EFFECTS OF EXTENDED REALITY ON BIOMECHANICS AND REHABILITATION IN THE CONTEXT OF ACL INJURIES: A COMPREHENSIVE REVIEW

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The review investigated Extended Reality (XR) applications in anterior cruciate ligament (ACL) injury risk screening and rehabilitation. Among 1135 studies, four met inclusion criteria. XR environments were investigated for their impact on knee biomechanics, attention, and proprioception. Findings revealed significant alterations in knee biomechanics induced by XR environments, including increased peak vertical ground reaction force and stiffer landings. XR immersion demonstrated altered movement strategies, hinting at potential distractions. While movements in XR and real environments were generally comparable, caution in approach velocity and differences in peak flexion angles suggested participant adaptations to virtual scenarios. While promising, further research is crucial for understanding long-term effects and practical clinical implementation.

KEYWORDS: rehabilitation, ACL, return to play, immersive technology, virtual reality

INTRODUCTION: Extended Reality (XR), including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality, has evolved beyond entertainment, infiltrating healthcare and rehabilitation. XR, as an immersive technology, has demonstrated effectiveness in neurorehabilitation, psychotherapy, and pain management (Georgiev et al., 2021; Pourmand et al., 2018; Rábago & Wilken, 2011). XR offers training sessions, simulating real-world scenarios, enhancing immersion, and replicating sport-specific responses. Preliminary research suggested XR's potential in preventing sports injuries by promoting optimal sensorimotor control and neuromotor system functionality (Rao et al., 2018; Villiger et al., 2017; Wright, 2014). However, its role in screening for Anterior Cruciate Ligament (ACL) injury risk mechanisms and rehabilitation require exploration. In light of the significant impact of ACL injuries on athletes' careers, ranging from long-term consequences like ligament instability and diminished athletic performance to increased osteoarthritis risk and potential career-ending scenarios (Dai et al., 2021; Grassi et al., 2022), the intersection of sports medicine, injury screening, and ACL rehabilitation becomes crucial. ACL rehabilitation extends beyond structural restoration, focusing on proprioception, neuromuscular control, and overall knee stability. Unlike traditional testing or rehabilitation settings, XR simulates real-world training and competition scenarios, fostering immersion and replicating sport-specific responses. Furthermore, XR emerges as a promising training modality for ACL rehabilitation, offering adaptability beyond environmental constraints. Shielded from the impact of weather conditions, customizable to individual requirements, and incorporating sports-specific exercises, XR training sessions may hold the potential to significantly augment functional recovery and foster a more effective return to play. This systematic review aims to assess the impact of XR studies on exercises used for injury prevention, return-to-play and its biomechanical outcomes and on ACL rehabilitation. Specifically, the review will focus on evaluating the impact of XR technologies, including VR and AR, on functional recovery, biomechanical outcomes in healthy individuals, and return-to-play readiness in individuals undergoing ACL rehabilitation.

METHODS: Articles were considered for inclusion in this review if they reported ACL-injury related outcomes of interventions involving XR. This included intervention within the contexts of rehabilitation, injury prevention, or performance outcomes in either healthy individuals or athletes with ACL injuries. To maintain the focus on original research and ensure data quality, systematic reviews, meta-analyses, case reports, book chapters, abstracts, and conference proceedings were excluded. Also, exclusion criteria involved populations like gamers or those with neurological, psychological, or amputation conditions, as well as studies unrelated to ACL rehabilitation outcomes. PubMed, Scopus, and Sports Discus were used. The last search for papers was on September 01, 2023, with an additional hand search based on reference lists. The search strategy (Table 1) employed a wide range of keywords, refined iteratively for specificity, resulting in a combination of keywords related to population, intervention, and outcome. From 1153 studies, 1138 were screened, with 1103 removed based on title and abstract. A double-blind hand search identified five additional studies. After full-text screening of 35 studies, four were included in the qualitative synthesis, following screening for risk of bias. The quality of selected studies was assessed using NIH Study Quality Assessment of Systematic Reviews (Ma et al., 2020). Two raters independently rated each paper, and differences were resolved through discussion. Papers with fair and good ratings were included, with one poor-rated paper excluded, resulting in the inclusion of four papers in the review.

Table 1. Search strategy.

Search Strategy	Keywords
Extended Reality (XR)	"Extended Reality" OR "Immersive" OR "Virtual Reality" OR "VR" OR "Virtual Environment" OR "Augmented Reality" OR "Mixed Reality" OR "External Focus" OR "Focus of Attention" OR "Attentional Focus"
	AND
Knee and Lower Limb	"Knee" OR "Lower Limb" OR "Orthopedic" OR "ACL" OR "Anterior Cruciate Ligament" OR "Sport" OR "Team Sports" OR "Football" OR "Soccer" OR "Basketball" OR "Handball" OR "Rugby" OR "Ski" OR "Baseball"
	AND
Injury and Rehabilitation	"Inj" OR "Rehab" OR "Diagnostic*" OR "Therap*" OR "Functional Assessment" OR "Performance" OR "Return to Play" OR "Test*" OR "Training" OR "Intervention" OR "Biomechanics" OR "Task-Specific" OR "Motor Learning" OR "Recovery" OR "Return to Play" OR "Biomechanical Analysis" OR "Athlete" OR "Sportsperson"

RESULTS: The four studies involved 119 participants (54 males, 65 females) across different locations (Taiwan, Netherlands, USA) from 2016 to 2022. XR interventions targeted healthy adults (n = 99; 4 studies) and ACL reconstruction patients (n = 20; 1 study). Study designs included experimental studies and a randomized controlled trial (Brazalovich et al., 2022; DiCesare et al., 2020; Gokeler et al., 2016; Lei & Cheng, 2022). As regards the aim of the separate studies, two examined the influence of VR-assisted training on the athlete's injury-risk and two evaluated the effects of XR systems on rehabilitation, using healthy participants. Focusing on 38 female adolescent soccer athletes, DiCesare et al. explored in an experimental study kinematic factors associated with ACL injury risk during a jump-landing task. Athletes in the VR scenario exhibited nuanced biomechanical responses, including reduced sagittal plane flexion, decreased ankle inversion, and altered hip abduction, providing insights into potential variations induced by VR (DiCesare et al., 2020). In a mixed-methods study involving 29 healthy adults, Brazalovich et al. delved into the impact of VR on knee landing biomechanics during a drop-landing task. The VR condition manifested in higher peak vertical ground reaction force, reduced knee flexion at initial ground contact, increased knee abduction angles, and a notable rise in landing errors compared to control conditions with eyes open and closed (Brazalovich et al., 2022). Gokeler et al. studied 20 individuals post-ACL reconstruction in AR environments during a step-down task (Gokeler et al., 2016). Significant interactions between AR and groups (ACL patients vs. healthy controls) were reported. Including increased vertical ground reaction force, higher knee extension moment, and altered knee angles, suggesting the potential of AR to influence biomechanical variables in a rehabilitation context. Lei and Cheng conducted a randomized controlled trial comparing VR and real laboratory environments during sidestepping with 12 healthy football players (Lei & Cheng, 2022). Movements were generally similar, but approach velocity was faster in the real environment. VR conditions exhibited caution in approach velocity and differences in peak flexion angles, suggesting participant adaptations to the virtual environment. Pre-planned sidestepping in VR differed significantly from the real environment, indicating potential influences on movement patterns.

DISCUSSION: The prevailing strategies for ACL (re)injury prevention involve screening athletes for detrimental movement patterns to identify those at risk or gauge readiness for return-to-play, often using standardized test batteries. Conventional laboratory-based testing and rehabilitation, however, may fall short in replicating sport-specific scenarios with their diverse physical and neurological demands. This limitation can result in the oversight of potentially injurious movement patterns, such as stiff landings or abnormal knee valgus, thereby increasing the risk of ACL injury. The potential of XR applications to address these limitations by creating immersive environments for standardized testing is recognized, although the supporting evidence is presently limited, forming the basis for this review. The primary revelation from this review is the substantial gap in research on XR environments for orthopaedic injury rehabilitation in the lower limb, particularly in the ACL domain. Only four studies met the inclusion criteria, exhibiting variations in movement tasks, population, XR environments, and outcome measures. This heterogeneity complicates direct comparisons between studies and hinders the extrapolation of findings to real-world scenarios. Moreover, the studies, while examining movement tasks and populations relevant to ACL return-to-play, establish only indirect links to the actual return-to-play setting. In the analysis of specific movement tasks, the studies explored diverse biomechanical aspects of drop-landing, jump-landing, and sidestepping maneuvers. Collectively, these studies underscore the XR potential to simulate diverse scenarios, ranging from simple room replication to sport-specific and psychological manipulations. When screening for ACL injury risk and for rehabilitation, XR technology exhibits promise, although evidence remains limited. DiCesare et al. demonstrated that standard testing, in contrast to a sports-specific scenario, provides a more precise depiction of biomechanical risk profiles during screening (DiCesare et al., 2020). The review's findings further suggest that altering the environment, virtually, can influence neuromuscular control. In a VR condition, significant effects on knee flexion, abduction angles, peak vertical ground reaction force, and landing errors were observed (Brazalovich et al., 2022). Previous research proposing that stiff landings increase knee loading and, consequently, ACL injury risk aligns with the biomechanical observations (Leppänen et al., 2017; Sugimoto et al., 2015). The VR environment's potential to identify individuals with deficits in neuromuscular control, particularly those sensitive to visual feedback, holds promise. This underscores the potential utility of XR for challenging the neuromuscular system and enhancing injury risk screening during rehabilitation. The increasing affordability, technological advancements, and portability of XR technology further enhance its appeal for both research and clinical practice. In the context of ACL rehabilitation, Gokeler et al. explored the influence of XR immersion on knee biomechanics in individuals who had undergone ACL reconstruction (Gokeler et al., 2016). The findings suggest altered movement strategies, possibly due to distraction, emphasizing the need for careful consideration of XR technologies in rehabilitation settings. However, the study's focus on a relatively simple task, such as step-down, raises questions about the transferability of findings to sports-specific movements, urging further research. While reviews on XR technologies in neurological disorders hint at successful applications, the current lack of concrete conclusions necessitates expanded research on the motor rehabilitation efficiency of XR.

CONCLUSION: In the context of injury risk assessment, XR shows promise as a tool to enhance the accuracy and sensitivity of screening athletes for lower limb injury risk. Additionally, the perturbative effect of XR technology on neuromuscular control underscores its potential utility in challenging the neuromuscular system and improving injury risk screening during rehabilitation. For ACL rehabilitation, XR demonstrates potential benefits, but the specific mechanisms behind its effectiveness remain largely uncharted. Notably, the neurobiological processes influencing how XR impacts proprioception and neuromuscular control remain poorly understood. A comprehensive understanding of these underlying mechanisms is pivotal for optimizing XR-based interventions. Furthermore, the long-term effectiveness of XR in ACL rehabilitation remains an unanswered question. Existing studies primarily offer short-term insights, warranting further research into the sustainability of XR intervention benefits over extended periods. Moreover, challenges associated with integrating XR into clinical practice, such as cost implications, accessibility limitations, and patient adherence, require deeper exploration. Addressing these challenges is vital to facilitate the seamless integration of XR technologies into standard clinical rehabilitation practices.

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