance [1].

Sports rehabilitation is a critical process requiring a multidisciplinary approach. AI supports the decision-making mechanisms of physiotherapists and sports physicians, enabling them to develop patient-specific treatment protocols. For example, real-time data from wearable technologies, processed by AI algorithms, can detect even the slightest anomalies in an athlete's recovery process [2]. Additionally, VR and augmented reality (AR)-based AI applications enhance the effectiveness of rehabilitation by accelerating motor learning [3]. However, AI's role in sports rehabilitation is not limited to treatment. Predictive analytics models can forecast athletes'

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How to cite this article
Demirci, N. (2024). The Future of Artificial Intelligence and Sports Rehabilitation: A Digital Transformative Perspective. Int. J. Digital Rehabilitation & Therapy, 1(1), 25-32.

Research Article/ DOI: 10.5281/zenodo.15510000

future injury risks and contribute to developing preventive strategies [4]. This offers significant potential for extending athletes' careers and achieving sustainable performance. Nonetheless, it is important to remember that these technologies also bring challenges such as ethics, data security, and clinical validity. In this article, we examine the intersection of AI and sports rehabilitation, evaluating future developments and current limitations in light of the literature.

2. THE ROLE OF ARTIFICIAL INTELLIGENCE IN SPORTS REHABILITATON

2.1. Personalized Rehabilitation Programs

AI can analyze a patient's physical condition to create personalized rehabilitation plans. Machine learning algorithms evaluate a patient's movement data to determine the most suitable exercises [5]. For example, Microsoft's Project Emma, developed to reduce hand tremors in Parkinson's patients, demonstrates how similar technologies can be applied to sports injuries.

2.2. Personalized Rehabilitation Programs for Sports Injuries

The rehabilitation process for sports injuries must be personalized based on the type and severity of the injury, as well as the athlete's characteristics. Personalized rehabilitation programs are crucial for ensuring a safe return to sports and minimizing the risk of re-injury. This article outlines the stages, fundamental principles, and an example rehabilitation plan in table format.

2.2.1. Fundamental Principles of Personalized Rehabilitation

Personalized rehabilitation programs are determined based on the following factors [6]:

- **Athlete's physical characteristics:** age, gender, fitness level
- **Type and severity of injury:** e.g., ligament tear, muscle strain, fracture
- **Sport-specific requirements:** agility, strength, endurance
- **Psychological factors:** motivation, fear-avoidance behavior

2.2.2. Rehabilitation Stages

Personalized rehabilitation typically consists of three main stages [7].

Table 1. Personalized rehabilitation stages

Stage	Goal	Applications
Acute Phase (0-1 week)	Reduce pain and swelling, maintain joint mobility	PRICE protocol (Protection, Rest, Ice, Compression, Elevation), light mobilization
Subacute Phase (2-6 weeks)	Improve strength and flexibility	Resistance exercises, proprioception drills, light functional movements
Functional Phase (6+ weeks)	Regain sport-specific skills	Plyometric exercises, sport-specific training, balance drills

Table 2. Example of a personalized rehabilitation program following an anterior cruciate ligament (ACL) injury [8].

Time	Goals	Exercises
0-2 Weeks	Maintain joint mobility	Quadriceps activation, passive extension, stationary cycling
3-6 Weeks	Increase muscle strength	Mini squats, step-ups, hamstring curls
7-12 Weeks	Improve proprioception	Single-leg balance, Bosu ball exercises
12+ Weeks	Prepare for return to sports	Agility drills, jumping and plyometric training

2.2.3. Personalization Criteria

Factors to consider when personalizing a rehabilitation program:

- **Physical Assessment:** Muscle imbalances, joint stability [9].
- **Sport-Specific Requirements:** Agility for soccer players, shoulder stabilization for swimmers.
- **Biomechanical Analysis:** Evaluation of running or jumping mechanics [10].

3. Real-Time Performance Analysis

Thanks to sensors and computer vision systems, athletes' movements can be monitored in real time. This allows for immediate detection of incorrect movements, reducing the risk of injury [11]. For example, wearable technologies used by some FIFA clubs analyze players' load data to prevent injuries [12].

3.1. Real-Time Performance Analysis in Sports Injuries

Real-time performance analysis is increasingly used to prevent sports injuries and optimize performance. This analysis monitors athletes' movements, biomechanics, and physiological responses in real time using sensors, wearable technologies, and AI-assisted systems to reduce injury risk.

Table 3. Key components of real-time performance analysis

Component	Description	Technologies Used
Motion Analysis	Measurement of joint angles, speed, and acceleration.	IMUs (Inertial Measurement Units), GPS, camera systems
Load Analysis	Determination of loads on muscles and joints.	Pressure sensors, force platforms
Physiological Monitoring	Parameters such as heart rate, oxygen consumption (VO_2 max), lactate levels.	Heart rate sensors, wearable ECG devices
AI Models	Data processing for injury risk prediction.	Machine learning algorithms (LSTM, CNN)

3.2. The Role of Real-Time Analysis in Injury Prevention

Real-time performance analysis contributes to injury prevention in the following ways:

- **Detection of Abnormal Movements:** For example, if a soccer player's knee joint stress levels are high during sudden turns, ACL injury risk can be identified [13].
- **Monitoring Fatigue and Overuse:** Repetitive movements (running, jumping) in athletes can lead to tendon damage. Training intensity can be optimized using real-time data [14].
- **Tracking Rehabilitation Progress:** Monitoring movement quality during an athlete's return from injury reduces re-injury risk [15].

Real-time performance analysis is revolutionary in preventing sports injuries. Advances in **machine learning and IoT-based systems** will enable more accurate determination of individual risk profiles. However, data security and ethical considerations must also be addressed.

4. ROBOTIC SUPPORT AND VIRTUAL REALITY

Robotic devices and virtual reality (VR) applications in rehabilitation enhance patient motivation and accelerate recovery. For example, robotic exoskeletons developed by Ekso Bionics assist paralyzed patients in walking and are also used in sports rehabilitation [16].

4.1. Robotic Support and Virtual Reality Applications in Sports Injuries

Sports injuries are common among both professional and amateur athletes. In addition to traditional methods, **robotic support systems** and **virtual reality (VR) technologies** are increasingly used in treatment and rehabilitation. These technologies speed up recovery, increase patient motivation, and provide objective data to physiotherapists, enhancing rehabilitation effectiveness.

Robotic rehabilitation devices are particularly used to restore mobility in joint and muscle injuries. These systems support patient movements, ensuring proper muscle activation and preventing overexertion [17]. Walking robots like **Lokomat** are effective in regaining walking function after lower extremity injuries [18]. Hand and arm robots help improve range of motion in shoulder and elbow injuries [19]. Robotic systems measure patient performance in real time, providing data to therapists and enabling personalized treatment protocols.

4.2. Rehabilitation with Virtual Reality (VR)

Virtual reality technology is used in sports injury rehabilitation as a motivational tool that encourages participation in treatment. VR makes the monotonous rehabilitation process more engaging by encouraging patients to exercise in virtual environments [20].

- **Motor Learning and Coordination Development:** VR-based simulations help athletes regain balance and coordination skills
- **Pain Management:** VR distracts chronic pain patients from pain, facilitating rehabilitation [21].

In recent years, hybrid models integrating robotic rehabilitation devices with VR systems have been developed. These systems combine the physical therapy benefits of robotic support with the motivational and cognitive advantages of VR, optimizing the treatment process [22]. Robotic support and VR applications in sports injury treatment complement traditional rehabilitation methods. These technologies shorten treatment times, improve patient compliance, and enhance

functional recovery. In the future, integrating AI and augmented reality (AR) technologies will enable even more personalized solutions in sports rehabilitation.

5. THE USE OF DIGITAL TECHNOLOGY IN REHABILITATION

The rapid growth of digital technologies in the field of medicine offers a unique solution to address concerns about accessibility in healthcare services [23]. A significant urban-rural divide exists in a large portion of countries worldwide, and there are deficiencies in rehabilitation services [24]. Digital technology in medicine has the potential to globally and significantly impact the accessibility and management of non-communicable diseases. This may include preventive, curative, and rehabilitation measures. The use of technology in the form of teleconsultation and health applications can overcome financial, temporal, and geographical barriers ([225. The implementation of digital technology offers unique advantages for densely populated yet resource-scarce countries. Features such as tool automation, data synchronization, and rapid information sharing with multiple stakeholders enable cost- and time-effective evaluation of large populations. Additionally, with improved online access to specialists, the likelihood of regular developmental screenings, early diagnosis, and monitoring of disability progression increases for individuals across all socio-economic strata [26]. Thus, such innovations have the potential to enhance access to services, promote good health and well-being for all, and reduce inequalities within and among communities and countries.

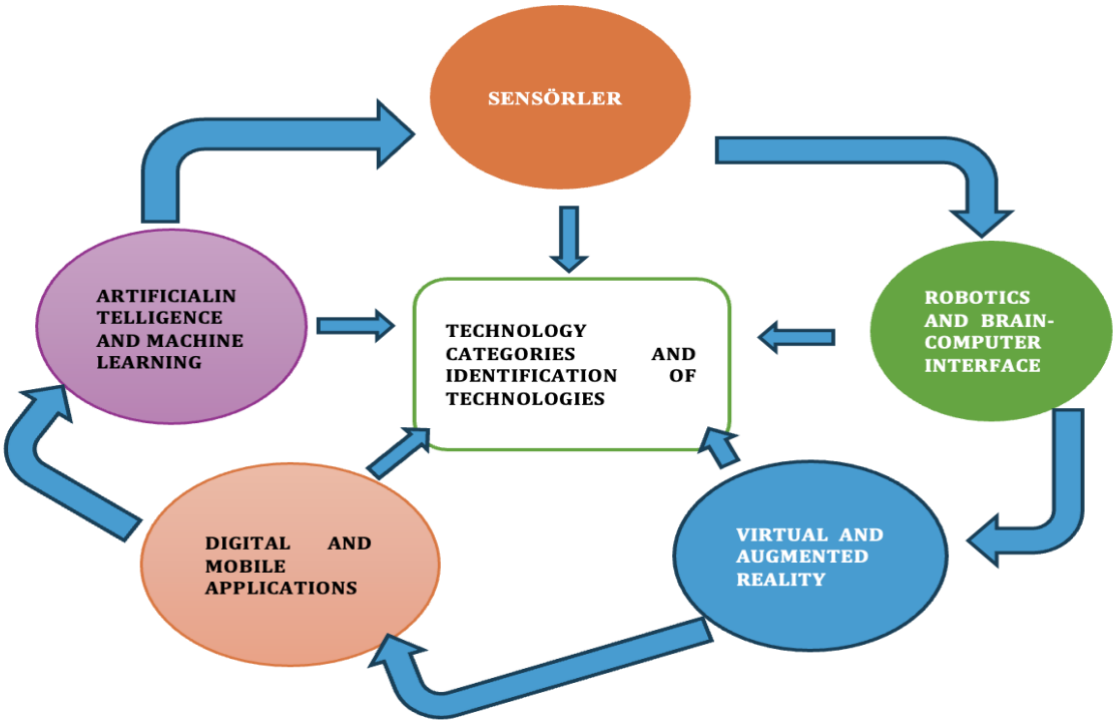

Figure 1. Technology categories and identification of technologies

Digital rehabilitation can be defined as the use of digital technologies as part of the rehabilitation process. Digital rehabilitation aims to optimize the functions of disabled individuals with health problems in interaction with their environment and to reduce their disabilities [27]. This includes, but is not limited to, the use of digital technology applications solutions used in rehabilitation services for the disabled, including technological and remote rehabilitation applications and services, mobile phones, computers, wearable and non-wearable technologies, sensors, 3D printers, robotics, Artificial Intelligence (AI), internet technologies, websites and applications, virtual and augmented realities and computer games, robot-assisted technologies, wearable devices, e-mails, video.

Table 1. Use of digital technology in rehabilitation

Technology Categories and Definitions	Application Features	Advantages	Disadvantages or Limitations
SENSORS			
Inertial Sensors [28].	Measurement, evaluation, and monitoring of movement, motor activity, gait analysis, falls, blood flow, and respiratory rate; control of keyboards and screens via motion coding; assistance in communication for hearing-impaired individuals.	Relatively inexpensive, portable, user-friendly, provides accurate and fast motion data for rehabilitation analysis; simple working principles.	Accuracy loss due to sensor placement, skin contact reliability, or interaction effects; requires multiple sensors for precise measurements.
Inertial Measurement Unit (IMU) [29].	Measurement, evaluation, and monitoring of movement and posture; fall prediction and biofeedback.	Compact design, low cost, easy to use, captures 3D linear acceleration and angular velocity for comprehensive motion analysis.	Requires at least 3 sensors for accurate measurements; attachment and reattachment can be cumbersome.
Accelerometer [30].	Measurement of movement, motor activity, physical activity, posture, respiratory rate, steps, falls, sleep, and gait analysis.	Captures linear acceleration in 1-3 planes, immune to magnetic interference, low cost, easy to attach.	Sparse data collection, often requires multiple sensors.
Electromyography [31].	Measurement of heart rate, gait analysis, motion coding for keyboards and screens; assistance in communication for hearing-impaired individuals.	Commercially available, low cost.	Often requires inertial sensors for bioelectric signal measurement.
ROBOTICS AND BRAIN-COMPUTER INTERFACE			
Robotic Gloves [32].	Measurement, evaluation, and monitoring of motor function; support for hand and finger movements; muscle strengthening.	Encourages therapy participation and motivation.	Varying working features, high costs, primarily passive without a therapist.
Robotic Devices for Upper and Lower Limbs [33].	Assistance in active and passive movement, gait improvement.	Capable of generating measurable forces and providing intensive therapy.	Requires large physical space and proper facilities; safety concerns for unsupervised home use.
VIRTUAL AND AUGMENTED REALITY			
Augmented Reality [34].	Improvement of physical functionality, range of motion, and gait.	Encourages therapy participation and motivation; no evidence of "simulator sickness."	Still in early stages; requires more research on effectiveness; may cause dizziness.
DIGITAL AND MOBILE APPLICATIONS			
App Applications [35].	Measure, assess, capture and monitor rehabilitation progress and health behavior, medication and rehabilitation compliance, and active and passive movement; provide and perform assessments; promote self-management, physical activity and healthy lifestyles; reduce falls; improve physical functioning, trunk control, manual dexterity, cognitive and language skills and mobility; provide psychosocial support, coaching, secondary prevention and obtain support from others	Low-cost, commercially available, provides access to some rehabilitation measures, is useful for integrating application solutions (e.g. for diagnosis, intervention or monitoring), increases engagement in treatment and supports the connection between the healthcare professional and the client through real-time transmission of health data	The accuracy of the ROMd measurement has not yet been tested or validated. Access and use may vary across countries due to cultural background, availability of high-speed connectivity, and trust in healthcare professionals. The appropriate use of digital technology may be affected by the health condition itself (e.g., motor disability, visual impairment, psychiatric comorbidities, cognitive dysfunction). Some apps can only be used in conjunction with another technology (e.g., smartwatch). Some apps do not provide a platform to facilitate interaction with healthcare professionals; some apps are out of date; some apps do not disclose sponsorship, author affiliations, credentials, and sources of information or references; and some apps do not always meet all of the client's rehabilitation needs. Security considerations are not always taken into account

Web Tabanlı Program [37].	Measuring, assessing, capturing and monitoring rehabilitation progress, health behaviors, medication and rehabilitation compliance; providing and performing assessments; promoting self-management, physical activity and healthy lifestyles; improving physical function, balance, postural control, endurance, strength and cognitive skills; obtaining support from others	Real-time feedback possible, low cost, commercially available, access to some rehabilitation measures, useful for combining application solutions (e.g. for diagnosis, intervention or monitoring), participation in therapy, supports the connection between the healthcare professional and the client through real-time transmission of health data	Access and use may vary across countries due to cultural background, availability of high-speed connectivity, and trust in healthcare professionals; appropriate use of digital technology may be affected by the health condition itself (e.g., motor disability, visual impairment, psychiatric comorbidities, and cognitive dysfunction); sometimes unreliable connections
ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING			
AI and Machine Learning [38,39].	Providing individualized therapy, training plan, real-time movement feedback and movement classification	Potential to predict patient conditions and adapt therapy.	It is still in its infancy; some decisions can be made by AI and machine learning algorithms, and acceptable model accuracy can be achieved after using the technology many times
Chatbots and Communication Agents [40].	Organizing the rehabilitation process, treatment of mental disorders and supported living	A fun tool for rehabilitation with rehabilitation management support, low cost and nostigmatization in the treatment of mental disorders	It is still in its infancy, more research is needed; most chatbots are not commercially available; some individuals may become overly attached, some chatbots may provide inappropriate responses regarding health issues; there are no laws and regulations regarding the use of chatbots, and legal liability for adverse events related to chatbots has not yet been clarified

Conclusion

AI offers innovations in sports rehabilitation, such as personalized treatments, real-time analysis, and robotic support. However, ethical and economic barriers must be overcome. In the future, as these technologies become more widespread, athletes will be able to return to the field faster and safer. AI technologies in injury prevention, diagnosis, and rehabilitation are revolutionizing athlete performance and safety. Machine learning, deep learning, and computer vision techniques provide early warning systems, personalized treatment plans, and data-driven decision support, shaping the future of sports medicine. However, challenges such as data privacy, ethical concerns, and clinical integration must be addressed. As AI-assisted systems become more accessible and user-friendly, athletes and healthcare professionals will maximize the benefits of these innovative solutions. Advancements in this field will protect not only professional athletes but also amateur sports enthusiasts, contributing to a healthier and more sustainable sports culture.

Conflict of Interest

The authors declare that there are no conflicts of interest related to the publication of this case study.

Author Contributions

Conception and design of the study: ND; Data collection: ND; Data analysis and interpretation: ND; Drafting the article and/or its critical revision; ND; Final approval of the version to be published; ND. All authors have read and agreed to the final version of the manuscript.

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