Available Online: 4 January 2026 DOI: 10.54254/2977-3903/2025.31061

A review of pre-injury assessment and post-injury rehabilitation based on virtual reality and motion capture system

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Abstract. Musculoskeletal injuries pose significant challenges to global healthcare system. Traditional assessment and rehabilitation methods are often subjective, non-engaging and lack precise quantification. This review explores the potential of integrating Virtual Reality (VR) and motion capture technologies to address these limitations across injury management. It systematically analyzes the architecture of such systems and demonstrates that they enable the creation of standardized, high-intensity, personalized and safe environment for pre-injury risk assessment and post-injury rehabilitation in populations. This is achieved by quantifying key biomechanical risk factors. The integration of VR and motion capture system indicates a shift toward novel technological approaches in injury management, despite facing challenges in cost and standardization that require future development.

Keywords: virtual reality, motion capture, injury assessment, rehabilitation

1. Introduction

Musculoskeletal Disorders (MSDs) are one of the leading causes of long-term disability and disease, closely associated with high expenditures in both healthcare and social resources. The musculoskeletal system is a fundamental structural component of the body, and the health status of this complex system is related to the performance of its components. Typical features of musculoskeletal disorders include pain and temporary or lifelong limitations in mobility and flexibility, which reduce people's ability to work and participate in social life. To date, work-related MSDs are considered major illnesses affecting millions of workers, resulting in costs of billions of dollars to companies and public health systems. Traditional approaches to addressing musculoskeletal disorders have several shortcomings, such as a lack of objective data measurement in complex, dynamic situations [1].

In recent years, the combination of Virtual Reality (VR) and Motion Capture technology has brought new solutions. They provide subjects with an immersive experience, ensuring the authenticity and accuracy of the sensation through VR devices, while also facilitating interaction with the corresponding subjects and scenarios [2]. Motion capture technology, on the other hand, can convert movements into measurable data.

This review aims to systematically examine and discuss the applications, progress, and future trends of VR and motion capture technology throughout the entire injury management cycle, which from pre-injury risk assessment to post-injury functional rehabilitation. Through a review of existing literature, it aims to demonstrate that the collaborative application of VR and motion capture is is leading the field toward a new era of injury management that is predictive, preventive, personalized, and participatory.

2. Overview of virtual reality and motion capture system

The integration of VR and Motion Capture technology provides a novel technological approachtechnological paradigm for modern rehabilitation medicine. By creating an immersive and quantifiable training environment, this system establishes a solid foundation for precise pre-injury risk assessment and efficient post-injury rehabilitation.

2.1. System architecture

A comprehensive VR and motion capture system for rehabilitation is a typical multi-module closed-loop feedback system. Its core function is to collect users' movement information in real time, translate it into interactions within a virtual environment, and provide instantaneous, personalized feedback based on the users' performance in the environment. This system typically comprises four core modules; the overall data flow is illustrated in Figure 1.

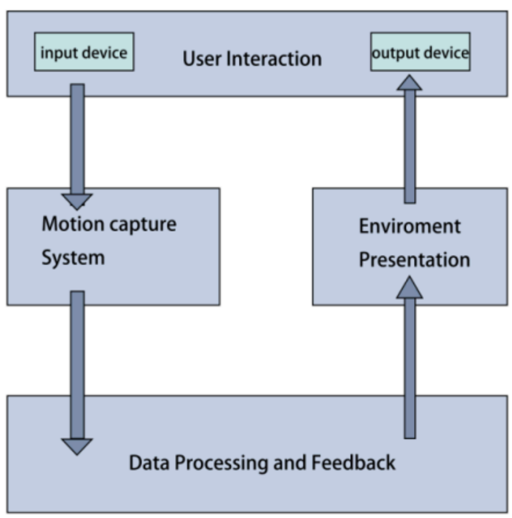

Figure 1. VR rehabilitation system data flow diagram

2.1.1. User interaction

This module is the interface through which users interact directly with the system, handling information input and output. It is composed of input devices and output devices. It converts physical signals from the user into system-recognizable data, and transforms information from the virtual environment into user-perceivable stimuli.

2.1.2. Motion capture system

This module quantifies movement performance and is responsible for collecting users' kinematic data with high precision from various types of sensors. It also processes data to output standard skeletal data for subsequent modules.

2.1.3. Virtual environment rendering

It is responsible for generating and rendering virtual scenes and for using the data from the motion capture module to drive the user's avatar in the virtual world. Thereby, it creates a training environment which is controllable, repeatable and safe.

2.1.4. Data processing and feedback

It receives raw data from the motion capture module and processes it in real-time and biomechanical analysis models, adjusts training parameters based on the previous performance, and provides a personalized rehabilitation process.

2.2. Key motion capture technologies

As shown in Table 1, the current motion capture technologies can be divided into four major categories. This classification shows differents in key indicators of motion capture systems [3].

Table 1. Classification and characteristics of motion capture technologies [3]

Type	Principle	Advantages	Limitations	Applications
Active Marker Motion Capture	Utilize optical markers to calibrate the spatial coordinate systems and acquire high-precision 3D kinematic data of human movements.	High accuracy; strong anti-interference; stable data output for quantitative analysis.	Restricts large-range movements; requires fixed laboratory space; cumbersome marker attachment.	Pre-injury gait biomechanical risk assessment; post-injury joint Range of Motion (ROM) precise rehabilitation training.
Passive Marker Motion Capture	Markers do not emit light	High portability; No extra interfere on subjects	Weeker stability and resistance to interference; lower stability in rapid motion;	Post-injury motor function recovery training
Electromagnetic Motion Capture	Calculate the distance between the base station and wearable sensors using electromagnetic wave reflection time differences to capture motion.	Compact device design; suitable for confined spaces	Lower accuracy; limited measurement range	Minimally invasive medical surgery navigation
Computer Vision Motion Capture	Uses cameras and AI algorithms to analyze video frames, extracting 2D/3D human pose coordinates without physical markers.	Marker-free operation; easy to deployment	Poor performance in motion blur scenarios	Industrial automation and quality inspection; home-based post-injury rehabilitation guidance

3. Applications in pre-injury risk assessment and post-injury rehabilitation

This section demonstrates how VR and motion capture systems address the limitations of traditional risk assessment methods. Unlike subjective observations, VR creates standardized and safe simulated environments, while motion capture provides objective, quantifiable data.

3.1. Pre-injury risk assessment

The primary objective of pre-injury risk assessment is to identify abnormal movement patterns through quantitative data. VR and motion capture (mo-cap) technology can establish a standardized, repeatable, and safe environment that enables early identification and quantification of these risks. .

3.1.1. ACL injury risk assessment for athletes

The assessment of Anterior Cruciate Ligament (ACL) injury risk is a prime application of VR and motion capture in proactive athlete management. Traditional video analysis lacks the precision to quantify the subtle biomechanical deficits that predispose athletes to ACL tears. Within a standardized VR environment, athletes perform sport-specific maneuvers such as jump-landings or cutting tasks. Motion capture systems then precisely measure critical risk factors, including excessive knee valgus angles, high peak knee abduction moments, and asymmetrical landing forces [4]. This data-driven approach enables sports medicine professionals to identify at-risk athletes before injury, facilitating targeted neuromuscular training interventions to mitigate risk and enhance athletic resilience.

3.1.2. Falling risk assessment for elderly people

For elderly people, falling can lead to serious complications such as fractures, pain, and an increased risk of future falls [5]. VR and motion capture offer a new approach to assessing falling risk.

For example, VR can simulate complex environmental hazards, such as an uneven street with obstacles. This approach allows subjects to navigate such scenarios without the physical risk associated with real-world testing [6]. The integration of motion capture with VR-based assessment forms a technological synergy that addresses the limitations of traditional fall risk evaluations,which often lack ecological validity. This integrated approach is particularly suitable for elderly patients who require both rehabilitation training and safety protection.

3.2. Post-injury functional rehabilitation and training

In the post-injury rehabilitation phase, VR and motion capture are used to create a high-intensity and repetitive environment and to provide quantitative data. This integrated approach effectively addresses key limitations of conventional rehabilitation methods, including training monotony, lack of objective metrics, and insufficient personalization, through the creation of engaging scenarios with real-time biomechanical feedback.

3.2.1. Neurological rehabilitation

In neurological rehabilitation, the combination of VR and motion capture technology provides innovative solutions for upper limb functional recovery in stroke patients. VR-based interventions demonstrate significant advantages over conventional rehabilitation therapy in improving upper limb motor function, muscle strength, and activities of daily living in stroke patients [7]. These advantages stem from VR-based therapy providing a high-intensity, task-oriented training environment, which contributes to brain functional reorganization and recovery.

This technology not only effectively improves motor function but also significantly enhances patient engagement, motivation, and treatment adherence through its immersive and motivating characteristics [8]. Motion capture technology plays a crucial role in this process by accurately quantifying kinematic parameters, including joint range of motion, movement velocity, and trajectory smoothness. This provides a reliable objective basis for therapists to adjust and optimize rehabilitation programs.

3.2.2. Musculoskeletal rehabilitation

VR and motion capture enable standardized rehabilitation for ACL reconstruction by quantifying movement patterns and provide objective data for safe return-to-sport decisions [9]. Immersive VR training improves movement quality and neuromuscular control in patients with ACL injuries [10]. The technology creates safe environments for practicing sport-specific tasks, such as jumping and cutting, while providing real-time biofeedback on knee kinematics. This approach supports comprehensive rehabilitation assessment by integrating strength, functional performance, and psychological readiness metrics [9].

The combination of quantitative movement analysis and psychological intervention through graded VR exposure makes this technology particularly valuable for ensuring both physical and psychological readiness for sports return.

4. Discussion

4.1. Challenges

Despite the significant potential demonstrated by VR and motion capture technologies in the rehabilitation field, their transition from research to widespread clinical application still faces several challenges. These challenges are primarily concentrated in three areas: technical integration, cost-effectiveness, and user experience.

4.1.1. Technical integration

A complete systems needs to combine motion capture equipment, VR rendering engines, and biomechanical analysis algorithms. However, data interfaces and communication protocols between these modules lack unified standards. For instance, the skeletal data structures output by motion capture systems from different manufacturers vary significantly, making cross-platform comparison and data integration difficult. This creates substantial interoperability barriers. This not only increase the technical barrier to system deployment and maintenance, but also limits the effectiveness of research in comparing data across different studies.

4.1.2. Cost effectiveness

The conflict between cost and accessibility is a major obstacle to the widespread adoption of the technology. Existing high-precision motion capture systems are expensive, and their acquisition and maintenance costs may exceed the budget of healthcare institutions. Conversely, while consumer-grade VR devices are lower in cost, their built-in tracking accuracy and stability often fall short of meeting the quantitative assessment requirements of clinical rehabilitation. Achieving effective cost control without compromising technical performance is key to to enabling the widespread adoption of this technology.

4.1.3. User experience

Regarding user experience, motion sickness inherent to VR devices remains a significant barrier to compliance, particularly during rehabilitation tasks that require rapid perspective changes or complex visual flow control. This physiological discomfort arises from a sensory conflict between the visual and vestibular systems. This issue is especially pronounced for patients with compromised vestibular function or neurological impairments, potentially leading to therapy interruption or rehabilitation aversion. Therefore, optimizing VR content design to mitigate motion sickness is an indispensable part of enhancing treatment compliance and completion rates.

4.2. Future directions

4.2.1. Construct unified management platforms

Future systems should evolve from standalone solutions to unified platforms serving both preventive screening and therapeutic intervention. This requires establishing standardized data protocols that enable seamless integration of diverse motion capture technologies with VR environments. Such integration will facilitate continuous monitoring from initial risk assessment through complete functional recovery, creating a truly cohesive care pathway.

4.2.2. Develop low-cost motion capture devices

A key priority is the development of motion capture devices that minimize motion interference while remaining affordable. Such advances will enable more natural movement assessment in both preventive and rehabilitative contexts, while significantly reducing equipment costs to broden accessibility across healthcare and sports settings. The exploration of novel, low-friction materials will be crucial to extending device lifespan and reducing failure rates, and thereby decreasing long-term operational costs and enhancing overall system reliability.

4.2.3. Integrate artificial intelligence for personalized rehabilitation

Future systems should incorporate sophisticated artificial intelligence to create truly personalized training experiences. Deep learning models are utilized to analyze user movement trajectories to real-time adjust training intensity (e.g., grasping difficulty in upper limb training for stroke patients) and predict rehabilitation stagnation risks, enabling proactive plan optimization.

5. Conclusion

This review discusses the integration of VR and motion capture technologies in injury management, from pre-injury risk assessment to post-injury rehabilitation. The study finds out that technology creates a standardized, safe environment for movement assessment while providing objective, quantifiable data for precise evaluation and personalized intervention. Specifically, motion capture systems enable the precise tracking of biomechanical parameters and delivers interactive experiences. The quantifiable data supports clinicians in evaluating injury severity, and designing personalized intervention plans tailored to individual patient needs.

The study further emphasizes the widespread adoption and efficacy are hindered by three critical constraints: technical integration barriers, cost-effectiveness, and challenges in user experience. To mitigate these drawbacks, the study argues that VR technology should be deeply integrated with deep learning algorithms and improves the personalization of both preventive and rehabilitative interventions.

The study also has limitations for depending on research and secondary data sources without primary empirical evidence derived from long-term longitudinal tracking or direct stakeholder interviews. Future research should prioritize longitudinal studies that wxamine both preventive and rehabilitative efficacy across diverse populations (i.g. between the long-term ACL injury risk reduction in athletes and rehabilitative efficacy).

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