Augmented reality applications in rehabilitation to improve physical outcomes: a systematic review.

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Abstract

Background: Augmented Reality (AR) is a relatively new technology which blends virtual objects with real scenes in real time and this may be an effective intervention to use in rehabilitation.

Objectives: To systematically review the evidence for the effectiveness of AR applications on rehabilitation outcomes within a physical context.

Method: A systematic search of the literature using specified search terms that included studies of any quantitative design testing AR applications in rehabilitation within a physical context.

Results: The included 13 studies were of varying designs and generally rated poorly on methodological quality assessment. All studies reported varying degrees of improvement in outcomes with the use of AR applications. The technologies used were mostly in the prototype phase of development and were a mixture of simple and complex systems.

Conclusion: AR applications for rehabilitation in a physical context are still in the early stages of development and thus evidence for effectiveness in rehabilitation is limited. The technology appears not ready for general practical use but the encouraging results support further research.

Keywords: augmented reality, mixed reality, physical rehabilitation, systematic review

Introduction

Virtual Reality (VR) applications are increasingly used as adjuncts to rehabilitation. Development of VR technology has made it possible to combine reality with virtual objects in real time, creating a mix of the real environment and the virtual environment to form Augmented Reality (AR). [1] AR is based on the combination of different technologies and is well known in everyday (media) life, for example, the TV weather channel forecaster in front of the weather map or the recognition of QR codes (square marker patterns) with camera-equipped cell phones. VR technologies completely immerse a user inside a synthetic environment; while immersed, the user cannot see the real world around him. [2] In contrast; AR or Mixed Reality allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. [3] Therefore, AR supplements reality but does not replace it. [3] Azuma defines AR systems as having three characteristics, namely: 1) they combine real and virtual objects, 2) it is interactive in real time, and 3) it is registered in 3-D. [2, p. 2] AR potentially has the advantage over VR in rehabilitation as it provides better sense of presence and reality judgments of the environment as the elements the patient uses to interact with the application are real. [2] In AR systems patients can, for instance see their hands and feet and how they are interacting with the application and the environment. [4] As technology involved in AR becomes more accessible and affordable, a greater uptake of AR interventions in clinical rehabilitation settings is likely. Therefore, it is important to evaluate the effectiveness of AR interventions in rehabilitation to guide future use. To our knowledge, no systematic review of AR applications in rehabilitation related to physical outcomes has been undertaken. This paper reports on a systematic review of the literature that investigated the effectiveness of AR applications in rehabilitation within a physical context. While there is a substantial body of work on studies of AR technology for physical rehabilitation and studies with healthy participants,[5-7] we are focusing on clinical studies with reported effects.

Method

A search for relevant literature was performed in the following databases: MEDLINE (Ovid) (1950- 2010), EMBASE (Ovid) (1980–2010), Cochrane Central Register of Controlled Clinical Trials and Cochrane Database of Systematic Review (2010), Database of Abstracts of Reviews of Effectiveness (DARE), PsycInfo (1966 – 2010), CINAHL (1982 – 2010), Web of Science (1900 to 2010), AMED (Ovid) (1985 to 2010), Scopus(2010), PEDro (Physiotherapy Evidence Database), ACM Digital Library (2000 to 2010), IEEE Visualization and Computer Graphics (IEEEXplore), MIT Press: Presence Teleoperators and Virtual Environments, Cyber Psychology and Behavior, IEEE Computer Graphics and Applications (IEEEXplore), Virtual Rehabilitation Conference (IEEEXplore), and International Symposium on Mixed and Augmented Reality (ISMAR) (IEEEXplore). Each database had its own indexing terms and functions, and hence different search strategies were developed for each database. In MEDLINE, the keywords search was used with Boolean operators and the search strategies for the remaining databases were adapted accordingly. Search strategies are listed in Appendix A. The search terms used for this review were: physical rehabilitation, rehabilitation, physiotherapy, occupational therapy, physical therapy, exercise, augmented reality and mixed reality. The reference lists of articles included in the review were examined to identify further studies for retrieval.

The following conferences proceedings were hand searched for relevant studies: International Symposium on Augmented Reality (ISAR 2000, ISAR 2001), the IEEE Workshop on Augmented Reality (IWAR 1998, IWAR 1999), and the International Symposium on Mixed Reality (ISMR 1999, ISMR 2001), since these proceedings could not be found or searched

for electronically. Again, the reference lists of articles included in the review were examined to identify further studies for retrieval.

Two reviewers (HA, HR) independently reviewed the titles and abstracts identified from the database searches and eliminated those articles that were definitely not within the topic of interest. Then, the full-text formats of the remaining articles were retrieved and independently assessed by the same reviewers to determine whether they met the defined inclusion criteria described in Table 1.

The review authors documented the reasons for exclusion independently and compared findings. For the most part, the reviewers reached the same conclusion independently, however, there was some disagreement. If the disagreement was about the type of intervention or the AR aspect, the second author (HR), an expert in the field of AR, decided whether to include the study or not. If the disagreement was about the rehabilitation aspect, then the third author (LH), an expert in rehabilitation, decided whether to include the study or not.

To be included in the review papers had to meet the inclusion criteria listed in Table 1. To restrict the search to a manageable proportion, AR interventions were included only if their primary aim was to enhance physical function, as opposed to psychological, cognitive, or sensory function.

The quality of the included studies was assessed independently by two reviewers (HA, LH) using three quality assessment tools: the Critical Appraisal Skills Programme (CASP) for cohort studies (for the non-randomised studies including single case, case series, and

questionnaire studies), the CASP for case control (for the case control studies), and the CASP for RCTs (for the randomised controlled trials).[8] Quality was assessed purely for descriptive purposes and not to exclude any article from the review. There were some disagreements between the two reviewers on some of the quality assessment answers but consensus on these disagreements was reached on discussion and therefore a third reviewer was not consulted. Two review authors (HA,LH) independently recorded information from the included studies on a pre-designed data extraction form and compare findings to ensure reliable data extraction; disagreements were solved with discussion or consultation of the second author (HR). Given the different types of studies found, the varying number of outcome measures used, and the small sample size of included studies, a meta-analysis of data was not possible.

Results

Figure 1 reports the results of the search; 14 articles [9-21] and 14 studies were included in this review. Two articles reported on the same study [17,18] and one article reported on two different studies.[21] Table 2 shows the characteristics of the included studies. The sample sizes of the these studies were small, varying from 1-20 participants. The age range for 8 of the 14 studies collectively ranged from 6-86 years (mean age could not be calculated as some studies only reported the age range). One study did not state any age range, but reported a mean age of 70 years for the experimental group and 60 years for the control group. [9] One study specified only that participants were over the age of 18 years old. [15] Participants included in the studies had a range of conditions, including, traumatic brain injury (n=2 studies), [19,20] stroke (n=4 studies), [15-18] Parkinson's disease (PD) (n=4 studies), [9,11,13,14] cerebral palsy (n=1 study), [11] multiple sclerosis (n= 1 study), [12] and upper limb disability (n=2 studies). [20,21]

In Table 3 shows the intervention duration, the technological apparatus, the outcome measures used, and a summary of the main findings of the included studies. Where possible statistical results have been included but a number of studies did not or were unable to report statistical findings. In all included studies there was no report of drop outs of participants, however, some studies applied the AR application within in a single session [9-11,14,21] and not over a series of sessions over time. As can be seen in Table 3 the type of AR varied from simple and basic systems [9-14] to more complex and advanced systems. [15-21] In most studies two or more outcome measures were used (Table 3). The most frequently used outcome measure was that of walking speed. [9-12,14,16] Four studies used stride length as an outcome measure, [10-12,16] and three studies [17-19] used the Box and Block outcome measure [22] to determine the effect of the therapeutic intervention. In two studies, [15,20] the Disability of the Arm, Shoulder and Hand (DASH) questionnaire [23] was included as a measure of use of upper limb in everyday life. On examination of the included studies, it was not often clear what the main or primary outcome measure was.

Varying degrees of post or during intervention improvements were reported as can be seen in Table 3. Studies reported improvements on stride length, walking speed, Box and Blocks test, the DASH questionnaire, movement accuracy and efficiency. Additionally, improvements were reported for range of motion, finger extension, number of freezing episodes (in participants with PD), balance, and the force required to hold objects. Two studies, reported on participants satisfaction with and user acceptance of the intervention. [13,21] A few adverse effects were reported, for example, in one study the participants reported that the headset was too heavy to use. [21]

The quality assessments of the included studies are summarised in Table 4 – 6. Only the results of the questions of the quality assessment tools requiring answers of "yes", "no", and "can't tell" are reported; the answers to the open-ended question were not included because there was an overlap of reporting of the answers to these questions with that reported in the data extraction tables. For only one study, a case control study, [12] were all the answers a "yes". Studies mostly did not explain how participants were recruited or identify confounding factors, reducing the generalisability of the results. The three randomised controlled studies did not account for assessor blinding and were underpowered.

Discussion

To our knowledge, this is the first systematic review that investigates the effectiveness of AR applications in rehabilitation within a physical context. In this systematic review, the results of different designs were included. The search only found 14 studies despite wide inclusion criteria. It would appear therefore that the research in AR is still in its infancy. Three systematic reviews of *virtual reality* in rehabilitation have been recently published; however, they differ from our review. Saposnik and colleagues [24] reviewed literature that investigated the effectiveness of VR interventions for upper limb function post-stroke. Any VR system was eligible for inclusion in this review, yet this review included no studies that we have included in our study, possibly as the authors excluded case reports or case series of three or less patients. Similarly, Laufer and Weiss [25] included any type of VR application in their review of VR in the rehabilitation of children with sensorimotor deficits, as did Galvin et al [26] in a review of VR interventions used in upper limb rehabilitation in children with neurological impairment. Neither of these two reviews had conclusive findings for the effectiveness of VR in a paediatric population.

AR applications appear to be still in a prototype stage of development. The papers reviewed describe the technology used and, as can be seen in Table 3, the type of AR varied from simple systems [9-14] to more complex and advanced systems. [15-21] Although we classified these systems as simple or complex, they were in fact fairly intricate applications for use in rehabilitation. In six studies, a "visual-feedback AR-apparatus" was used as the therapeutic intervention, comprising visual cues incorporated within glasses to assist walking. [9-14] In one study, the researchers used a device called "optical stimulating glasses" which allowed the peripheral field of view to be stimulated through two modes: (1) a continuous horizontal optic flow produced by vertical lighting lines scrolling backward; and (2) lighting stimuli that were synchronised to the step phases of gait by a connection with switches underneath the feet. [9,27] In another study, the researchers used a device called "visual cue glasses" which used two light emitting diodes at the top of each lens to generate a virtual image of a horizontal line on the floor below the patient's main field of view. This visual image combined with an auditory click provided a simultaneous rhythmic cueing whilst the person walked. [14] In two studies, Baram et al. [11,12] used a device called the "visual-feedback virtual reality apparatus", a closed-loop head mounted device that provided a display, attached to the frame of the eyeglasses, to generate a virtual tiled floor in a checkerboard arrangement that responded dynamically to patient motion. [28] In another study, Baram et el. [10] used a device that comprised a head-mounted 3-axis rotational accelerometer, a body mounted 3-axis translational accelerometer and a see-through head-mounted display, all connected to a wearable computer. [29] The device could operate in two modes: (1) the open-loop mode where the virtual tiled floor provided perpetual motion in the direction of the observer at a constant speed despite the patient's motion; and (2) an adaptive closed-loop mode where the virtual floor appeared to be fixed in space as a real floor. In this study, a device, called "virtual cueing spectacles" was used to provide visual cues in the environment which were generated

by a light-emitting diode display on one side of the spectacles that produced a series of horizontal lines that were reflected off a lens into the patient's eye. [10]

Eight studies reported on the use of an advanced AR system. Two of these studies [17,18] used the same AR system. This system comprised a head-mounted display which projected virtual objects for a reach and grasp exercise. An assistive device, composed of either a body-powered orthosis or a pneumatic-powered device, physically assisted the upper limb in the reach and grasp task. [17,18] In another study the AR system was a 42-inch table-top liquid crystal display (LCD), camera tracking system and tangible user interface. [19] In one study the complex AR system comprised an overhead mounted web camera which tracked the position of the fiducial marker on the patient's hand or wrist. [15] A further AR system described was one which a video see-through head-mounted device and a Sensable Phantom Omni haptic device were used in combination to generate realistic 3-D visual and haptic feedback to the user. [21]

Jaffe et al. [16] used training on "treadmill with virtual obstacles" to improve walking function post-stroke. This complex AR system comprised a fixed external camera, a video head-mounted device, a foot switch, and a foot vibrator which generated a view of real time virtual images of obstacles. The AR exercise system used by Sveistrup et al. [20] was called the "interactive rehabilitation exercise" (IREX) and comprised a projection screen and a fixed external camera which generated a virtual environment.

Given the complexity of some of the systems described above, one may reiterate Heidi Sveistrup's question "Can the same objective be accomplished with a simpler approach?"[30,p.17] However this question cannot be asked of AR technology until it is

developed to a stage where it can be compared with existing rehabilitation interventions, for example in the Jaffe et al [16] study improving functional gait post-stroke by stepping over "real" objects versus steeping over "virtual" obstacles. Virtual reality in rehabilitation has been born out of the hypothesis that the virtual environment can provide real-time, realistic motivating environments for patients to practice in, potentially enhancing the principles of rehabilitation, particularly in scenarios where the patient may not otherwise have the opportunity to practice such motor tasks. [24-26] In the Jaffe et al study [16] example, the "virtual" obstacles could possibly be manipulated to a greater extent than the "real" objects and thus be made to suit the needs of individual patients. Although many AR applications may not yet be at a stage for common clinical usage, let alone research beyond the proof of concept stage, this paper provides the reader with a glimpse of the technologies to come. With this insight come clinical questions, such as, will there be adverse reactions (for example, nausea and dizziness). Other questions may be that will we gain the correct movements using these technologies that are required for real life movement, are there fatigue issues for the patient (both from a cognitively-induced source or from possibly getting the patient moving earlier than what they are ready for, for example in the case of acute stroke). The financial cost implications and how much can a therapist control the parameters of the virtual environment and thus of the movements generated may be further questions asked. [31,32]

Regardless of the complexity of these AR systems, all 14 studies reported improvement in outcome thus demonstrating promise of AR as an adjunct therapy in physical rehabilitation programmes. However, the limited number of studies, the varying study designs of the included studies, and the poor quality generally of the articles included prevent any conclusions regarding the effectiveness of AR intervention from being made at this point in time.

A small number of studies reported on participants' satisfaction with end user acceptance of the intervention. [9,17] In both studies participants expressed both acceptance and satisfaction with the technology. More studies should focus on participants' satisfaction and acceptance of AR interventions as this would encourage the uptake of their use and assist in their development. Only one study reported on a negative aspect of their technology; participants reported that headset housing was too heavy to use. [21] Reporting of negative factors or adverse reactions to use of the technology should be encouraged to enhance the safety and comfort of using this technology.

Limitations and Strengths

As with any other review, there is a possibility that some studies were missed despite a systematic and thorough search of the published literature. Limiting the search to English may be considered a limitation. Only a keywords search was used with no subject headings and it might be possible that diverse or extra search terms would have yielded more studies. Authors of studies were not contacted to ask for an update on their work. The use of two experts' (HR, LH) opinions for inclusion or exclusion of studies when the intervention characteristic AR aspect or the physical rehabilitation aspect was not clear might have influenced the results of the review (for instance another expert might have a different definition of AR and hence would include something that was excluded; we tried to compensate for this by giving a quasi-standard definition of AR).[2] In addition the suggestions of these two experts were also used to select the databases, journals and conferences searched, again possibly introducing an element of bias. Studies involving people who had sustained burns were excluded: The interventions involved, when considering the presently available literature on this topic, were considered to be of cognitive

nature as opposed to that of a physical nature; this exclusion however might be considered as a limitation in this review too.

The major strength of this review was the relatively large number of databases and conference-proceedings searched. The involvement of two experts, one in the field of AR and the other in the field of rehabilitation might also be considered as a strength of this review. The checking of each step of the review by two researchers further added to the robustness of the review.

Conclusion

The existing evidence on the effectiveness of AR application in rehabilitation within a physical context is limited and the technology appears not yet at the stage for general practical use. However, the encouraging results indicated that further research in this area should be undertaken and more patient-based studies conducted.

Key Points

- Augmented Reality blends virtual objects with real scenes in real time.
- The technologies for Augmented Reality applications are still mostly in the prototype phase of development and not yet at a stage for general practice use.
- Promising results support further research in this area.

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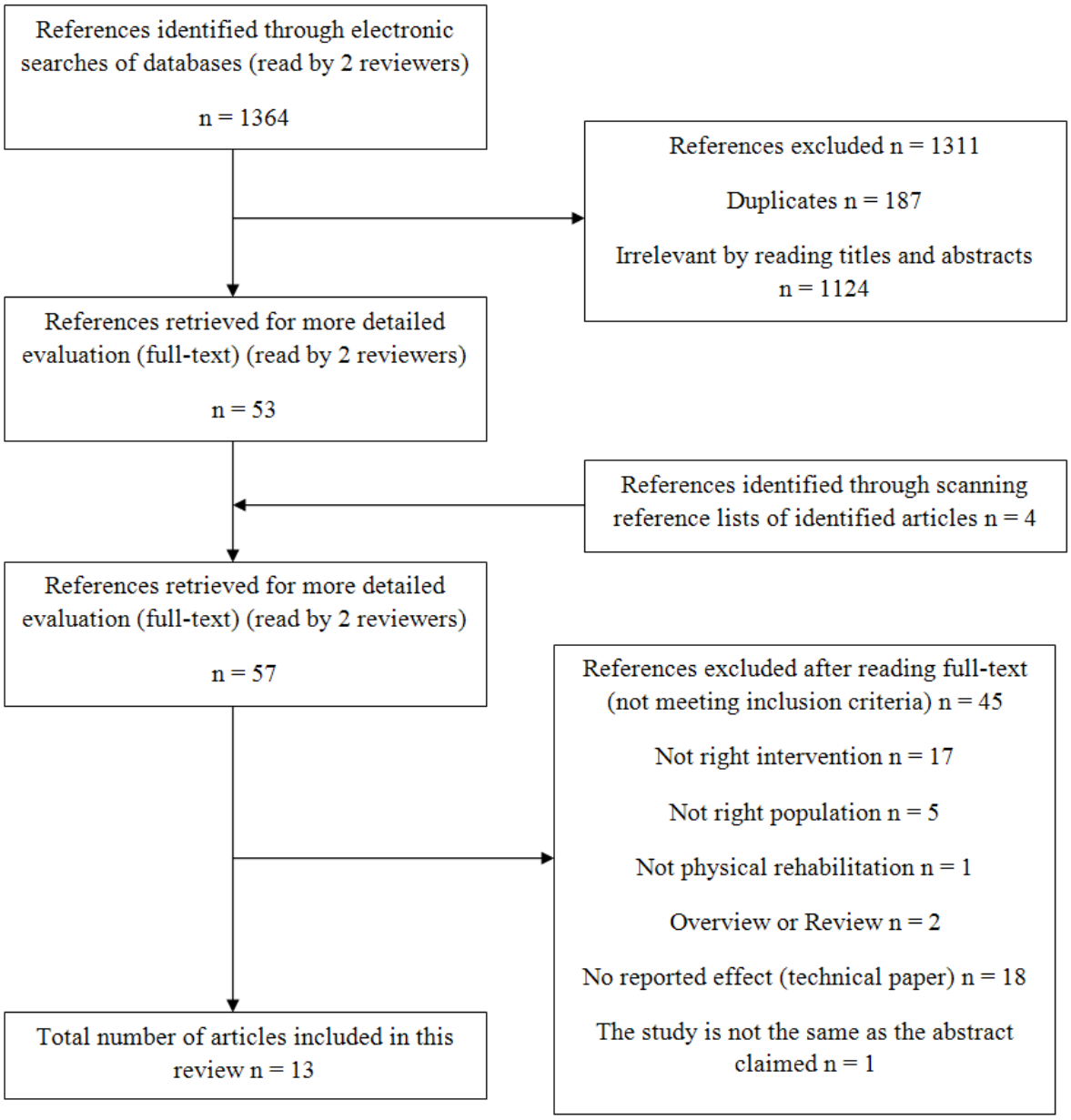

Figure 1: Flow chart of the articles identified, included and excluded.

Table 1: Inclusion and Exclusion Criteria for the Review

Criterion	Inclusion Criteria	Exclusion Criteria
Study Design	All quantitative study designs were included: randomised or quasi-randomised controlled trials, crossover studies, observational studies, pre-post studies, cohort studies, case series, single case, questionnaire, repeated measures and case-control studies.	Purely qualitative studies
Study participants	Participants were not limited to any age, sex, race, nationality, culture, diagnosis, and level of severity or condition.	Studies involving only healthy participants
Type of technology used	Studies investigating AR interventions that met one of the following criteria: - Combination of real and virtual - Interactive in real-time - Real or perceived registration in 3D	Studies using virtual reality intervention
Study outcomes	Studies which included objective and standardised measures of physical outcome	
Language	English language	

Table 2: Characteristics of Included studies

Authors	Population Sample Size and Sex	Age range (years)	Diagnosis	Type of study
Ferrarin et al. (2004)[9]	n = 6 (3=Expt, 3=Cont) Expt=all M, Cont=NR	Mean 70 (Expt.), 60 (Control)	PD	Case control - repeated measures
Baram et al. (2002)[10]	n = 14, Sex=NR	57 - 82	PD	Case series - repeated measures
Baram and Lenger (2009)[11]	n = 20 (10=VD,10=AD) M=7, F=13	6 - 26	CP	Case series – before and after
Baram and Miller (2006)[12]	n = 28 (Exp16, Cont 12) M=13,F=15	20 - 67	MS	Case control - repeated measures
Kaminsky et al. (2007)[13]	n = 6, M=4,F=2	49 - 76	PD	Case series - repeated measures
McAuley et al. (2009)[14]	n = 15, M=14,F=1	47 - 86	PD	Case series - repeated measures
King et al. (2009)[15]	n = 4, sex=NR	> 18	Stroke	Case series
Jaffe et al. (2004)[16]	N=20, M=8, F=12	48.8 - 79.6	Stroke	RCT
Luo et al. (2005a)[17]	n = 3, sex= all M	NR	Stroke	Case series
Luo et al. (2005b)[18]	n = 1, sex= all M	NR	Stroke	Single case
Mumford et al. (2010)[19]	n = 3, sex= all M	20 - 21	TBI	Case series
Sveistrup et al. (2003)[20]	n = 3 (Expt=2, Cont = 1) sex= all M	NM	Frozen shoulder	RCT preliminary results only
Sveistrup et al. (2003) [20]	n = 14 (Expt=9,Cont= 5) sex = NR	NM	TBI	RCT preliminary results only

Authors	Population Sample Size and Sex	Age range (years)	Diagnosis	Type of study
Taylor et al. (2009)[21]	n=20,M=8,F=12	18 - 60	Upper limb disability	Questionnaire study

Expt: experimental group; Cont: control group; n: sample size; M: male, F: female; PD: Parkinson's disease, MS: multiple sclerosis; CP: cerebral palsy; TBI: traumatic brain injury; NR: not reported

Table 3: Interventions, Technological Apparatus, Outcome Measures, and Summary of Main Findings

Authors	Intervention - Duration		Technological Apparatus	Outcome Measures	Summary of Main findings
	Experimental group	Control group			
Simple AR Systems					
Ferrarin et al. (2004)[9]	Visual-feedback AR-apparatus 1 session Patient walked 10 meter track for each of 5 conditions of feedback	Visual-feedback AR-apparatus 1 session Controls walked 10 meter track for each of 5 conditions of feedback	Visual Cue in Glasses: A pair of protective glasses were fitted with LEDs. The functioning of each LED display was controlled by a microprocessor system. This system was connected to two foot-switches so that the optical stimulation was temporally synchronised with the phases of the gait cycle.	mean speed, step length and cadence	Patients with PD showed up to 11% (on average) increase in gait velocity with continuous optic flow in the forward direction and controls showed small variations only. A large increase in stride length for all participants was noticed when stimulation synchronised with the swing phase, associated with an attentional strategy. The device demonstrated good applicability and technical functionality following a thorough testing.

Authors	**Intervention - Duration**		**Technological Apparatus**	**Outcome Measures**	**Summary of Main findings**
	Experimental group	Control group			
Baram et al. (2002)[10]	Visual-feedback AR-apparatus 1 session Patient walked 10 meter track for each of 5 conditions of feedback	None	Visual Cue in Glasses: comprising head-mounted 3-axis accelerometers, a wearable computer and see-through head-mounted display to creates a virtual tiled floor.	Speed and stride length	Patients with PD improved performance using the device by about 30% on average with higher speed and longer stride length.

Authors	**Intervention - Duration**		**Technological Apparatus**	**Outcome Measures**	**Summary of Main findings**
	Experimental group	Control group			
Baram and Lenger. (2009)[11]	visual-feedback AR apparatus or auditory feedback apparatus 1 session Patient walked 10 meter track for each of 3 stages of feedback	None	Visual Cue in Glasses + auditory stimuli: same as equipment described above for [11], but included an auditory stimulus	Speed and stride length	Patients using visual feedback showed an average improvement in walking speed of 21.7% (± 36.1%) and in stride length 8.7% (± 9.5%), while patients using auditory feedback showed an average improvement in walking speed of 25.4% (±28.7%) and in stride length 13.6% (±13.1%).

Authors	**Intervention - Duration**		**Technological Apparatus**	**Outcome Measures**	**Summary of Main findings**
	Experimental group	Control group			
Baram and Miller (2006)[12]	Visual-feedback AR-apparatus 1 session Patient walked 10 meter track for each of 4 stages of varying feedback	visual-feedback AR-apparatus 1 session Control walked 10 meter track for each of 4 stages of varying feedback	Visual Cue in Glasses: a closed-loop HMD where display attached to the eyeglasses frame to give the participant a virtual tiled floor in a checkerboard arrangement.	Speed, stride length, and number of steps	Patients with BWS below the median demonstrated an average on-line improvement of 13.5% in walking speed, while patients with BWS above the median showed improvements in speed of 1.5%. Patients with BWS below the median showed an average improvement in short-term residual therapeutic in walking speed of 24.5%, and 9.1% in patients with BWS above the median. Patients obtained similar results for improvements in stride length. No change was observed in the healthy control group.

Authors	Intervention - Duration		Technological Apparatus	Outcome Measures	Summary of Main findings
	Experimental group	Control group			
Kaminsky et al. (2007)[13]	Visual-feedback AR-apparatus Worn over 10 days The frequency of use or distance walked was not clearly mentioned	None	Visual Cue in Glasses: One one side of a pair of spectacles was embedded a light-emitting diode display that emitted horizontal lines which were in turn reflected by a lens into the wearer's eye. The wearer gets the impression that the lines on the ground in front of them.	Participant counts of losses of balance and freezing episodes, pre- & post-intervention completion of the Parkinson's Disease questionnaire, observation of baseline and intervention gait, and an interview regarding user satisfaction with VCS	Satisfaction with VCS was expressed by all participants. Decreased length of freezes and number of freezes were demonstrated among some participants.

Authors	Intervention - Duration		Technological Apparatus	Outcome Measures	Summary of Main findings
	Experimental group	Control group			
McAuley et al. (2009)[14]	Visual-feedback AR-apparatus 1 session Patient walked 30 meter track for each of 5 conditions of feedback	None	Visual Cue in Glasses: Two LEDs were connected in series to the top edge of both lenses of a light weight frame pair of glasses. The bottom edge of each lens was crafted so to reflect the light from the LEDs into a horizontal virtual cue line. By changing the nose position of the glasses the position of the line can be changed to match to the stride length of the wearer.	Unified Parkinson's Disease Rating Scale (UPDRS), subjective feedback, and speed of walking	Improvement in walking speed over a 30m course by a mean of 21.5% in 8 of 15 patients with PD and a subjective improvement in a further 2 patients. No change in UPDRS scores before or after the 30-mintue study period.

Authors	Intervention - Duration		Technological Apparatus	Outcome Measures	Summary of Main findings
	Experimental group	Control group			
Complex AR Systems					
King et al. (2009)[15]	AR-Game 9 x 60-minute sessions, over 4-weeks period	None	Monitor-based, fixed external camera (exocentric), marker tracking, simple AR system	Fugl-Meyer, Wolf Motor Function Test, and The disabilities of the arm, shoulder and hand (DASH), a questionnaire	Two of the four participants showed improvements in Fugl-Meyer and Wolf tests. All four participants showed a decrease score in the DASH questionnaire. Two participants showed significant ($p<.05$) improvements in timed game-play, the other two only a trend towards improvements for this outcome. Participants reported positive feedback and identified factors which would make them motivated to play more, and how games could be improved.

Authors	Intervention - Duration		Technological Apparatus	Outcome Measures	Summary of Main findings
	Experimental group	Control group			
Jaffe et al. (2004)[16]	Training on a Treadmill stepping over virtual obstacles 6 x 1-hour session, over 2-week period	Training on a Treadmill stepping over real foam obstacles 6 x 1-hour session, over 2-week period	Fixed external camera (exocentric), VR HMD (no see through), foot switch, foot vibrator	Gait velocity, stride length, walking endurance, and obstacle clearance capacity	Greater improvement in gait velocity was shown with training with virtual objects compared to training with real objects (20.5% vs. 12.2%) during the fast walk test ($p < 0.01$). Training in both methods produced similar results in the self-selected walk test (33.3% vs. 34.7% improvement). In general, all participants demonstrated clinically meaningful improvements in gait velocity, stride length, walking endurance, and obstacle clearance capacity due to either training method. These changes were maintained for 2 weeks post-training.
Luo et al. (2005a)[17]	AR Element + assistive device 18 x 30-minute sessions, over 6-weeks period	None	Optical see-through (OST) HMD (egocentric) with magnetic tracking and specialised interaction and measuring devices	Force data, hand tracking positions and Box & Blocks test	Significant decrease in force required to hold object and better grasping of objects ($p = 0.03$) and an increase of 1 to 4 blocks acquired in the Box & Block test

Authors	**Intervention - Duration**		**Technological Apparatus**	**Outcome Measures**	**Summary of Main findings**
	Experimental group	Control group			
Luo et al. (2005b)[18]	AR Element + assistive device 18 x 30-minute sessions, over 6-weeks period	None	Optical see-through (OST) HMD (egocentric) with magnetic tracking and specialised interaction and measuring devices	Box & blocks, Rancho, Speed and maximum displacement for volunteer extension against no load	The preliminary results showed an encouraging trend of modest improvement of finger extension capability in the impaired hand, and suggested participants' acceptance of the technology.
Mumford et al. (2010)[19]	AR-based training 12 x 60-minute sessions, over a 4-week period	None	Back projection System with spatially aligned tangible object, tangible user interface (TUI)	System measured variables: movement speed, movement efficiency, placement accuracy; Box and Block test, McCarron Assessment of Neuromuscular Dysfunction	Significant improvements for all outcome measures except speed which had varied improvements between participants and between left and right hands

Authors	Intervention - Duration		Technological Apparatus	Outcome Measures	Summary of Main findings
	Experimental group	Control group			
Sveistrup et al. (2003)[20]	AR exercise 18 x 1-hour session, over 6-week period	Conventional stretching/exercise 18 x 1-hour session, over 6-week period	Projection Screen, fixed external camera, reflected egocentric view	Pain; range of motion and strength; and the Disabilities of the arm, shoulder and hand (DASH) questionnaire	Preliminary results: 2 in AR group and 1 in control group improved DASH by > 15-point change.
Sveistrup et al. (2003)[20]	Conventional exercise or AR exercise 18 x 1-hour session, over 6-weeks period	No exercise sessions just normal programme	Projection Screen, fixed external camera, reflected egocentric view	Laboratory measures of quiet stance, gait speed and activity specific confidence, the Community Balance and Mobility Scale (CB&M)	Preliminary results: both the AR and the conventional exercise group improved on the CB&M

Authors	**Intervention - Duration**		**Technological Apparatus**	**Outcome Measures**	**Summary of Main findings**
	Experimental group	Control group			
Taylor et al. (2009)[21]	AR+ Haptic device 1 session	None	Video-see through (VST) HMD (egocentric), Phantom input and force feedback device, marker tracking, simple AR system	Background questionnaire and feedback questionnaire.	The system was not too easy or too hard to use, group participants showed improvements in range of motion and motor skills, and were motivated to continue using the system for therapy.

Table 4: Quality assessment using CASP for Cohort studies.

Authors	Q1. Did the study address a clearly focused issue?	Q2. Did the authors use an appropriate method to answer their question?	Q3. Was the cohort recruited in an acceptable way?	Q4. Was the exposure accurately measured to minimize bias?	Q5. Was the outcome accurately measured to minimize bias?	Q6. Have the authors identified all important confounding factors?	Q7. Have they taken account of the confounding factors in the design and/or analysis?	Q8. Was the follow up of Participants complete enough?	Q9. Was the follow up of Participants long enough?	Q10. Do you believe the results?	Q11. Can the results be applied to the local population?	Q12. Do the results of this study fit with other available evidence?
Baram et al. (2002)[10]	Yes	Yes	Can't tell	Yes	Can't tell	Yes	Can't tell	Yes	No	Yes	Can't tell	Yes
Baram and Lenger. (2009)[11]	Yes	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	No	Yes	Can't tell	Yes
Kaminsky et al. (2007)[13]	Yes	Yes	Can't tell	Can't tell	Yes	Can't tell	Can't tell	Yes	No	Yes	Can't tell	yes
McAuley et al. (2009)[14]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Can't tell	Yes
King et al. (2009)[15]	Yes	Yes	Can't tell	Yes	Yes	Can't tell	Can't tell	Yes	No	Yes	Can't tell	Yes

Authors	Q1. Did the study address a clearly focused issue?	Q2. Did the authors use an appropriate method to answer their question?	Q3. Was the cohort recruited in an acceptable way?	Q4. Was the exposure accurately measured to minimize bias?	Q5. Was the outcome accurately measured to minimize bias?	Q6. Have the authors identified all important confounding factors?	Q7. Have they taken account of the confounding factors in the design and/or analysis?	Q8. Was the follow up of Participants complete enough?	Q9. Was the follow up of Participants long enough?	Q10. Do you believe the results?	Q11. Can the results be applied to the local population?	Q12. Do the results of this study fit with other available evidence?
Luo et al. (2005)[16]	Yes	Yes	Can't tell	Yes	Yes	Can't tell	Can't tell	Yes	No	Can't tell	Can't tell	Yes
Luo et al. (2005)[17]	Yes	Yes	Can't tell	Can't tell	Can't tell	Can't tell	No	Yes	No	Can't tell	Can't tell	yes
Mumford et al. (2010)[19]	Yes	Yes	Yes	Yes	Yes	Can't tell	Yes	Yes	No	Yes	No	Yes
Taylor et al. (2009)[21]	Yes	No	Can't tell	Can't tell	Yes	No	Can't tell	Yes	No	No	No	

Table 5: Quality assessment using CASP for Case control studies.

Authors	Q1. Did the study address a clearly focused issue?	Q2. Did the authors use an appropriate method to answer their question?	Q3. Were the cases recruited in an acceptable way?	Q4. Were the controls selected in an acceptable way?	Q5. Was the exposure accurately measured to minimise bias?	Q6. Have they taken account of the potential confounding factors in the design and/or analysis?	Q7. Do you believe the results?	Q8. Can the results be applied to the local population?	Q9. Do the results of this study fit with other available evidence?
Ferrarin et al. (2004)[9]	Yes	Yes	Can't tell	Can't tell	yes	No	Yes	Can't tell	Yes
Baram and Miller (2006)[12]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 6: Quality Assessments using CASP for RCTs.

Authors	Q1. Did the study address a clearly focused issue?	Q2. Was this a randomised controlled trial (RCT) and was it appropriately so?	Q3. Were participants appropriately allocated to intervention and control groups?	Q4. Were participants, staff and study personnel 'blind' to participants' study group?	Q5. Were all of the participants who entered the trial accounted for at its conclusion?	Q6. Were the participants in all groups followed up and data collected in the same way?	Q7. Did the study have enough participants to minimise the play of chance?	Q8. Were all important outcomes considered so the results can be applied?
Jaffe et al. (2004)[16]	Yes	Yes	Yes	Can't tell	Yes	Yes	Can't tell	Yes
Sveistrup et al. (2003)[20]	Yes	Yes	Yes	Can't tell	No	Can't tell	Can't tell	Yes
Sveistrup et al. (2003)[21=0]	Yes	Yes	Yes	Can't tell	No	Can't tell	Can't tell	Yes

APPENDIX A: Search Strategies for Databases

Medline	**1.** (Augment* reality OR Mix* reality).af. **2.** (physical rehabilitation or rehabilitation or physiotherapy or occupational therapy or physical therapy or exercise).af. **3.** No. 3 AND No. 4 **4.** Limit 3 to English language Date: 9-6-2010
AMED	1. (Augment* reality OR Mix* reality).af. 2. (physical rehabilitation or rehabilitation or physiotherapy or occupational therapy or physical therapy or exercise).af. 3. No. 3 AND No. 4 4. Limit 3 to English language Date: 9-6-2010
EMBASE	1. (Augment* reality OR Mix* reality).af. 2. (physical rehabilitation or rehabilitation or physiotherapy or occupational therapy or physical therapy or exercise).af. 3. No. 3 AND No. 4 4. Limit 3 to English language Date: 9-6-2010
PshycINFO	1. (Augment* reality OR Mix* reality).af. 2. (physical rehabilitation or rehabilitation or physiotherapy or occupational therapy or physical therapy or exercise).af. 3. No. 3 AND No. 4 4. Limit 3 to English language Date: 31-5-2010
CINHAL	1. S1: (Augment* reality) (TX) 2. S2: (Mix* reality) (TX) 3. No. 1 OR No. 2 Date: 9-6-2010
Cochrane Central Register of Controlled Clinical Trials	1. (Augment* reality); ti,ab,kw 2. (Mix* reality); ti,ab,kw 3. No 1 OR No 2 Date: 9-6-2010

Cochrane Database of Systematic Review (2010)	1. (Augment* reality); ti,ab,kw 2. (Mix* reality); ti,ab,kw 3. No 1 OR No 2 Date: 9-6-2010
Database of Abstracts of Reviews of Effectiveness (DARE)	1. (Augment* reality); ti,ab,kw 2. (Mix* reality); ti,ab,kw 3. No 1 OR No 2 Date: 9-6-2010
Web of Science	1. S1: (physical rehabilitation OR rehabilitation OR physiotherapy OR occupational therapy OR physical therapy OR exercise); (To) 2. S2: (Augment* reality OR Mix* reality); (To) 3. No 1 AND No 2 Date: 1-6-2010
Scopus	1. S1: (“physical rehabilitation” OR “rehabilitation” OR “physiotherapy” OR “occupational therapy” OR “physical therapy” OR “exercise”); (TITLE-ABS-KEY) 2. S2: (“Augment* reality” OR “Mix* reality”); (TITLE-ABS-KEY) 3. No 1 AND No 2 Date: 8-6-2010
PEDro (Physiotherapy Evidence Database)	1. Augment* reality 2. Mix* reality 3. No 1 OR No 2 Date: 31-5-2010
Virtual Rehabilitation	1. S1: (“Augment* reality” OR “Mix* reality”) (Full Text & Metadata) 2. S2: (“physical rehabilitation” OR “rehabilitation” OR “physiotherapy” OR “occupational therapy” OR “physical therapy” OR “exercise”) (Full Text & Metadata) 3. No 1 AND No 3 Date:16-6-2010

ISMAR	1. S1: (“Augment* reality” OR “Mix* reality”); (Full Text & Metadata) 2. S2: (“physical rehabilitation” OR “rehabilitation” OR “physiotherapy” OR “occupational therapy” OR “physical therapy” OR “exercise”) (Full Text & Metadata) 3. No 1 AND No 3 Date:16-6-2010
Cyber psychology and behaviour	1. S1: (“Augment* reality” OR “Mix* reality”); (All) 2. S2: (“physical rehabilitation” OR “rehabilitation” OR “physiotherapy” OR “occupational therapy” OR “physical therapy” OR “exercise”); (All) 3. No 1 AND No 3 Date: 21-6-2010
MIT press (Presence Teleoperators and Virtual Environments	1. S1: (“Augment* reality” OR “Mix* reality”); (All) 2. S2: (“physical rehabilitation” OR “rehabilitation” OR “physiotherapy” OR “occupational therapy” OR “physical therapy” OR “exercise”); (All) 3. No 1 AND No 3 Date: 21-6-2010
Visualization & Computer Graphics	1. (“augment* reality” OR “Mix* reality”); (pt) 2. (“physical rehabilitation” OR “rehabilitation” OR “physiotherapy” OR “occupational therapy” OR “physical therapy” OR “exercise”); (pt) 3. No 1 AND No 2 Date: 28-6-2010
Computer graphics and applications	1. (“augment* reality” OR “Mix* reality”); (pt) 2. (“physical rehabilitation” OR “rehabilitation” OR “physiotherapy” OR “occupational therapy” OR “physical therapy” OR “exercise”); (pt) 3. No 1 AND No 2 Date: 21-6-2010
ACM digital library	(("augmented reality" OR "mixed reality") and (rehabilitation OR physiotherapy OR exercise OR "physical rehabilitation" OR "occupational therapy" OR "physical therapy")) Date: 13-7-2010