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Application of Sensor-Based Technologies in Sports Injuries

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Abstract:

***Background*: Athletes often suffer from various types of musculoskeletal injuries. It becomes essential to undergo rehabilitation for return to sports. There are many physiotherapy interventions that can be used in sports injuries. However, use of sensor based technology helps to reduce the rehabilitation time. The present review of literature was undertaken to find the application of sensor based technology in sports injuries.**

***Methods:* Various databases such as PubMed, Google Scholar and ScienceDirect were used for searching the literature using keywords such as sensor-based technology, robots etc.**

***Results:* It was found that sensors utilizing inertial measurement unit (IMU) sensors were found to be commonly used for gathering movement related data. Among the injuries analyzed, joint sprains and knee injuries were the most extensively investigated.**

***Conclusion:* Application of sensor based technologies has improved the prevention of sport injuries. However, there is a need to incorporate sophisticated data processing, method, real life implementation, and representation of under explored areas like adaptive systems, which present potential areas for future innovation.**

Keywords: Prevention, Rehabilitation, Robots, Sensor technology, Sports injury.

I. Introduction

Sports players often suffer from various musculoskeletal or neurological injuries that require rehabilitation enabling them for a quick return to their sport. Various physiotherapy interventions are used for the same. However, use of sensor based technology is emerging as a new trend that helps in injury prevention as well as reduction of the rehabilitation time. Sensor based technology includes devices that uses sensors to detect, measure and convert physical quantity such as temperature, pressure, light etc. into measurable electrical signals, which then can be used for various purposes such as evaluation of the athletes' performance as well as assessment of the conditions. The advent of sensor-based technologies has dramatically transformed sports injury management and prevention, offering new levels of insight into athlete biomechanics. Traditional methods often fail to capture the complex dynamics of human movement, but sensor technologies overcome these limitations by providing real-time, objective data. This makes them essential tools for healthcare professionals, coaches, and athletes alike. Devices like inertial measurement units (IMUs), accelerometers, gyroscopes, and magnetometers are commonly used to monitor parameters such as muscle activity, impact forces, and movement patterns, demonstrating their effectiveness in identifying injury risks and guiding rehabilitation strategies across various sports and injury types.

Wearable sensors and motion tracking systems have been used in different areas of sports, including performance analysis and enhancement [1]. Similarly, GPS-based wearable sensors have proven effective in predicting non-contact lower body injuries in footballers by monitoring external training loads and movement patterns [2]. Sensor-based technologies have also significantly advanced the rehabilitation of specific injuries, such as anterior cruciate ligament (ACL) tears, where systems for telemonitoring and tracking guides personalized recovery plans [3].

The integration of sensor fusion techniques combining data from multiple sensors, enhances the accuracy and reliability of injury assessments [4]. This integrated approach offers a deeper understanding of injury mechanisms, enabling the development of tailored interventions that optimize both recovery and performance. As the field continues to progress, there is substantial potential for innovation in sensor-based technologies, especially in improving real-world applicability and addressing research gaps in under represented areas. The ongoing development of these technologies promises to have an even greater transformative impact on sports injury management in the future. The present literature review explores the current applications, effectiveness, and future directions of sensor-based technologies in sports injury management, highlighting their critical role in advancing the field.

II. Methodology

The literature review was conducted by using a comprehensive search covering numerous databases including PubMed, Google Scholar and ScienceDirect. Key words such as sensors, sport injury, prevention, and rehabilitation were used. The selected articles were published between 2010 and 2025 and focused on sensor technology in human-based studies.

III. Application of Sensor Based Technology in Upper Limb Conditions

Emerging sensor-based technologies have revolutionized the assessment, prevention and rehabilitation in overhead sports and neuromuscular disorders. Various technologies such as motion sensors, heart rate variability monitors, and inertial sensors provide valuable insights into detecting early signs of fatigue and movement dysfunction, which can lead to injuries [5]. These tools are particularly crucial in overhead athletes like baseball players and swimmers, where even subtle kinematic deviations can be the precursor to more severe injuries.

The use of motion capture and electromyography (EMG) systems, as demonstrated in various studies, reveals that sensor-based technologies can identify maladaptive movement patterns and muscle activation imbalances that are often difficult to detect through conventional clinical assessments [6, 7]. A study on shoulder impingement syndrome underscores how sensor technologies can reveal compensatory muscle activity and disruptions in scapulohumeral rhythm, offering new avenues for targeted rehabilitation strategies [6].

The impact of robotic and sensor-assisted therapies for upper limb rehabilitation was also explored particularly for individuals with neurological or musculoskeletal impairments. The authors emphasized the importance of computer- and robot-assisted therapy in optimizing upper extremity rehabilitation. Their study compared robot-assisted group therapy with individual arm therapy, concluding that combining 30-minute robot-assisted therapy with 30-minute individual therapy was as effective as double sessions of individual therapy. The robot-assisted approach, however, was 50% more cost-effective per patient session [8].

Furthermore, sensor feedback systems have shown promising results in rehabilitation settings. It has been demonstrated that real-time visual feedback during therapeutic exercises helped wheelchair basketball players improve muscle activation and reduce pain. This highlights the role of sensors not only in injury prevention but also in optimizing recovery outcomes by providing immediate data to adjust therapy as needed [9]. Tramontano *et al.* showcased the effectiveness of sensor technology PABLO- Tyromotion system for rehabilitation of upper limb in patients with MS (multiple sclerosis). This system incorporates interactive therapy games and feedback to train shoulder, elbow, and wrist movements. Their study found that the group who were given this system for 12 sessions over 4 weeks showed significant improvements in quality of life, strength and mobility index compared to those in group who did not received such system [10]. Sensor technologies also play an essential role in evaluating the effectiveness of surgical interventions, like SLAP tear repairs. By capturing fine differences in muscle activation and joint kinematics, these technologies provide valuable insights into the recovery process, which could lead to more personalized and effective treatment plans [11]. Overall, these studies illustrate the profound impact of sensor-based technologies on upper limb injury management, from prevention to rehabilitation. By enabling real-time, detailed monitoring of movement patterns and muscle activity, they provide clinicians and athletes with the tools necessary to make more informed decisions and tailor interventions more effectively.

IV. Application of Sensor Based Technology in Lower Limb Conditions

The lower limb plays a pivotal role in human mobility, endurance, and athletic performance. Injuries to the lower extremities, particularly the knee, ankle, and foot, are common in both recreational and professional athletes**.** Understanding the biomechanics of lower limb movement and the impact of injury is essential for developing effective rehabilitation strategies. Key application of sensor based technologies in lower limb includes injury prevention, gait and biomechanics monitoring, sport performance monitoring, rehabilitation monitoring, posture injury prevention, musculoskeletal monitoring, functional assessment, injury analysis, and finally neurological and sensory integration analysis**.**

A. Injury Prevention

Injury prevention in sports has significantly benefited from advancements in wearable sensor technologies. The utility of a uniaxial gyroscope in identifying potential indicators of lateral ankle sprain through dynamic motion analysis has been demonstrated, reinforcing the role of inertial sensors in proactive injury prevention [12]. Similarly, the effectiveness of GPS-based wearables in monitoring external training loads among professional football players has been observed [2]. These devices allowed practitioners to adjust training intensities, thus reducing the incidence of lower limb injuries.

Pressure-sensing technologies also contribute meaningfully to injury risk assessment. The role of pressure plates has been emphasized in identifying plantar pressure distribution patterns and center of pressure displacement—biomechanical markers associated with chronic ankle instability and increased injury risk [13]. Complementing this, researchers have evaluated a wearable IMU system that measured agility performance and lower limb asymmetries post-knee ligament injury [14]. Their novel metrics, the Transitional Angular Displacement of Segment (TADS) and its Symmetry Index (SI), were effective in capturing dynamic joint asymmetries during change-of-direction tasks, offering a valuable post-injury monitoring tool.

Additionally, Cordeiro *et al.* investigated dynamic knee stability following ACL reconstruction using a combination of 3D motion analysis, EMG, and video capture during soccer in step kicks that highlighted the neuromuscular adaptations in joint mechanics and muscle activation, reinforcing the need for individualized rehabilitation protocols [15].

RunScribe Plus sensors were used to monitor in situ running biomechanics in collegiate cross-country athletes across a competitive season. Metrics such as cadence, stride length, contact time, pronation excursion, and loading rates were tracked bi-weekly. Injured athletes (n=8) exhibited deviations from team norms in the days leading up to injury, including prolonged contact time and increased pronation in cases of bone injuries, as well as increased stride length [16]. These findings underscore the potential of wearable technology to serve as predictive tools for overuse injuries, enabling the implementation of tailored interventions and injury-preventive training adaptations.

B. Gait and Biomechanics Monitoring

Wearable sensor technology has become increasingly valuable in monitoring gait and biomechanics, offering insights into movement patterns and aiding in the assessment and rehabilitation of musculoskeletal disorders.

Inertial Measurement Units (IMUs) have been widely adopted for their portability and accuracy. The use of IMU-based systems in performing efficient and reliable gait assessments across a variety of clinical and athletic settings has been observed [17]. Similarly, a multi-sensor integration-based approach for monitoring rehabilitation progress in subjects with anterior cruciate ligament reconstruction (ACL-R) has been used [3]. The system combined wireless motion sensors, surface electromyography (EMG), and digital video capture to assess knee joint kinematics and neuromuscular activity during walking. The study confirmed the system's potential as a comprehensive, objective tool for tracking recovery and optimizing rehabilitation protocols. Ahmadian *et al.* evaluated the effect of a wearable IMU-based system for ambulatory measurement of 3D knee and ankle joint angles during the triple single-leg hop (TSLH) test. The setup used Physilog 3 modules for technical validation and Physilog 5 for clinical application. Sensors were strategically positioned on the thigh, shank, and foot to record joint kinematics, both unilaterally and bilaterally and captured dynamic performance during hopping tasks with high precision [18].

The tibiofemoral kinematics were analysed by comparing anterior tibial displacement and tibial rotation during open kinetic chain (seated knee extension) and closed kinetic chain (single-leg wall squat) movements in individuals with chronic unilateral ACL deficiency. Using the Qualisys 3D Motion Analysis System— comprising six infrared cameras operating at 150 Hz and 17 reflective markers placed at key anatomical landmarks, high-resolution, three-dimensional joint kinematics with great accuracy was captured [19].

Finally, Capin *et al.* presented a comprehensive biomechanical analysis system integrating an eight-camera VICON motion capture system (120 Hz), an embedded force platform (1080 Hz), and bilateral EMG recordings from seven lower extremity muscles, including the rectus femoris, medial and lateral vastus, hamstrings, and gastrocnemii. Their multimodal setup allowed for the detailed assessment of both kinematic and kinetic parameters during gait, offering robust insights into muscle function and movement mechanics [20].

C. Sports Performance and Rehabilitation

Wearable sensor technologies have increasingly contributed to optimizing sports performance and rehabilitation strategies by providing real-time, objective, and quantifiable data. Among these, Inertial Measurement Units (IMUs) are particularly notable for their utility in analysing movement patterns during physical exertion and under fatigue conditions. Kramer *et al.* discussed the use of these sensors to continuously track movement and general physical activity. The objective data gathered can be used to tailor rehabilitation protocols, evaluate athletic readiness, and track progress over time [21].

Kasović *et al.* contributed further to this domain by examining electromyographic (EMG) activation patterns of the knee during a single-leg vertical jump task to detect neuromuscular differences two years after anterior cruciate ligament (ACL) reconstruction. Their investigation concluded that muscle activation timing and duration, particularly in the rectus femoris and biceps femoris, differed significantly depending on the type of graft used in reconstruction [22]. These findings underscore the importance of neuromuscular assessments in rehabilitation planning and highlight how sensor-based technologies can uncover subtle yet functionally significant adaptations post-injury.

Additionally, the relationship between arthrokinematic motion quality and dynamic postural control in individuals with chronic ankle instability (CAI) has been explored. Their use of vibroarthrography, in combination with balance assessments, enabled the identification of functional deficits, contributing to more targeted rehabilitation strategies [23]. This integration of vibration-based diagnostics with biomechanical performance measures provides a nuanced understanding of joint function under load.

Liang *et al.* extended the application of IMUs in biomechanics by demonstrating their role in human activity recognition and musculoskeletal force estimation. By processing raw accelerometer and gyroscope data through advanced machine learning and deep learning models, the study estimated key parameters such as ground reaction forces, joint torques, and muscle loads [4]. Moreover, Liang *et al.* emphasized the importance of proper sensor placement—on anatomical landmarks such as the waist, hips, thighs, shanks, and feet—to reduce signal misalignment and improve the reliability of motion capture during dynamic tasks [4].

These technologies not only enhance real-time feedback mechanisms for athletes and clinicians but also contribute to long-term rehabilitation planning and return-to-play decisions. When integrated into performance environments, they facilitate evidence-based training, ensure early detection of performance-limiting deficits, and promote safe, individualized recovery pathways.

D. Posture Analysis and Injury Risk

Postural deviations during athletic activities are a significant contributor to musculoskeletal injuries, particularly in the spine and lower back. Recent advancements in wearable sensor technology have revolutionized posture monitoring, offering real-time, non-invasive solutions that provide athletes and clinicians with accurate feedback on spinal alignment and balance control. Jenkins *et al.* developed an innovative wearable prototype consisting of independent sensor nodes embedded with inertial measurement units (IMUs), designed to monitor spinal posture during various physical activities. The system was integrated with a mobile application that provided continuous feedback, alerting users to deviations from ideal postural norms. This real-time feedback loop empowered athletes to make immediate corrections during functional movements such as weightlifting, running, or plyometric drills. Particularly in exercises that demand high spinal precision, like deadlifts or Olympic lifts, the system helped prevent chronic overuse injuries and sudden mechanical strain [24]. By encouraging users to develop better body awareness and neuromuscular control, the wearable system demonstrated substantial potential in reducing long-term injury risk and improving performance consistency. Additionally, its low cost, portability, and adaptability make it applicable beyond athletic settings— including workplace ergonomics, injury rehabilitation, and even everyday wellness routines.

Building upon the importance of postural control, Gera *et al.* investigated the application of wearable inertial sensor systems to assess balance and postural sway in athletes following mild traumatic brain injury (mTBI). Using a compact, waist-mounted device (Opal; APDM Inc.) that integrated a tri-axial accelerometer, gyroscope, and magnetometer, the study instrumented the modified Clinical Test of Sensory Integration and Balance (mCTSIB). Athletes who had suffered an mTBI within the previous 2–3 days were evaluated under various sensory conditions (eyes open/closed on firm/foam surfaces). The findings revealed significantly larger sway areas in concussed athletes compared to healthy controls, particularly in more challenging conditions like eyes closed on foam. This highlighted a diminished ability to reweight sensory input—suggesting impaired integration of vestibular, visual, and proprioceptive cues. Furthermore, the sway data showed strong correlations with subjective dizziness scores, underscoring the system's potential to objectively quantify balance deficits and inform safe return-to-play decisions [25].

Together, these studies underscore how wearable sensor systems can play a pivotal role in posture-related injury prevention and recovery. Deficits early, these technologies are reshaping how injuries are prevented, managed, and rehabilitated in modern athletic and clinical environments.

E. Musculoskeletal Monitoring

Advancements in wearable and biomechanical sensor technologies have significantly enhanced the capacity to monitor musculoskeletal function, particularly in dynamic and high-stress environments such as sports. Zhang *et al.* introduced an innovative stretchable wireless strain sensor system designed to measure tendon deformation at high rates without compromising accuracy. The sensor employed a stretchable passive resonant circuit constructed from biocompatible and mechanically durable materials. This design not only ensured excellent signal stability but also offered high sensitivity to subtle strain variations, making it highly suitable for real-time tendon monitoring during intense physical activity [26].

The flexibility and robustness of this sensor system allows it to conform to complex body contours, making it a promising tool for continuous, non-invasive musculoskeletal assessment. Such technology holds potential for tracking tendon health, monitoring rehabilitation progress, and identifying risk factors for overuse injuries, particularly in tendon-heavy sports like sprinting, jumping, and weightlifting. In an earlier and equally significant study, Kulig *et al.* investigated the dynamics of the knee extensor mechanism during volleyball approach jumps, focusing on the influence of patellar tendinopathy. They utilized an integrated biomechanical assessment system comprising an eight-camera three-dimensional motion analysis setup and force platforms. Reflective markers were placed on key anatomical landmarks to capture joint kinematics and ground reaction forces during high-impact jumping movements. Their findings revealed subtle yet critical differences in mechanical energy absorption and generation at the knee joint between healthy athletes and those with tendinopathy, highlighting the role of biomechanical monitoring in detecting early signs of injury [27].

Together, these studies demonstrate the importance of advanced sensor integration in understanding joint mechanics, tendon behaviour, and muscular coordination. Such tools not only facilitate early injury detection and performance optimization but also support data-driven rehabilitation strategies tailored to individual biomechanical profiles.

V. Discussion

The present literature review aimed to evaluate the application of sensor devices in sport injury-prevention, rehabilitation, and performance assessment. The findings revealed a rapid expansion in sensor based methods that offer objective, real-time data for biomechanical analysis. Sensor-based technologies, such as Inertial Measurement Units (IMUs), Electromyography (EMG), pressure plates, GPS-based wearables, robots and motion capture systems, each offer unique strengths and limitations in the context of lower limb injury prevention, rehabilitation, and performance analysis. IMUs, which include accelerometers, gyroscopes, and magnetometers, are highly portable and provide real-time data on joint kinematics, gait, and posture. They are particularly effective for dynamic activities, making them ideal for field use in both sports and rehabilitation settings. IMU sensors were the most widely used sensor device. However, their accuracy can be influenced by sensor placement, and they may require calibration to ensure reliable data. EMG, on the other hand, is excellent for assessing neuromuscular function by capturing muscle activation patterns, making it valuable in rehabilitation, especially post-surgery or injury. The downside is that EMG signals can be disrupted by movement artifacts, limiting their practicality in high-intensity activities.

Pressure plates are highly effective for analyzing plantar pressure distribution and diagnosing foot-related disorders like chronic ankle instability, but their stationary nature limits them to controlled environments and makes them unsuitable for real-time, mobile assessments. GPS-based wearables excel in tracking external training loads and movement patterns, especially in outdoor settings like football or running. However, they are less effective at providing detailed internal body mechanics, such as joint angles or muscle activity, and can lose accuracy in obstructed environments. Finally, motion capture systems, like the VICON system, provide the most accurate and detailed biomechanical data, particularly in lab settings, making them ideal for precise joint motion analysis. However, they are expensive, require dedicated setups, and lack portability, restricting their use to research or specialized clinical environments. In conclusion, while IMUs and EMGs offer effective solutions for real-time, mobile monitoring of both biomechanical and neuromuscular factors, other technologies like pressure plates and motion capture systems provide more specialized, high-accuracy data in controlled settings, but their practicality is limited outside of specific research or clinical applications.

VI. Conclusion

Sensor-based technologies are transforming the scope of sport injury management and rehabilitation by enabling objective, real-time, and ecologically valid biomechanical assessments. Their versatility across injury prevention, performance monitoring, and functional evaluation offers promising avenues for both clinicians and sports professionals.

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