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Extended reality in musculoskeletal rehabilitation and injury prevention - A systematic review

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ABSTRACT

Objective: Unlike in neurological patient populations, the effects of Extended Reality within the context of sports medicine have rarely been studied. This systematic review was conducted to investigate the value of Extended Realty-assisted rehabilitation and injury prevention strategies on injury rehabilitation and prevention outcomes.

Methods: PubMed and Web of Science databases were consulted. The search strategy consisted of the terms Virtual Reality (Intervention), rehabilitation and injury prevention (Outcome) and healthy athletes or athletes with a musculoskeletal sports injury (Population). After eligibility and Risk of Bias screening, ten articles were included. Risk of Bias analysis resulted in a level of evidence varying between C (three articles), B (six articles) and A2 (one article) scores.

Results: Extended Reality was found to provide an added value for both sports injury prevention and rehabilitation outcomes. It particularly provides clinicians with the opportunity to address the underlying biomechanical risk profile for common sports injuries, allowing the athletes to train protective movement patterns more effectively.

Conclusion: More large-scale high-quality prospective research is needed in order to determine whether Extended Reality-assisted therapy is superior to conventional therapy in sports rehabilitation and injury prevention circles with strong conclusive evidence.

1. Introduction

Extended Reality (XR) (encompassing Virtual Reality (VR), Augmented Reality (AR) and video games and related applications) is highly popular in gaming and animation scenes, where it has multiple applications. Nowadays, it is making its entrance in healthcare as well. It is frequently used in the context of neurorehabilitation, psychotherapy and (chronic) pain management, where it has proven to provide a substantial added value in the clinical outcome of patients (Rábago & Wilken, 2011; Georgiev, Georgieva, Gong, Nanjappan, & Georgiev, 2021; Pourmand, Davis, Marchak, Whiteside, & Sikka, 2018).

Existing research has demonstrated that XR is able to increase the motivation and interest of the patient during therapy (Maggio et al., 2019) and to improve the patient's self-perceived effectiveness, which can influence his positive attitude towards training and rehabilitation (Lee et al., 2016). XR has the capacity to provide real-time sensorimotor stimuli (which are unknown and unexpected to the patient), as well as instant feedback regarding performance outcomes. As such, the patient's field of view can be manipulated by the interaction with a sensory-stimulating environment, which is an ideal sensorimotor control training (Adamovich et al., 2009; Merians et al., 2014; Rao et al., 2018; Villiger et al., 2017; Wulf, McNevin, & Shea, 2001; Wright, 2014). Next to these benefits, XR has been demonstrated to enable significant increments in muscle strength as well, by facilitating neuromuscular coordination and quality and magnitude of neuromuscular recruitment (Kim et al., 2013). Another advantage is the use of external focus as a particular type of feedback. An external focus of attention means that a patient's attention is directed towards the outcome or effect of the movement, rather than the movement itself (i.e. internal focus, in which the clinician provides the patient with feedback by drawing his attention to body positions and movements), making the exercise or training far more functional and effective (Tarakci, Ozdincler, & Tarakci, 2013; Wulf et al., 2001). The virtual environment's provision of external feedback, induces a change of

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attention in the patient which has shown to result in a change of motor control, potentially improving the consolidation and variability of motor output of the trained skills (de Bruin et al., 2010). Next to these benefits, XR is suggested to possess the ability to reduce sensory, affective and cognitive pain and anxiety levels, which facilitates training responses and (consolidation of) rehabilitation outcomes as well (Frey et al., 2019).

XR-assisted rehabilitation offers patients a very flexible and adjustable training method, being less dependent on environmental conditions, in contrast with conventional therapeutic rehabilitation settings. The training time can be chosen, there is no influence of the weather conditions and the training content consists of a lot of variation and is able to provide patients with very particular sports-specific exercises and skill training as well, which is also expected to facilitate consolidation and transfer in function of return to play (RTP) and secondary injury prevention.

Extended Reality is already well known and frequently used in the rehabilitation of neurological disorders. Existing study results have indicated that video game-guided rehabilitation has the capacity to improve balance, gait and performance in the activities of daily living in patients after stroke and patients with Parkinson's disease and cerebral palsy (Barcala, Grecco, & Colella, 2013; Pompeu et al., 2012; Thomas et al., 2016). More so, several systematic reviews have concluded that XR is beneficial when used as an adjunct to usual care, which increases the patient's overall therapy time within the same rehabilitation period (Laver et al., 2012). Although XR has hardly made its entrance in sports injury prevention, preliminary research has demonstrated that sensorimotor training may prevent sports injuries (Emery et al., 2015; Reneker et al., 2019). An optimal sensorimotor control promotes a healthy and efficiently functioning neuromotor system, which in its turn favors injury prevention (Reneker et al., 2019). Based on the (preliminary) existing evidence, XR is thought to have the ability to improve both primary and secondary sports injury prevention and rehabilitation outcomes. After injury, the aim of athletes is to return to high-level sports activities. The difference between performing rehabilitation exercises in a controlled clinical setting under supervision of the physiotherapist and sport performances in real on-the-field, competition-specific, circumstances is substantial. XR renders the opportunity to simulate training or competition situations more realistically. Unlike outdoor motion capture solutions, XR offers a fully standardized, safe and controlled laboratory environment. If combined with untethered freedom of movement, it can induce a sense of immersion to facilitate athlete's responses that approximate real-world sport responses. These advantages have inspired researchers to use advanced technology to improve our understanding of altered movement patterns in real-life situations (Gokeler et al., 2013). XR allows the manipulation of the training environment in function of the training and sport-specific skill demands of the individual athlete/patient, which would be impractical or impossible to create in the real world/a conventional rehabilitation setting (Adamovich et al., 2009).

Based on the possibilities and benefits that have been described as regards the implementation of XR in rehabilitation settings, this systematic review aims to gather the existing evidence as regards the value of using XR-assisted training in sports rehabilitation and injury prevention in particular. Based on the available evidence, it is hypothesized that athletes submitted to XR-assisted sports rehabilitation and injury prevention, will demonstrate better training/rehabilitation outcomes (mostly as concerns proprioception, balance, strength, pain scores and biomechanical movement patterns) and a lower risk of (recurring) injury compared to athletes enrolled in a conventional sports physiotherapy/injury prevention regimen.

This review will discuss XR's application possibilities in musculoskeletal injury rehabilitation and prevention, amongst which Virtual Reality (VR), Augmented Reality (AR) and video applications will be considered. XR is an overreaching term including any immersive technology that creates computer-generated environments or objects. AR extends the real world by adding virtual objects and information into the real world, while VR creates a fully computer-generated 360° environment in which the real world is fully concealed during use (IONOS, 2021). Virtual Reality (VR) consists of a computerized virtual environment in which a user can experience various senses. Most environments are visual and auditory. VR has multiple applications in gaming and entertainment, but is also suggested to be valuable in rehabilitation of patients (Maples-Keller et al., 2017). As video games like the commonly used Wii Fit product of Nintendo is also frequently used in training and rehabilitation settings, this review will consider these video game applications under the common term ‘Extended reality(as well.

2. Methods

This systematic review, gathering the evidence as regards the effectiveness of XR in rehabilitation and prevention of musculoskeletal sports injuries, was composed based on the guidelines of Preferred Reporting Items for Systematic reviews and Meta-Analyses (Institute & Oxford, 2015).

2.1. Eligibility criteria

Articles were included in the present review if they reported the results of an intervention with Extended Reality (Intervention (I)) within rehabilitation or injury prevention (Outcome (O)) in healthy people or athletes with a musculoskeletal injury (Population (P)). Systematic reviews, meta-analyses, case reports were excluded, book chapters, abstracts and conference proceedings (S). The search of eligible articles was conducted using respective PICOS-question (Uo, 2016) and several inclusion and exclusion criteria (Table 1). Articles discussing the use of XR in neurologic patients or the population of gamers were excluded as well. Given the fact that XR only recently made its entrance in the field of (sports)medicine research, no limitations were set on year of publication.

2.2. Information sources

PubMed and Web of Science databases were used as information sources to gather eligible articles. The last search for relevant articles was run on the March 13, 2022. An additional hand search based on the reference lists of the included articles was additionally conducted as well that same time.

2.3. Search strategy

The particular research question used to guide this systematic review progress was ‘What is the value of Extended Reality within musculoskeletal injury rehabilitation and prevention?’. This question was redefined in function of the PICO principle by searching synonyms and keywords for each element of the question (Population, Intervention, Control and Outcome). This search strategy was initiated using a wide range of key words and combination, and refined every single time, making it more specific to ensure that only the most relevant articles were retrieved during the screening process.

Several Medical Subject Headings (MeSH terms) were used to facilitate searching (Wikipedia and Medical Subject Headings, 2020). This method resulted in a search strategy consisting of multiple combinations of keywords related to population, intervention and outcome in both databases (Tables 2 and 3). The

Table 1
Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Population	Human (men and women), healthy people, athletes, recreational and professional athletes, musculoskeletal sports injuries	Children (<13 year), elderly (>65 year), neurologic/cardiac/respiratory/ burned patients, psychological illness, amputation, gamers
Intervention	Extended Reality, Virtual reality, Augmented Reality, Video games	Hypnosis, robot (assisted) training, non-physical training stimuli (e.g. computer gaming without physical movement)
Control	/	/
Outcome	Rehabilitation, sports rehabilitation, injury prevention	Neurorehabilitation (i.e. the rehabilitation of patients with neurological disorders), surgery, fall prevention, telerehabilitation, pain, cost effectiveness
Study design	Original research papers, Clinical trials	Systematic reviews, meta-analyses, case reports, book chapters, conference proceedings
Language	English, French, Dutch	All other languages

Table 2
Search strategy for the PubMed database.

Keywords				
P (population)		**Intervention**		**Outcome**
athletes OR "patients" [Mesh] OR player OR patient*	AND	"virtual reality" [Mesh] OR "virtual reality exposure therapy" [Mesh] OR "virtual gaming" OR "augmented reality" OR "mediated reality" OR "reality simulation" OR "perceptual information" OR "virtual reality" OR "extended reality" OR "computer simulation"	AND	rehabilitation OR "functional outcomes" OR "pain scores" OR "patient satisfaction" OR "patient experience" OR rehab* OR "injury prevention" OR revalidation

Table 3
Search strategy for the Web of Science database.

Keywords				
P (population)		**Intervention**		**Outcome**
athletes OR player OR patient	AND	'virtual reality' OR 'virtual reality exposure therapy' OR 'virtual gaming' OR 'augmented reality' OR 'mediated reality' OR 'reality simulation' OR 'perceptual information' OR 'extended reality' OR 'computer simulation'	AND	rehabilitation OR 'functional outcomes' OR 'pain scores' OR 'patient satisfaction' OR 'patient experience' OR rehab OR 'injury prevention' OR revalidation

keywords and MeSH-terms were combined with boolean operators.

2.4. Study selection

All search results from PubMed and Web of Science were gathered in Endnote, where duplicates were identified and removed. Subsequently, every article was double and independently screened on title and abstract in Rayyan. Rayyan is a computer software that facilitates and accelerates the double blind work process in screening and selecting articles for inclusion in a systematic review (Rayyan, 2021).

If considered potentially relevant, the full article was consulted in the second screening phase, during which two independent researchers (blinded for each other's assessment), comprehensively read and assessed the full text using the predefined inclusion criteria (Table 1). In case of disagreement, a decision was made in a consensus meeting with the entire team of reviewers. Finally, a double blind hand search of the reference lists of the included articles was executed. Ultimately, ten articles were included in this systematic review. The entire process and the number of included articles in every phase of the review process described above, can be found in Fig. 1.

2.5. Data items and collection process

The most important features of each one of the included papers were summarized in an evidence table. To reduce bias and improve validity and reliability of this review, this information extraction was also conducted blindly by two independent reviewers. In case of disagreement, a third assessor was consulted.

2.6. Risk of bias in individual studies

In order to assess the methodological quality of the included studies, items from several checklists provided by the Dutch Cochrane Centre (Cochrane, 2018) were used, selecting only those questions which were mostly applicable to judge the risk of bias within this review's particular article selection. As such, relevant methodological assessment criteria for (1) randomized controlled trials, (2) side-effects and etiology, (3) prognostic studies and (4) diagnostic testing were integrated. The scoring items mostly involved (1) the process of participant inclusion in the final analysis, (2) the objective representation of the results and (3) the reasons for possible dropout.

The given items were answered with "+" (1 point), "-" (0 points) or "?" (0 points). If the article gave insufficient information to answer the question, no points were given. Eleven items were used to score the risk of bias (RoB), implying each article could be given a maximum of eleven points on this review's risk of bias assessment. Cut-off values were established arbitrarily to differentiate between "low", "medium" and "high" methodological quality (0–4: low, 5–6: medium, 7–11: high). RoB rating was performed by two independent researchers blinded from each-other's appraisal. In case of disagreement, consensus was reached through extensive mutual discussion.

Consecutively, each article was given a certain level of evidence, granted based on the EBRO guidelines found in 'Health literacy: from reference to review' by Mira Meeus (Meeus & Gebruers, 2016) (Table 4). These levels were used to determine the strength of conclusion of this systematic review.

The included articles were divided into two clusters: a rehabilitation and a prevention cluster. For each cluster, the articles'

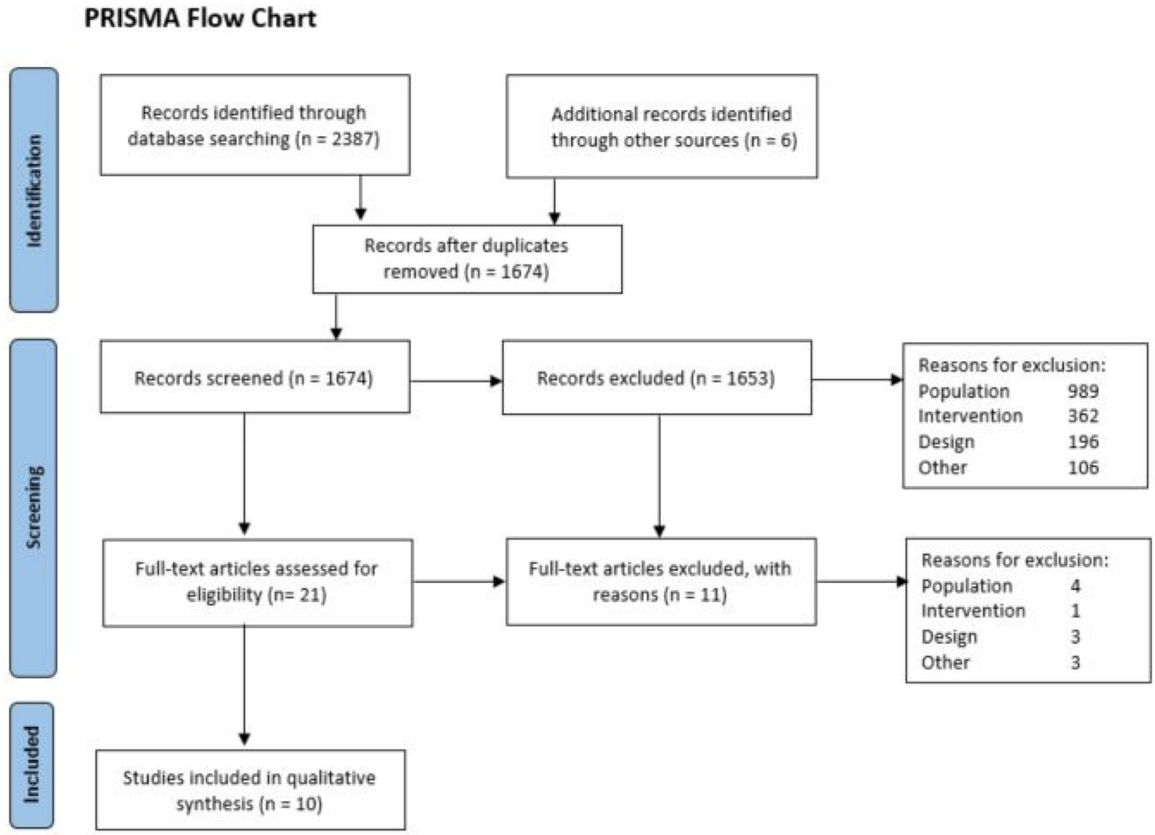

Fig. 1. Prisma flowchart.

Table 4
Assigning levels of evidence following the former EBRO method.

	Intervention	Diagnostic accuracy studies	Harm, etiology or prognosis
A1	Systematic reviews and meta-analyses, based on minimally 2 independent A2 studies		
A2	RCT's: double-blinded; with sound methodology; and with sufficient sample size	Studies using a reference test (golden standard) with previously defined cut-off values; independent assessment of index and reference test; sufficient sample of patients subjected to both test	Prospective cohort studies with sufficient sample size and follow-up; adequately controlled for confounding factors; and precluding selective loss-to-follow-up
B	Comparative studies, but lacking the quality criteria of A2 (including cohort studies and case-control studies)	Studies using a reference test, but lacking the quality criteria of A2	Prospective cohort studies, but lacking the quality criteria of A2, retrospective cohort studies and case-control studies
C	Non-comparative studies		
D	Expert opinion		

content was briefly situated and the results for each intervention group were described. For each cluster the general results were summarized. To map the risk of bias across studies, based on the subdivision of eligible articles in a rehabilitation and prevention cluster, the mean score for each cluster was calculated using the same 11-item scoring system, after which the levels of evidence were compared between clusters. Based on the comparison of scores between clusters, both were granted an appropriate level/strength of conclusion as well.

3. Results

3.1. Study selection

The search resulted in 2387 hits (771 from PubMed and 344 from Web of Science). Additional hand search resulted in the inclusion of 6 candidate articles for potential inclusion. After removal of duplicates, 1653 articles were excluded based on title and abstract, the remaining 21 articles were screened on full text. 11 articles were excluded because they did not meet the inclusion criteria. Finally, 10 articles were included in this review. The selection process can be found in the flowchart below (Fig. 1).

3.2. Study characteristics

The ten included studies, consisted of a total of 596 participants of which 290 males and 306 females. Sample sizes of the separate studies varied from 20 to 130 participants. There was no participant overlap between studies. The populations exposed to the (XR) intervention were athletes (3 studies), healthy adults (2 studies) and patients rehabilitating from an ankle sprain (2 studies), total knee arthroplasty (1 study) or ACL reconstruction (2 studies). Designs consisted of clinical trials (Baltaci et al., 2012; Gianola et al., 2020; Ibrahim, Mattar, & Elhafez, 2016; Punt et al., 2015, 2017) (amongst which four randomized controlled trials (RCT) (Gianola et al., 2020; Ibrahim et al., 2016; Punt et al., 2015, 2017), observational studies (DiCesare et al., 2020; Ibrahim et al., 2016; Kiefer et al., 2017), a diagnostic study (Gokeler et al., 2013) and an experimental study (Reneker et al., 2020). In five of the ten studies a control group was included (Gianola et al., 2020; Ibrahim et al., 2016; Punt et al., 2015, 2017; Reneker et al., 2020), four of them used randomization procedures (Gianola et al., 2020; Ibrahim et al., 2016; Punt et al., 2015, 2017). In five of the ten articles, a follow-up period was used between six weeks and six months in order to check if the sustainability of the training results. As regards the aim of the separate studies, some compared XR-assisted exercise therapy to conventional therapy and/or a control group (Baltaci et al., 2012; Gianola et al., 2020; Punt et al., 2015, 2017), others evaluated the exercise effects of VR-assisted training (Gokeler et al., 2013; Kiefer et al., 2017; Reneker et al., 2020) and one examined the influence of VR-assisted training on the athlete's injury-risk (DiCesare et al., 2020). The included studies were conducted between 2012 and 2020, in Europe, the United States of America and Asia.

3.3. Risk of bias within studies

The results of the methodological quality assessment are presented in Table 5. A score ≥7/11 is defined as high quality, which four articles succeeded to attain. The most prevalent methodological shortcomings were the absence of (1) double-blinding and (2) correction for confounders. Three articles were considered to be of medium quality (5/11 and 6/11) and three studies received a low quality score (≤4/11). These papers were not blinded or randomized, there was no sufficient follow-up period (≥6 weeks) and no report of the reasons for dropout was given.

3.4. Risk of bias across studies

The cluster prevention (DiCesare et al., 2020; Kiefer et al., 2017; Reneker et al., 2020) received a mean quality score of 5/11 with levels of evidence that vary between B and C, which was 7/11 for the rehabilitation cluster (Baltaci et al., 2012; Condino et al., 2019; Gianola et al., 2020; Gokeler et al., 2013; Punt et al., 2015, 2017) with associated levels of evidence ranging between A2 and B.

3.5. Results of individual studies

A comprehensive summary of the most important features and outcomes of the individual studies included in this review, can be consulted in the table of evidence (Table 6). In the section below, these results are discussed in detail by means of cluster. Within the prevention cluster healthy athletes were included (DiCesare et al., 2020; Kiefer et al., 2017; Reneker et al., 2020) whereas samples consisted of patients enrolled in the rehabilitation trajectory after having sustained an ankle sprain, total knee arthroplasty or an ACL rupture requiring surgical reconstruction, as well as healthy participants enrolled in a study assessing a VR application in lower limb strength and shoulder ROM rehabilitation in the rehabilitation cluster (Baltaci et al., 2012; Fu et al., 2015; Gianola et al., 2020; Gokeler et al., 2013; Ibrahim et al., 2016; Punt et al., 2015, 2017).

3.5.1. Prevention

Three studies examined sports injury prevention possibilities within a VR environment (DiCesare et al., 2020; Kiefer et al., 2017; Reneker et al., 2020). Dicesare et al. (DiCesare et al., 2020) and Kiefer et al. (Kiefer et al., 2017) both included 38 female adolescent soccer athletes. The aim of the study of Dicesare et al. was to examine the presence of biomechanical injury-risk factors (lower limb kinematics) during sport-specific/functional tasks (DiCesare et al., 2020). Participants performed a vertical drop jump in both standard clinical lab and VR-guided sport-specific situations, the latter implying that participants were looking at a big screen on which a corner-kick scenario was displayed. Drop vertical jump performance was compared between a regular drop vertical jump and a drop vertical jump during a header as a reaction to the VR simulated corner-kick. Study results indicated that lower limb kinematics were significantly associated with the occurrence of future musculoskeletal injuries, in particular ACL injuries. This association was only demonstrated based on the VR-guided kinematic testing results, revealing increased hip abduction at peak knee flexion and increased ankle inversion at initial ground contact in participants sustaining an ACL injury during follow up. The conventional clinical lab situation did not evoke deviating kinematic patterns during drop jump. The authors concluded that the use of VR (1) allows a more accurate reflection of the biomechanical risk

Table 5
Checklist for randomized controlled trial, side-effects and etiology, prognostic study (cohort) and diagnostic testing Used abbreviations: + = yes; − = no; ? = unclear/unsure; LOE = level of evidence.

Studies	Criteria											Score /11	LOE
	1	2	3	4	5	6	7	8	9	10	11		
IM Punt et al. (2017)	+	+	+	+	+	+	−	−	+	+	+	9	B
CA Dicesare et al. (2019)	?	−	+	+	?	?	?	−	−	+	−	3	C
A Gokeler et al. (2014)	−	−	?	+	+	+	−	−	−	+	−	4	B
JC Reneker et al. (2020)	?	−	+	+	+	+	−	−	+	+	−	6	B
IM Punt et al. (2015)	+	+	−	+	+	+	−	−	+	+	+	8	B
AW Kiefer et al. (2017)	?	?	−	+	+	+	?	−	+	+	+	6	C
G Baltaci et al. (2012)	+	+	?	+	−	+	+	−	+	+	?	7	A2
S Gianola et al. (2020)	+	+	+	+	+	+	−	+	−	+	+	9	B
ms Ibrahim et al. (2016)	+	−	?	+	+	+	−	+	?	+	−	6	B
S Condino et al. (2019)	+	−	?	?	?	?	?	+	?	+	−	2	C

Items RCT 1. The intervention allocation to patients was randomized?2. The effect assessors were blinded to the treatment?3. A full follow-up of a sufficient proportion of all included patients is available (>85%)? If no: is selective loss-to-follow-up sufficiently excluded?4. Selective publication of results is sufficiently excluded?5. A valid reference test was applied?.
Items side-effects and etiology 6. The compared groups are adequately defined? 7. It was screened double-blind (exposure and outcomes)?8. They corrected in the analysis for the most important prognostic factors (confounders: age, length, mass and hours of physical activity, randomized field theory correction)?.
Items prognostic study (cohort) 9. Was the follow-up sufficiently long? 10. The results of the study are explicitly described in objective terms?.
Items diagnostic testing 11. Dropouts were reported and the reason of their dropout was explained?.

Table 6
Evidence Table demonstrating most important features of the included studies.

Title, author, year, design	Participants	Intervention	Feedback	Objective	Outcome measures	Results	LOE	ROB
Effect of Wii Fit™ exercise therapy on gait parameters in ankle sprain patients: A randomized controlled trial Punt IM et al. 2017 Single blinded RCT	90 patients with lateral ankle sprain grade 1 or 2 18-64y 51 ♂ 39 ♀	**a. Wii Fit™ group** (30): balance board, instructions from an independent physical therapist (6 weeks 12 sessions of 30 min) **b. Conventional therapy group** (30): appointment in a private practice, therapy focussed on joint mobilization, muscle strengthening and proprioceptive exercises (6 weeks 9 sessions of 30 min) **c. Control group** (30): no exercise therapy	a. Visual b. Tactile c. None	The effectiveness of exercise therapy using Wii Fit™ in ankle sprain patients on temporal-spatial and kinematic gait parameters compared with conventional therapy and a control group	Primary outcome: gait speed Secondary outcomes: temporal-spatial (cadence, step length, single-support time, symmetry index of the step length and symmetry of the single-support time), kinematic (max dorsiflexion and max plantar flexion) and re-injury rate	**a, b, c.** Improvement in gait speed, cadence and step length between baseline and 6 weeks follow-up, no improvement of the symmetry index of step length, one re-sprained ankle on the initial side and one on the opposite side during one year follow-up **a.** Single-support time improved between baseline and 6 week follow-up **a, b.** Symmetry index of the single-support time improved between baseline and 6 months follow-up **b, c.** Maximum plantar flexion during the swing phase improved between baseline and 6 week follow-up None of the groups improved dorsiflexion	B	9
Realistic soccer-specific virtual environment exposes high-risk lower-extremity biomechanics Dicesare CA et al. 2019 Observational study	38 ♀ soccer athletes 14-17y	**a. Standard** drop vertical jump task **b. VR based** head kick jump (realistic sport scenario)	a./b. Visual	To examine injury-risk biomechanics on individuals performing sport-specific tasks within a simulated sport environment using VR	Hip, knee and ankle joint kinematics in the frontal and sagittal planes during landing	**a.** Increased hip abduction at the point of peak knee flexion and increased ankle inversion at initial contact **b.** Reduced hip flexion, hip abduction and ankle flexion at peak knee flexion, and reduced frontal plane ankle inversion at initial contact	C	3
Immersive virtual reality improves movement patterns in patients after ACLR: Implications for enhanced criteria-based return-to-sport rehabilitation Gokeler A et al. 2014 Diagnostic study	20 athletes after ACLR 19-28y 10 ♂ 10 ♀ 20 healthy controls 20-25y 10 ♂ 10 ♀	**a.** Step down task in **normal environment** **b.** Step down task in **VR environment**	a. None b. Visual, auditory	The evaluation of the influence of immersion in a VR environment on knee biomechanics in patients after ACLR	vGRF, knee extension moment, knee angle at vGRF and knee flexion excursion	**b in ACLR.** Increased vGRF, peak internal knee extension moment, knee angle at peak vGRF and knee flexion excursion **b in CTRL.** No difference in vGRF, decreased knee extension moment, peak knee angle and knee flexion excursion VR was employed to invite subjects to a more external focus, less internal focus allows for more efficient movement performance	B	4
Virtual immersive sensorimotor training VIST in collegiate soccer athletes: A quasi experimental study Reneker JC et al. 2020 Pilot, quasi-experimental study	130 participants 19-22y 73 ♂ 57 ♀	**a. Experimental group** (78) **b. Control group** (52) Nine exercises for sensorimotor training using IVR during 6 weeks	a. Visual, tactile b. None	To determine the effects of virtual immersive sensorimotor training intervention	Training effect measured via change in performance, the difference in the in clinical measures of functional sensorimotor control, the injury incidence rate and on-field performance during soccer competitions	**a.** Significant training effect for smooth pursuit, saccades, near-point convergence, peripheral vision, visual figure, joint position target and cervical neuromotor control Significant improvements for the clinical tests for cervical neuromotor control and endurance Significant improvement on isometric strength measurement, balance	B	6

Table 6 (*continued*)

Title, author, year, design	Participants	Intervention	Feedback	Objective	Outcome measures	Results	LOE	ROB
						stances and total balance score compared to b at post-testing No significant protective effect on injury incidence and overall on-field performance metrics		
Wii Fit™ exercise therapy for the rehabilitation of ankle sprains: Its effect compared with physical therapy or no functional exercises at all Punt IM et al. 2015 Single blinded RCT	90 patients with lateral ankle sprain grade 1 or 2 18–64 years 51 ♂ 39 ♀	**a. Wii Fit™ group** (30): balance board, instructions from an independent physical therapist (6 weeks 12 sessions of 30 min) **b. Conventional therapy group** (30): appointment in a private practice, therapy focussed on joint mobilization, muscle strengthening and proprioceptive exercises (6 weeks 9 sessions of 30 min) **c. Control group** (30): no exercise therapy	a. Visual b. Tactile c. None	To compare the effectiveness of exercise training using the Wii Fit™ in ankle sprain patients with physical therapy and a control group not receiving any treatment	Primary outcome: self-reported physical function measured with the Foot and Ankle Ability Measure Secondary outcomes: visual analog scale for pain at rest and while walking, delay to return to sport because of the ankle sprain, patients' satisfaction with the treatment, subjective perception of the effectiveness of the allocated treatment	**a.** Improved pain at rest during 6 week follow-up **a, b, c.** Improved foot and ankle ability scores, decreased pain during walking	B	8
Sport-specific virtual reality to identify profiles of anterior cruciate ligament injury risk during unanticipated cutting Kiefer AW et al. 2017 Observational study	38 ♀ soccer athletes 14-17y	All athletes entered VR and performed four acclimation tasks within the soccer specific virtual environment	Visual	The effect of a biofeedback-driven augmented NMT on skill transfer of ACL injury resistant movement patterns during performance of sport specific VR scenarios	Head position, internal hip rotation and knee abduction	Significant reduction in internal hip rotation was observed on the plant leg during the loading phase of cutting and an observed reduction during the push-off phase, from pre- to post-training No significant trend of a reduction in knee abduction was also observed	C	6
Comparison between Nintendo Wii Fit™ and conventional rehabilitation on functional performance outcomes after hamstring anterior cruciate ligament reconstruction: Prospective, randomized, controlled, double-blind clinical trial Baltaci G et al. 2012 Double blinded RCT	30 ♂ with ACLR 22-36y	**a. Wii Fit™ rehabilitation** (15): games were chosen to influence physical and functional movement, cognitive functioning and driving (1 h/session, 3 sessions/week) **b. Conventional rehabilitation** (15): weight bearing activities, closed kinetic chain flexion exercises, prone hanging for full knee extension, straight leg rise and isometric quadriceps sets to increase quadriceps control	a. Visual b. Tactile	To compare the outcomes of Nintendo Wii Fit™ with those of conventional rehabilitation on subjects with ACLR	Coordination, proprioception, response time, star excursion balance test and isokinetic test for knee strength	**a, b.** No significant differences in terms of isokinetic knee strength at 12th week No difference in dynamic balance and functional squat tests including coordination, proprioception and response time at first, 8th and 12th weeks of the rehabilitation	A2	7
Effects of early virtual reality-based rehabilitation in patients with total knee arthroplasty Gianola S et al. 2020 Single blind RCT	Baseline (3–4 days after TKA): 85 subjects Discharge (10 days after TKA): 74 subjects 45-80y. 37 ♂ 48 ♀	**a. Experimental group**: (B: 44; D: 35) VR rehabilitation **b. Control group**: (B: 41; D: 39) traditional rehabilitation **Both groups**: passive knee motion on a Kinetec knee and functional exercises (stair negotiation, level walking) (1 h/day until discharge)	a. non mentioned b. none	To compare the efficacy of early rehabilitation with VR via the VRRS versus traditional rehabilitation in improving functional outcomes after primary TKA	Pain intensity, disability knee, health related QoL, global perceived effect, functional independent measure, drugs assumption, isometric strength of Q and H, flexion ROM, ability to perform proprioception exercises	a. Global proprioception significantly higher No significant difference in VAS pain scores, QoL, Q and H isometric strength, knee active ROM, medication use	B	9
Efficacy of virtual reality-based balance versus Biodex balance system training on the	30 healthy adults (employees of the Faculty of	**a.BBSG** (15): trained using the Biodex Balance System (12 sessions, three 15-min sessions	**a.**visual **b.**tactile and visual	To test the efficacy of VR-based balance exercises at improving postural reactions and body	Usability, enjoyment, balance improvement and fatigue	**a.** Significantly higher fatigue after the training session **b.**Significantly higher	B	6

(*continued on next page*)

Table 6 (*continued*)

Title, author, year, design	Participants	Intervention	Feedback	Objective	Outcome measures	Results	LOE	ROB
body balance of adults Ibrahim MS et al. 2016 RCT	Physical Therapy) 35-55y 14 ♂ 16 ♀	per week) **b.VRG** (15): trained using the Nintendo ® Wii Fit Plus and its balance board (12 sessions, three 15-min sessions per week)		balance in comparison with the established BBS instrument.		enjoyment No significant difference in usability between the groups, but there was a preference towards the VRG. No significant difference in balance improvement between the groups, but there was a higher mean rank in the VRG.		
Wearable augmented reality application for shoulder rehabilitation Condino S et al. 2019 Observational Study	5 physiotherapists 20 healthy volunteers 23-52y 14♂ 11 ♀	**a.AR- game(25)** (‘painting discovery’)	**a.**visual, auditory	To improve the shoulder ROM delivering more specific, intensive and enjoyable therapy with real-time feedback of performance.	Performance	Overall, the participants agreed that the AR rehab game has a motivational value. Results reveal that the users experienced arm−shoulder fatigue. For all items, there was no statistically significant difference ($p > 0.05$) in answering tendencies among participants with different levels of experience with VG, AR, and Microsoft HL.	C	2

- Level of Evidence (LOE).
A1. Systematic reviews that comprise at least consistent.A2. High-quality randomised comparative clinical trials (randomised, double-blind controlled trials) of sufficient size and consistency B. Randomised clinical trials of moderate quality or insufficient size, or other comparative trials (non-comparative cohort study, patient control study).C. Non-comparative trails. D. Opinions of experts, such as project group members.
- Risk of bias (ROB) score/11.
- Used abbreviations: RCT = Randomized Controlled Trial; ♂ = male; ♀ = female; VR = Virtual Reality; ACLR = Anterior Cruciate Ligament Reconstruction; vGRF = vertical component of the Ground Reaction Force; CTRL = control group; VIST = Virtual Immersive Sensorimotor Training; IVR = Immersive Virtual Reality; NMT = Neuromuscular Training; ACL = Anterior Cruciate Ligament; TKA = Total Knee Arthroplasty; QoL = Quality of Life; Q = Quadriceps; H = Hamstrings; ROM = Range Of Motion; VRRS = Virtual Reality Rehabilitation System; B = baseline; D = discharge; BBSG= Biodex balance system group; VRG= Virtual reality group; AR = augmented reality; VG = video games; HL = HoloLens.

profile in screening procedures, (2) increases the validity and sensitivity of injury risk assessment and (3) is therefore suggested to have a significant added value in injury prevention management.

Kiefer et al. investigated the effect of biofeedback-driven augmented neuromuscular training on skill transfer of ACL injury resistant movement patterns (e.g. reduced hip internal rotation and knee abduction) (Kiefer et al., 2017). In the pre- and post-training assessment sessions, quality of movement was established during particular cutting scenario's. During the 8-week training period, athletes performed four acclimation tasks within a soccer specific virtual environment with a training frequency of three times per week. This virtual environment was created using a head mounted display in conjunction with custom-designed sport-specific VR-scenarios and aiming to quantify the neuromuscular training response. Quality of movement during cutting was assessed prior to and after intervention, assessing head position, internal hip rotation and knee abduction as particular outcome parameters. Head and lower limb movement trajectories were tracked three-dimensionally using 31 retro-reflective markers and 39 motion capture camera's. Significant reduction in internal hip rotation on the plant leg during the loading phase and the push-off phase of an unanticipated cutting task was observed when comparing the pre-training with the post-training results using the VR augmented neuromuscular training. The authors concluded that respective VR induced improvement in sport-specific lower limb biomechanics lowered the athlete's susceptibility to future ACL injury, although these results were not compared with the ones of a more conventional training approach.

The third article of Reneker et al. (Reneker et al., 2020) included 130 participants and investigated the effects of virtual immersive sensorimotor training on 1) the change in performance pre-to-post intervention, 2) the difference in functional sensorimotor control measures, 3) the injury incidence rates and 4) the athlete's on-field performance during soccer competition. An experimental group received sensorimotor training using immersive Virtual Reality (IVR) (using the ‘Oculus Quest’, consisting of a six degrees-of-freedom headset and two manual touch controllers) during 6 weeks, while the control group received no therapy. The use of VR resulted in a significant training effect for smooth pursuit, saccades, near-point convergence, peripheral vision, visual figure, joint position target and cervical neuromotor control in the experimental group, while no differences could be established in the control group (p-values between <0.0001 and 0.005). Significant improvements in cervical neuromotor control and endurance were also established in the VR group compared to the control group, which was the case for isometric strength measurements and balance scores as well (p-values between <0.0001 and 0.005). In the control group, no differences could be established in any of these outcome measures when comparing baseline to post-testing outcome measures. As regards the effects of VR on injury incidence and overall on-field performance capacity, no significant (protective) effects could be demonstrated. The authors concluded that the significant improvements in both the performance and clinical tests, provide evidence for the presence of a significant transfer effect of these complex skills towards real-time athletic situations. The results of this study also promote the use of VR to enhance injury prevention approaches.

3.5.2. Rehabilitation

Seven studies examined the use of VR in the rehabilitation of musculoskeletal injuries (Baltaci et al., 2012; Condino et al., 2019; Gianola et al., 2020; Gokeler et al., 2013; Ibrahim et al., 2016; Punt et al., 2015, 2017). Two studies written by Punt et al. (Punt et al., 2015, 2017) included 90 lateral ankle sprain patients which were divided into three groups: a Wii Fit™, a conventional therapy and a control group. The first article (Punt et al., 2017) investigated the effectiveness of exercise therapy using Wii Fit™ on temporal-spatial and kinematic gait parameters, comparing the three groups of participants. Improvements in gait speed, cadence and step length between baseline and 6 weeks of intervention were found in all groups. No improvement of the symmetry index of step length was established in any of the groups and only one re-sprained ankle on the initial side and one on the opposite side during one year follow-up was seen in every group. Only in the Wii Fit™ group's single-support time improved between baseline and 6 weeks of intervention. Symmetry index of the single-support time improved between baseline and 6 months of follow-up in both the Wii Fit™ and conventional therapy group. In the conventional therapy and control groups, maximum plantar flexion during the swing phase improved between baseline and 6 weeks follow-up. None of the groups improved as regards dorsiflexion range of motion. Wii Fit™ training demonstrated to have similar effects on temporal-spatial gait parameters as conventional physical therapy, which made the authors conclude that it can be considered as alternative treatment in the rehabilitation of ankle sprain patients, without any particular added value. In the second article (Punt et al., 2015), rehabilitation outcomes of exercise training using the Wii Fit™ system were compared with standard physical therapy and a control group receiving no therapy at all. There was no difference between groups, all participants improved in foot and ankle ability scores and pain was decreased during walking. The authors concluded that Wii Fit™ might be suggested rather than conventional rehabilitation for ACL patients, because Wii Fit™ could also address functional exercise goals, albeit purely speculative.

Baltaci et al. aimed to compare the outcomes of Nintendo Wii Fit™ training with those of conventional rehabilitation in subjects after Anterior Cruciate Ligament Reconstruction (ACLR) (Baltaci et al., 2012). 30 male patients having undergone ACLR participated in the study. The Wii Fit™ group had to perform functional tasks (games) stimulating functional performance capacity and cognitive functioning. The conventional therapy group had to perform several exercises such as weight bearing activities, straight leg raises and isometric quadriceps settings to increase quadriceps control. No significant difference in terms of isokinetic knee strength was established after 12 weeks of intervention when comparing both groups. Coordination, proprioception and response times did not differ neither between groups, Although no in between group differences could be established, the authors concluded that a Wii Fit™ Balance program might be suggested instead of conventional rehabilitation, since it is safe, feasible, cheap and attains similar functional outcome scores compared to standard physiotherapy strategies.

20 athletes having undergone ACLR and 20 healthy controls participated in a study of Gokeler et al. (Gokeler et al., 2014). They were asked to perform a step down task in a normal (traffic light changing from red to green projected on a grey screen) and in a VR environment (traffic environment depicted a city street with high buildings and a crosswalk with a pedestrian traffic light and cars projected on the screen passing from left to right), mimicking the simple daily task of stepping down the side-walk to cross the street. Kinetics and lower limb kinematics were evaluated using a force plate and 11 infrared-reflective markers tracked by 12 infrared cameras. The aim of the study was to evaluate the influence of immersion in a VR environment on knee biomechanics in patients after ACLR during a step-down task. Increased vertical component Ground Reaction Force (vGRF), peak internal knee extension moment, knee angle at peak vGRF and knee flexion excursion was seen among the athletes after an ACLR in the VR environment, compared to their performance in a non-VR condition. Among the healthy controls in the VR environment no differences in respective outcomes could be established when comparing their outcomes of the normal and VR-guided testing conditions. The effect of Virtual Reality evoked greater interruptions in joint biomechanics in patients following ACLR compared to the control condition and control group. These findings made the authors conclude that immersion in Virtual Reality may have influenced the focus of attention, making functional and return to play (RTP) screening using VR more sensitive to residual functional deficits after ACLR, compared to conventional clinical evaluation conditions.

Gianola et al. aimed to assess the efficacy of an early VR-based rehabilitation protocol compared to a traditional rehabilitation regimen in patients having undergone primary total knee arthroplasty. 85 patients were randomized to a VR-based rehabilitation group or a traditional rehabilitation group (Gianola et al., 2020). Outcomes were assessed at baseline (3–4 days after TKA) and at discharge. Eleven patients dropped out of the study. The data from 74 patients were available for the final analyses. Results revealed that proprioception had improved significantly better in the VR-based rehabilitation group compared to the control group. There was no significant in-between group difference in pain and medication use reduction, or in increments in quality of life, quadriceps and hamstrings isometric strength and active knee Range Of Motion (ROM). The authors concluded that VR-based rehabilitation is not superior to traditional rehabilitation in terms of pain relief and other functional outcomes but seems to improve the global proprioceptive qualities in patients after TKA.

Ibrahim et al. investigated the efficacy VR-based balance exercises in comparison with the established Biodex Balance System (BBS) by assessing improvements in body balance and postural reactions (Ibrahim et al., 2016). Thirty healthy adults, were recruited in this study and randomly and equally assigned into two experimental groups of 15. There was a Biodex Balance Group who trained using the BBS and a virtual-reality group who trained using the Nintendo ® Wii Fit Plus and its balance board. There was no control group. According to the results there was no significant difference in balance improvement between the two groups, although there was a higher mean rank for the virtual-reality group. Nonetheless, there was a significantly greater perception of fatigue in the Biodex Balance Group after the training session, whereas the virtual reality group presented a significantly greater perception of enjoyment.

Condino and colleagues evaluated the AR-game system designed to improve the shoulder Range Of Motion (ROM) by delivering more specific, intensive and enjoyable therapy with real time visual and auditory feedback of performance (Condino et al., 2019). Five physiotherapists and 20 healthy volunteers were recruited in this observational study, there was no control group. The participants agreed that the AR rehab game has a motivational value. Nonetheless there was no statistically significant difference for all items in answering tendencies among participants with different levels of experience with video games, augmented reality and Microsoft HoloLens. Furthermore results reveal that the users experienced arm-shoulder fatigue after training.

Overall, seven of the ten articles demonstrated an improvement when using XR-assisted therapy in injury prevention (assessment) and rehabilitation approaches (DiCesare et al., 2020; Gianola et al., 2020; Gokeler et al., 2013; Kiefer et al., 2017; Punt et al., 2015, 2017;

Reneker et al., 2020), but only two articles could demonstrate a significant additional effect compared to conventional physiotherapy (Gianola et al., 2020; Kiefer et al., 2017; Reneker et al., 2020).

4. Discussion

This systematic review aimed to summarize the currently available scientific evidence regarding the value of XR-assisted training in sports rehabilitation and injury prevention. It partially confirms this review's hypothesis stating that athletes submitted to XR-assisted physical therapy deliver satisfactory results in terms of proprioception, balance, muscle force, pain scores, biomechanical movement patterns in rehabilitation. In comparison with control conditions, study results mostly revealed improvements in proprioception as a result of VR-guided sensorimotor training, but VR has not yet proven to be of particular value in preventing injuries as no significant protective effect on injury incidence could be established to date (Reneker et al., 2020). Including VR applications in the rehabilitation protocols of patients after ankle sprain, ACL reconstruction and total knee arthroplasty, proved to result in significant improvements in pain, isometric muscle strength, balance and overall proprioception [18, 42, 487], whereas no differences could be established in isokinetic strength and kinematics (Baltaci et al., 2012; Punt et al., 2017). VR-assisted training for rehabilitation and secondary prevention purposes was also established to result in lower levels of perceptual fatigue, improved patient experience as well as more efficient, more qualitative and more specifically sport-adapted kinematic profiles in the lower limb during functional sport-specific tasks (Gokeler et al., 2013; Ibrahim et al., 2016; Kiefer et al., 2017). Next to its value in (secondary) prevention training regimen, XR also proves to be worthy of implementation in screening procedures for lower limb injury risk identification. Although the evidence for XR-implementation in injury prevention is currently limited and has only reported its value in risk assessment screening procedures, preliminary results are in favor of the use of XR-conditions as this seems to improve the sensitivity of screening procedures aiming to identify athletes at increased risk of lower limb injury (DiCesare et al., 2020).

The main differences between clusters concerns randomization and blinding of patients and assessors. Overall, this leads to a higher strength of conclusion in results and stronger evidence as regards the use of XR for rehabilitation purposes, compared more limited evidence regarding its potentially added value for sports injury prevention purposes.

4.1. Specific effects of XR use on performance

This systematic review aimed to evaluate the effects of XR on performance, including motor skills (proprioception, balance, and strength) and quality of movement (biomechanics). Results of this review indicated that XR-guided training in musculoskeletal rehabilitation might be of added value for the improvement of proprioception and balance skills, although more large scale research is necessary to support these preliminary findings. Research performed in different (patient) populations, gave rise to similar conclusions. As such, VR implementation in the rehabilitation of ACLR patients, Parkinson patients and stroke patients would facilitate improvements of knee proprioception (Aydo Äź du et al., 2017), balance and gait quality/performance (Feng et al., 2019) and both static in dynamic balance control (Marks, 2017) in these particular patient populations, respectively. Nonetheless, as regards its effects on proprioception and balance skills, the authors conclude that XR has the ability to improve functional outcomes when used in addition to conventional physical therapy. There is currently no evidence for the isolated use of XR to promote improvements in proprioception, balance and body posture during rehabilitation.

To what concerns the value of VR-guided training for strength improvements, this review could only gather limited evidence (only improvements in isometric lower limb strength in healthy collegiate soccer players could be documented) (Reneker et al., 2020). Other research investigating the value of VR-guided training and rehabilitation in non-musculoskeletal patient populations established that VR has the ability to promote improvements in (lower limb) muscle strength in children with cerebral palsy (Cho et al., 2016), patients with incomplete spinal cord injury (Villiger et al., 2017), patients having undergone Total Knee Replacement (TKR) surgery (Hong & Lee, 2019) and community dwelling elderly (Lee et al., 2017). These findings should be interpreted carefully however, as control (conventional physiotherapy) conditions are only rarely used in these research settings, which makes it impossible to objectify the additional effects of XR. As regards biomechanical quality, this review's results revealed that XR-simulated sport-specific training contexts enabled significant improvements in lower limb biomechanics, and that XR applications also seem to have an additional value in biomechanical/kinematic assessment procedures where it has demonstrated improving the sensitivity and accuracy of the detection of biomechanical errors in the context of injury risk identification. This because it externalizes the athlete's focus of attention, making him move more naturally and intuitively like is the case in real athletic training and competition conditions. These results are supported by other literature which has mostly investigated the role of the use of Extended Reality for the improvement of lower limb kinematics in healthy subjects (observational and fundamental research) (Bennour et al., 2018), patients with neurological disorders (Oh et al., 2018) and stroke patients (Oliva-Pascual-Vaca et al., 2016). Albeit with very little scientific evidence due to low methodological quality and small sample sizes, these studies demonstrated that VR training is able to improve lower limb sagittal plane kinematics during gait (Bennour et al., 2018), has the capacity to improve gait speed and movement accuracy in stroke patients (Oliva-Pascual-Vaca et al., 2016) and might be of value in the assessment and training of gait and turning capacity in patients with neurological disorders (Oh et al., 2018).

4.2. Specific effects of XR on pain perception

Within this review, only one study assessed the effects of VR-implementation on pain outcomes during rehabilitation after ankle sprain, and did not report any additional effect of VR in terms of pain relief (Punt et al., 2015). Other work of Phelan and colleagues assessed the effects of using VR as an adjunct to pharmacological therapy in the management of burn pain and established that active VR scenarios (e.g. rounding up and herding sheep through obstacles and making basketball shots with varied feedback) reduced the subjective awareness of pain whereas patients also perceived the effectiveness of treatment to be good (Phelan et al., 2018). Another study of Arane and colleagues also concluded that the interaction with immersive VR might divert the patient's attention, leading to a slower response to incoming pain signals. The rationale behind these pain reduction effects would mostly be related to the limited attentional capacity of patients (Arane, Behboudi, & Goldman, 2017). VR application distracts and entertains, making the patient's focus shift systematically to virtual objects, allowing mediation of pain (management) (Ahmadpour et al., 2019). Based on their review, Pourmand and colleagues conclude that the use of VR is effective for short-term pain relief in both acute and chronic pain. Particularly, VR distraction providing immersive environments wherein patients interact with the virtual scenario, appear most effective (Pourmand et al., 2018). In conclusion, XR would distract the attention from pain, causing the patients to feel better and consider this treatment modality to be entertainment rather than on 'obligated treatment' session. This yet needs to be investigated in musculoskeletal rehabilitation conditions because in this domain, evidence as regards the value of XR for the purpose of pain reduction is non-existent at present.

4.3. Benefits of XR in injury prevention

As regards its application possibility in the prevention of sports injuries, this review concluded that XR is likely to have a beneficial effect on the training results of XR-guided prevention programs as well as permitting more valid injury risk identification screening due to the fact that it provides a natural, realistic and maximally sports specific training and testing environment, obliging the athlete to focus on external sport-context specific stimuli rather than his own movement patterns (internal focus). A study performed by Reneker et al. from 2019 observed a 27% total reduction in injury rate after VR-guided sensorimotor training. These results indicate an improvement in clinical measures of sensorimotor control, potentially decreasing the risk of sports-related concussion injuries (Reneker et al., 2019). Although the evidence of the implementation of XR in sports injury prevention remains limited due to scarcity in existing research, other studies already established its added value in fall prevention in the elderly as well. Falls are the main cause of injuries in older people. Therefore, Stanmore et al. investigated the effectiveness of exergaming (gamified video-based exercises) as a possible approach to reduce the risk of falls and associated injury. This was done by comparing the incidence of falls between groups, both consisting of adults older than 55 years, staying in assisted living facilities. The incidence of falls demonstrated to be significantly lower in the exergame group, making the authors conclude that this VR approach is effective to serve the purpose of fall (injury) prevention. This was confirmed by others as well, as VR-guided training approaches using Wii fit™ were able to reduce the number of falls to a higher extent compared to conventional training approaches (Fu et al., 2015).

XR seems to be promising for prevention training and screening purposes as it allows greater conformity with daily and sport-specific contexts compared to conventional training and clinical assessment procedures.

4.4. Strengths and limitations

As in most systematic reviews, this study was limited by the available literature, which was scarce. This review only consisted of 10 studies as its research question specially focused on prevention and rehabilitation of musculoskeletal injuries in athletes and healthy subjects. This resulted in the demarcated inclusion of athletes/patients rehabilitating from particular conditions (ankle sprain, TKA and ACLR) most common in sports and (2) most likely benefiting from the implementation of XR (as this training approach primarily focusses on functional improvement of proprioception, balance, quality and efficacy of movement and strength). A second limitation is that the included articles were highly variable as regards adopted exercise protocols, type of sports/athletes included, and selected outcome measures, which prevented direct comparison of the included studies and made it difficult to come to specific conclusions to support the existing evidence.

Nonetheless, this is the first systematic review attempting to provide an overview of the existing evidence as regards the value of the use of XR in injury rehabilitation and prevention. Considering 1) the fact that XR is becoming more and more popular in the field of training and sports medicine, 2) the attractiveness of XR-guided training protocols and 3) the crucial fact that the athlete's/patient's response to rehabilitation or prevention programs is largely dependent on adherence, this review might be a first step towards stimulating the conduction of future research concerning the use of XR in injury prevention and rehabilitation. When attempting to do so, researchers should aspire sufficient standards of methodological quality and apply uniformity as regards the choice of outcome measures.

5. Conclusion

To our knowledge, this is the first systematic review discussing the potential of XR to improve clinical outcomes and training responses in musculoskeletal rehabilitation and injury prevention. Due to the relatively small number of studies, it was not possible to reach any definitive consensus regarding the general value and specific application possibilities. As regards its potential in injury prevention, no valid guidelines or practical advice can be drafted at present because of the low to moderate methodological quality of the included studies, affecting the strength of conclusion. There is however more evidence for use of XR in the musculoskeletal rehabilitation, since its additional value as regards implementation on top of conventional physiotherapy was brought to the evidence at a moderate to high quality level. Nonetheless, more large-scale prospective research is needed in order to determine if XR-assisted therapy is superior to conventional therapy in both injury prevention an rehabilitation.

Authorship

Each author played a significant and crucial role in this review's data collection, processing and writing phases, and ultimately, the finalization of this manuscript.

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