Digital Mirrors: Virtual and Augmented Reality for Phantom Limb Pain

Espelhos Digitais: Realidade Virtual Aumentada para o Tratamento da Dor do Membro Fantasma

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Abstract

Introduction: *Phantom limb pain (PLP) affects 50 - 85 % of individuals following amputation and remains refractory to many conventional therapies. Virtual reality (VR) and augmented reality (AR)–based interventions have emerged as promising alternatives by engaging sensorimotor cortical circuits and providing enriched visual feedback. This systematic review evaluates current evidence on the efficacy of VR/AR treatments for PLP in post–amputation populations.*

Methods: *We searched PubMed and Scopus databases for studies that evaluated nonimmersive or immersive VR/AR therapies in adults with PLP. The research was performed in January 2025, and seventeen studies (five randomized controlled trials and twelve prospective studies) met inclusion criteria. Data on intervention type, control modality, pain outcomes and secondary measures (quality of life, usability) were extracted and synthesized.*

Results: *Among 17 studies, six used non-immersive VR/AR, while eleven applied immersive systems. Various VR/AR implementations were used, including creation of a virtual limb from a mirror image of an intact limb, control of a virtual limb via electromagnetic sensors, creation of a braincomputer interface, and use of a tablet-based virtual treatment. All the non-immersive AR/VR interventions yielded reductions in phantom-limb pain intensity, irrespective of the specific technology or delivery format.*

Eleven studies reported decreased PLP after AR/VR immersive treatments, of which seven reported significant reductions. The studies documented uniformly high ratings of realism, immersion, and overall satisfaction with the VR/AR experience.

Discussion: *The strongest evidence for clinically relevant PLP relief (≥ 30 % pain reduction) comes from EMG–driven phantom–motor execution and fully immersive VR protocols. Mirror–style VR and tablet–based AR yield smaller but still positive effects. Methodological heterogeneity across studies—treatment dose, outcome instruments, follow–up duration—precludes direct comparisons. The decreasing cost of head-mounted displays (HMDs) is lowering barriers to clinical adoption.*

Conclusion: *VR/AR–based therapies can produce meaningful analgesia for PLP, particularly when they combine active motor execution, multisensory feedback, and immersive environments. Future large–scale RCTs with standardized protocols and direct comparisons between nonimmersive and immersive formats are needed to optimize treatment strategies.*

Key-words: *Phantom Limb, Virtual Reality, Amputees*

Resumo

Introdução: A dor de membro fantasma (DMF) afeta entre 50 % e 85 % dos indivíduos após amputação, sendo de difícil controlo com as atuais terapias convencionais. As intervenções baseadas em realidade virtual (RV) e realidade aumentada (RA) surgem como alternativas promissoras ao envolver os circuitos sensórios-motores e a fornecer

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feedback visual mais realista. O objetivo deste estudo é rever sistematicamente a evidência atual relativa à eficácia dos tratamentos por RV/RA na DMF nos doentes amputados.

Métodos: Foram consultadas as bases de dados PubMed e Scopus para identificar estudos que avaliassem terapias de RV/RA não imersivas ou imersivas em adultos com DMF. A investigação realizou-se em janeiro de 2025, e dezassete estudos (cinco ensaios clínicos randomizados e doze estudos prospetivos) cumpriram os critérios de inclusão. Foram extraídos e sintetizados dados sobre o tipo de intervenção, escalas de quantificação da dor e medidas secundárias (qualidade de vida, usabilidade).

Resultados: Dos 17 estudos incluídos, seis foram classificados como não imersivos. Utilizaram-se várias implementações de RV/RA, incluindo a criação de um membro virtual a partir da imagem espelhada de um membro intacto, controlo do membro virtual via sensores eletromagnéticos, interfaces cérebro-computador, e tratamentos virtuais em *tablet*. Todas as intervenções não imersivas mostraram reduções na intensidade da DMF, independentemente da tecnologia ou formato de apresentação. Onze estudos reportaram diminuição da DMF após tratamentos imersivos de RV/RA, sendo que sete alcançaram reduções estatisticamente significativas. Estes trabalhos documentaram também avaliações uniformemente altas de realismo, imersão e satisfação global com a experiência.

Discussão: A evidência mais robusta para um alívio clinicamente relevante e duradouro da DMF (≥ 30 % de redução da dor) provém de protocolos de execução motora virtual guiada por EMG e de RV totalmente imersiva com exercícios de jogos nos membros inferiores. As abordagens não imersivas em formato espelho e a RA em *tablet* apresentaram efeitos menores, mas ainda positivos. A heterogeneidade metodológica — tipo de tratamento, instrumentos de medida, duração do seguimento — limita as comparações diretas. O aumento da acessibilidade de sistemas imersivos de baixo custo tem reduzido barreiras à sua adoção clínica.

Conclusão: As terapias baseadas em RV/RA podem proporcionar analgesia significativa na DMF, sobretudo quando combinam execução ativa de movimentos, feedback multissensorial e tratamentos imersivos. Futuramente, são necessários ensaios clínicos aleatorizados de grande escala com protocolos padronizados, comparando formatos não imersivos versus imersivos, e com seguimento a longo prazo para definir o tratamento mais eficaz.

Palavras-chave: Membro Fantasma, Amputação, Realidade Virtual

Introduction

Phantom limb pain (PLP) is a painful sensation perceived in a part of the body which no longer exists. Among individuals with limb amputations, the lifetime prevalence of PLP is estimated to range from 50% to 80%. It is important to distinguish PLP from pain localized to the residual limb (stump pain). PLP is often described as burning, stabbing, gnawing, pressure, or projected pain that extends into the region previously occupied by the lost limb. This condition is frequently associated with secondary effects such as depression, limitations in daily life activities, and a reduced quality of life.[1, 2]

The mechanisms underlying PLP and the respective contributions of the central nervous system (CNS) and peripheral nervous system (PNS) remain subjects of ongoing debate among researchers and clinicians. Currently, the most posited CNS theory is the cortical remapping theory (CRT), in which the brain is believed to respond to limb loss by reorganizing somatosensory maps. This reorganization involves the expansion of adjacent cortical regions into areas previously associated with the amputated limb, leading to altered sensory experiences and the emergence of PLP. To assess the functional significance of this type of cortical reorganization in more detail, Flor et al. used neuromagnetic source imaging combined with a comprehensive assessment of painful and nonpainful phantom phenomena, and referred sensation in persons with unilateral upper limb amputations. Individuals with painful phantom phenomena exhibited a significant medial and superior shift of the mouth representation toward the former hand area in the primary somatosensory cortex contralateral to the amputation. This cortical reorganization was not observed in those with non-painful phantom sensations. Moreover, the non-painful group did not differ significantly from healthy controls, suggesting a specific link between phantom limb pain and cortical reorganization.[2,3]

Also, earlier theories emphasized peripheral mechanisms, particularly the role of neuromas—abnormal proliferations or thickenings of nerve tissue—as the primary source of PLP, despite reports of pain immediately after surgery. Contemporary investigations on the peripheral causes of PLP now highlight several factors: the inability of severed nerves to reestablish prior connections (with or without neuroma formation), the involvement of the dorsal root ganglion (DRG), and the influence of preamputation pain. Although amputation primarily disrupts the PNS, it also induces changes within the CNS, particularly in sensory and motor signaling pathways.[2,3]

There are a variety of treatment options such as mirror therapy (MT), motor imagery, sensory discrimination, or virtual visual/optical feedback. However, while some studies have shown that these therapeutic choices have benefits over placebo, current guidelines for treating PLP remain unclear.[4]

Visual feedback therapy is a relatively recent approach that enables patients to observe and monitor real-time activity related to the affected area. The missing limb is visualized through mirrors, virtual reality systems, or prerecorded videos of the intact limb. Simultaneously, patients are encouraged to synchronize their phantom limb movements with the visual input, promoting sensorimotor integration. The theoretical basis of mirror therapy lies in the cortical reorganization that occurs in the somatosensory cortex following amputation, which the authors mentioned before. Therefore, MT aims to counteract or inhibit this maladaptive reorganization, thereby alleviating PLP.[4,5,6]

While mirror therapy has been shown to be a relatively effective non-invasive treatment for PLP, it is limited by constraints related to realism, the physical placement of mirrors, and its applicability only to unilateral amputations.[5] The conceptual foundation of mirror therapy has since evolved with virtual reality (VR) - completely immersing an individual in a virtual world- and augmented reality (AR) that adds digital elements, such as the missing limb, to a real environment. VR can be immersive, with a computer-generated environment accessed via headset, and non-immersive, that involves interaction with virtual elements through external devices, such as screens or tablets, without creating a fully immersive experience. These technologies have demonstrated success in treating PLP, particularly in patients unresponsive to traditional mirror therapy.[5,6]

The aim of this review is to evaluate and summarize the current research on the effect of immersive VR and AR in the treatment of PLP.

Methods

Literature Research

A thorough systematic review of the current literature was performed, according to PRISMA statement guidelines. The authors conducted a search using PubMed and Scopus databases, with the following keywords: “Phantom limb pain” and “Virtual reality.” The research was performed in January 2025. After duplicate articles were removed, abstracts of all articles were read in full, and those indicating use of VR or AR for the treatment of PLP were critiqued for matching inclusion criteria. To be included, studies needed to 1) be published in English or Portuguese since the year 2000, 2) include participants with PLP from amputation, 3) utilize any form of VR or AR therapy, and 4) assess the treatment of PLP using VR or AR therapy. The exclusion criteria were: 1) studies focusing on pre-amputation treatments, 2) cost-analysis studies, book chapters, editorials or reviews/ meta-analysis, and 3) studies with a sample size inferior to 5 persons. The schematic of evidence acquisition is presented in Figure 1.

Data extraction and quality assessment

Studies were divided into immersive and nonimmersive VR/AR environments. To be classified as an immersive AR/VR study, participants had to use some form of a head mounted display (HMD) that displayed virtual objects in a completely VR or AR environment. Due to the diverse array of VR and AR systems utilized by the immersive and nonimmersive studies, studies were then further divided by the modality of VR or AR utilized.

Two independent reviewers were responsible for the selection and data extraction from each study. The reviewers registered information regarding 1) study author name and publication date, 2) study design, 3) sample size, 4) description of intervention, 5) pain outcome measures. Any discrepancies between analysis were resolved by discussion among all authors for consensus.

The risk of bias and quality of each included article was accessed with validated tools by two reviewers, according to the design of each study. Randomized clinical trials (RCTs) were accessed with the revised Cochrane Risk-of-Bias Tool for Randomized Clinical Trials (RoB2) and Nonrandomized observational prospective and retrospective studies were evaluated with the MINORS tool (Methodological Index for Non-Randomized Studies).

The RoB 2 tool evaluates the risk of bias in randomized controlled trials across five domains: the randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selection of the reported result. Based on these domains, each RCT is classified as low risk, some concerns, or high risk. The MINORS tool involves assessing the methodological quality of non-randomized studies using a validated checklist. For non-comparative studies (like single-group clinical trials), only the first 8 items are applicable, and each is scored as: 0) Not reported, 1) Reported but inadequate, 2) Reported and adequate. The maximum score is 16 for such studies. The risk of bias of the RCTs is represented in Table 1 and the risk of bias of the nonrandomized studies is represented in Table 2.

Data synthesis

The search results showed that current literature regarding effectiveness of these therapies on PLP after amputation contained heterogeneous information, making it unsuitable for statistical synthesis.

Source of Funding

This study did not receive any external funding.

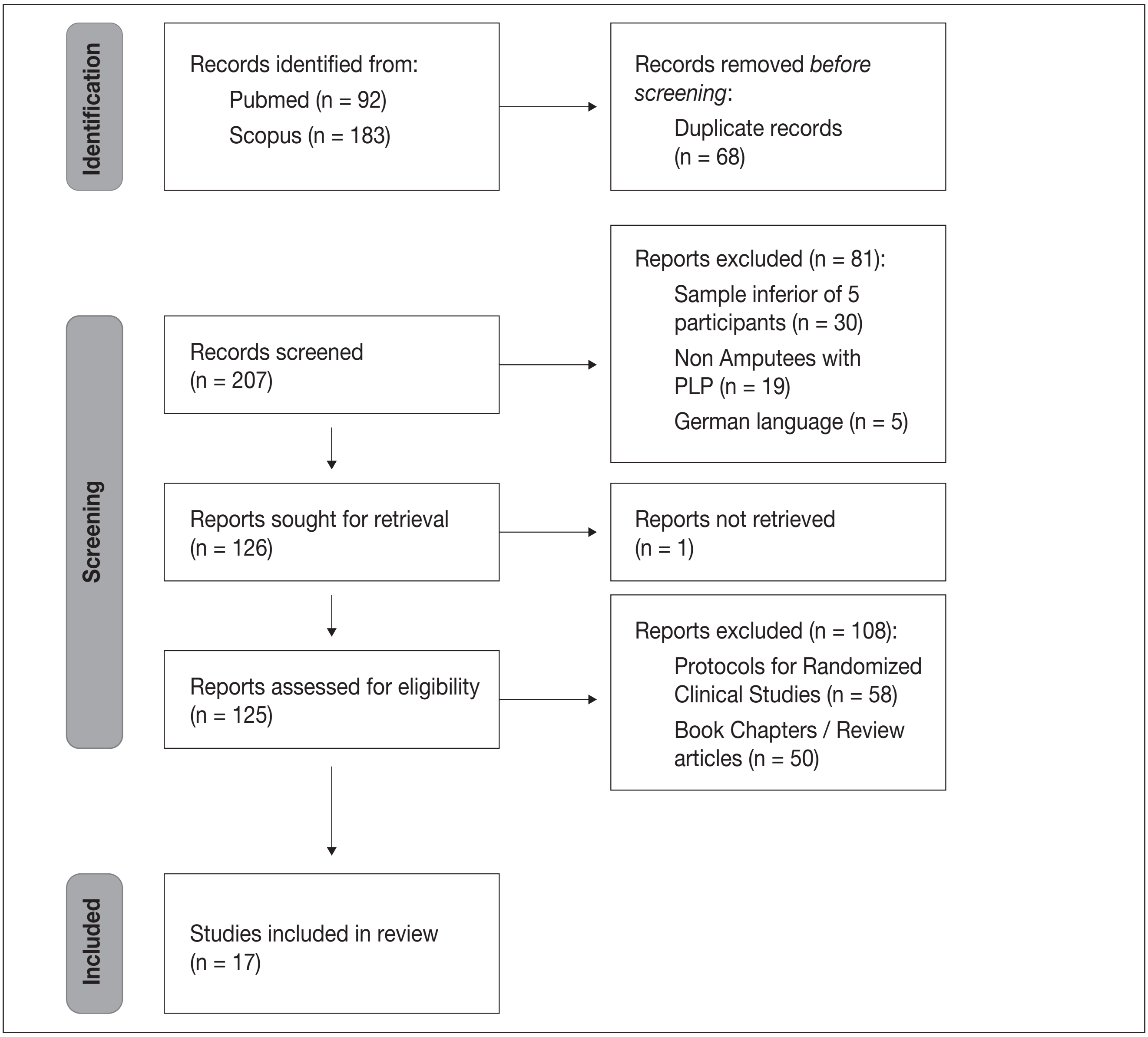

Figure 1 - Identification of studies via databases and registers.

Table 1 - Risk of Bias of Randomized Clinical Trials, according to Cochrane Risk-of-Bias Tool for Randomized Clinical Trials (RoB2).

Studies	Rothgangel et al [7]	Abbas et al [8]	Lendaro et al [9]	Steckel et al [10]
Randomization process	+	+	+	?
Deviation from the intended intervention	?	?	+	-
Missing outcome data	+	+	+	-
Measurement of the outcome	?	?	+	?
Selection of reported result	+	+	+	+

+ Low risk of bias; ? Some concerns; - High risk bias.

Table 2 - Risk of Bias of Non-Randomized Clinical Trials, according to Methodological Index for Non-Randomized Studies (MINORS tool).

Study	MINORS Score	Interpretation
Osumi et al [11]	10 / 16	Moderate quality
Rutledge et al[12]	13 / 16	High quality
Kulkarni et al[13]	11 / 16	Moderate quality
Cole et al[14]	11 / 16	Moderate quality
Ortiz-Catalan et al[15]	12 / 16	Moderate quality
Thøgersen et al[16]	11 / 16	Moderate quality
Perry et al[17]	11 / 16	Moderate quality
Ambron et al[18]	11 / 16	Moderate quality
Annapureddy et al[19]	11 / 16	Moderate quality
Prahm et al[20]	11 / 16	Moderate quality
Perry et al[21]	11 / 16	Moderate quality
Murray et al[22]	11 / 16	Moderate quality
Keesom et al[23]	13 / 16	High quality

Score intervals (0-4 for low methodological quality, 5-6 for moderate, and 7-8 forgood methodological quality).

Results

Study Designs and Baseline Characteristics

After the removal of duplicate studies in the databases, 207 articles remained, and their abstracts were screened by title and abstract. 125 studies were potentially relevant and full reports obtained and screened. 108 studies didn´t meet the inclusion criteria, with common causes of exclusion being a lack of AR/VR intervention or unrelatedness to the treatment of PLP. In total, 17 studies were included in this systematic review: 4 RCTs and 13 observational studies.

The reviewed protocols differed in number and duration of intervention and the timing of follow up evaluations. Studies also used different outcome measures, including PLP assessment, with the Short Form McGill Pain Questionnaire (SF MPQ) being the most frequently used.

Non-immersive studies

Out of the 17 included studies, six were classified as non-immersive. Various VR/AR implementations were used, including creation of a virtual limb from a mirror image of an intact limb, control of a virtual limb via electromagnetic sensors, creation of a braincomputer interface, and use of a tablet-based virtual treatment.

In the Rothgangel et al study,[7] patients were divided into teletreatment, MT, and control groups. The teletreatment group performed four weeks of traditional mirror therapy (viewing their intact limb in a physical mirror) and then six weeks of tablet-based augmented-reality mirror therapy, in which a live video of their residual limb was overlaid with a mirrored image of their intact limb on the tablet screen. Perry et al[21] and Ortiz-Catalan et al[15] used an EMG-driven augmented-reality system: surface electrodes on the residual limb that animated a virtual limb in real time, combining passive observation with active myoelectric control exercises.

In Abbas et al[8], lower-limb amputees in the intervention group received twice-weekly non-immersive VR training—simple interactive balance and strength tasks displayed on a standard monitor—added to their conventional exercise regimen. In a multicenter RCT, Lendaro et al[9] patients performed extended reality sessions on a tablet that fused live video of their residual limb with a mirrored 3D model of an intact limb.

Table 3 summarizes the design and characteristics of each included study and obtained outcomes.

All the non-immersive AR/VR interventions yielded reductions in phantom-limb pain intensity, irrespective of the specific technology or delivery format. Perry et al[21] and Ortiz-Catalan et al[15] demonstrated statistically significant 30–50 % decreases in pain scores immediately post intervention. Similarly, Abbas et al[8] and Lendaro et al[9] each reported decreased PLP intensity after their respective monitor or tablet-based VR/AR protocols. In the three arm RCT by Rothgangel et al[7], all groups—augmented-reality

Table 3 - Study characteristics for publications utilizing non-immersive VR/AR systems.

Author (year) Study Design;	Sample (N); Type of Amputation (ULA or LLA)	VR vs. AR	AR/VR Modality	Outcome measures	Primary Findings
Perry et al[21] Prospective study	N=7 (5 of 7 with PLP) ULA	VR	Participants underwent 20 sessions over ~1 month, combining passive visualization and active myoelectric control of a virtual avatar limb using surface EMG signals from the residual limb. Visual feedback provided in real-time; included training and free-play with increasing complexity of movements.	VAS, SF-MPQ,	1) Among the 5 participants reporting PLP at baseline, 60% reported a reduction in average daily PLP, and 80% reported a decrease in worst PLP. 2) SF-MPQ scores showed improvement in 4 of 5 PLP patients. 3) 6 of 7 participants achieved >80% classification accuracy in basic motion classes (e.g., wrist flexion, hand open/close).
Ortiz-Catalan et al[15] Prospective study	n=14 ULA	VR/AR	Surface EMGs: participants used their virtual limbs to interact with a car racing game or match target limb postures.	NRS, PRI, SF-MPQ, WPD	1) Significant 47% decrease in PLP via WPD (SD: 39; absolute mean change: 1.0 [0.8]; p=0.001). 2) Significant 32% decrease in PLP via NRS (SD: 38; absolute mean change: 1.6 [1.8]; p=0.007). 3) Significant 51% decrease in PLP via PRI (SD: 33; absolute mean change: 9.6 [8.1]; p=0.0001). 4) PRI improvements of 2%, 6%, and 24% retained at 1-, 3-, and 6-month follow-ups, respectively. 5) Significant 43% reduction in pain during daily activities (SD: 37; absolute mean change: 2.4 [2.3]; p=0.004) and 61% reduction in sleep-related pain (SD: 39; absolute mean change: 2.3 [1.8]; p=0.001).
Rothgangel et al[7] RCT	n=75 LLA	AR	Teletreatment: Participants were divided into teletreatment, mirror therapy, and control groups. Teletreatment and mirror therapy groups received 4 weeks of mirror therapy, while the control group received 4 weeks of sensorimotor exercises. Mirror therapy and control groups then continued their interventions for 6 weeks, while the teletreatment group	NRS, PSFS, VAS, EuroQool Questionnaire, GPES, Pain Self-Efficacy Questionnaire	1) Traditional mirror therapy did not significantly reduce average PLP intensity versus control at 4 weeks (mean difference –1.2; 95% CI –2.4 to 0.0; p = 0.054). 2) All three groups showed a reduction in the average intensity of PLP at 10 weeks and 6-month follow-up, with no statistically significant differences between the groups.

			used a tablet-delivered virtual limb system for 6 weeks.		
Perry et al[17] Prospective study	n=8 ULA	VR	Surface EMGs: participants were given a "free-play" period to move and visualize their virtual limbs.	SF-MPQ, VAS	1) Participants reported a statistically significant reduction in their worst phantom-limb pain ratings over the trial period (β = –0.474; p = 0.015). 2) Ratings of present ("current") pain intensity also improved significantly (β = –0.248; p = 0.042). 3) Nonsignificant improvement in "average PLP" (β = –0.248; p = 0.078), suggesting that more sessions or larger samples may be needed to confirm an effect on average pain levels. 4)Total scores on the SF-MPQ decreased significantly (β = –0.096; p = 0.003), reflecting improvements not only in intensity but also in the qualitative dimensions of the pain experience.
Abbas et al[8] RCT	n= 32 LLA	VR	Both groups received a traditional rehabilitation program for 6 weeks. The VR group added 25 minutes of VR functional rehabilitation, with a camera and an infrared sensor to seize motion. Both legs were presented virtually intact and controlled by the patient. It included recreational games.	VAS, SF-12 (MHS and PHS), BDI	1) For the VR group, the pain scores showed a significant improvement (P < 0.05) as they decreased from (6.56 – 1.23) to (2.25 – 0.62). 2) The results showed significant improvement in the mean and standard deviation of BDI scores within the control and VR group after the intervention (P < 0.05). 3) The results showed significant improvement in the mean and standard deviation of MHS and PHS scores within the control and VR groups (P < 0.05). However, when comparing between groups, the VR group showed a higher significance in improving the MHS scores (P < 0.05), and no significant difference in the PHS scores (P<0.05).
Lendaro et al[9] RCT	N= 80 ULA/ LLA	AR/VR	Phantom motor execution (PME) group: using myoelectric signals to control movements in extended-reality (XR) environments Phantom motor imagery (PMI)	PRI, NRS, WPD, PGIC, Pain interference (sleep, daily activities, work)	1) There was no significant difference between the PME and PMI groups in the reduction of the PRI at the end of treatment (p = 0.75; Cohen's d = 0.07). 2) Both groups demonstrated significant within-group

			group: viewing VR-based limb movement without active muscle use.		reductions in pain. The PME group showed a 64.5% reduction in PRI, with a mean change of −9.35 and a large effect size (d = 0.88). Similarly, the PMI group experienced a 68.2% reduction in PRI, with a mean change of −10.03 and an even larger effect size (d = 1.20). 3). Both groups demonstrated reductions in WPD and pain interference in sleep, daily activities, and work. These effects were sustained through 3-, and 6-month follow-up.

AR: Augmented Reality; BDI: Beck's Depression Inventory; EuroQol: EuroQol Quality of Life Questionnaire; GPES: Global Perceived Effect Scale; LLA: Lower Limb Amputation; NRS: Numerical Rating Scale; PGIC: Patient Global Impression of Change; Pain interference: assessed via interference with sleep, daily activities, and work; PSEQ: Pain Self-Efficacy Questionnaire; PRI: Pain Rating Index; PSFS: Patient-Specific Functional Scale; RCT: Randomized Clinical Trial; SF-12 (PHS, MHS): 12-Item Short Form Survey – Physical/Mental Health Summary; SF-MPQ: Short-Form McGill Pain Questionnaire; ULA: Upper Limb Amputation; VAS: Visual Analogue Scale; VR: Virtual Reality; WPD: Weighted Pain Distribution.

mirror therapy, traditional mirror therapy, and sensorimotor exercises—showed reduced pain, but no between–group differences reached significance. Moreover, follow-up analyses by Rothgangel et al[7] and Ortiz-Catalan et al[15] found that reductions in PLP intensity at the end of the intervention were not statistically significant.

Immersive studies

Eleven of the 17 included studies met the criteria for an immersive VR or AR intervention. Across the eleven immersive trials, three distinct virtual-reality paradigms were deployed. In the first group of studies (Osumi et al[11], Cole et al[14], Murray et al[22]), participants wore fully occluding head-mounted displays that presented a "virtual mirror box," either by mirror-reversing intact-limb movements or by mapping direct stump motions to a virtual phantom in a 3D environment. The second approach (Rutledge et al[12], Kulkarni et al,[13] Ambron et al[18], Steckel et al[10]) combined immersive headsets with motion-capture sensors or interactive interfaces—such as stationary-bike pedals—to translate participants' real-time limb motions into goal-oriented VR games and exercises. Finally, four studies (Thøgersen et al[16], Annapureddy et al[19], Keesom et al[23], Prahm et al[20]) utilized see-through augmented-/mixed-reality headsets linked to residual-limb EMG pattern recognition, enabling users to control personalized virtual limbs—ranging from anatomically accurate arms to stylized tentacles—in interactive motor tasks and gamified therapeutic scenarios.

All the immersive VR/AR paradigms produced notable reductions in phantom-limb pain intensity, regardless of whether they employed fully virtual mirror boxes, motion-capture game environments, or EMG-driven AR limb control (Table 4). For instance, Osumi et al[11] and Cole et al[14] reported 30–50 % decreases in PLP following a series of fully occluding HMD mirror-therapy sessions, while Murray et al[22] described a subjective reduction of PLP with this intervention. Across the active motion capture VR trials, average PLP reductions of 28–40 % were noted, though statistical significance differed by study. Rutledge et al[12] and Ambron et al[18] both demonstrated significant analgesic effects ($p < 0.05$), whereas Kulkarni et al[13] and Steckel et al[10] reported comparable mean pain decreases that failed to achieve statistical significance (Kulkarni: $p = 0.05$; Steckel: $p > 0.05$).

The EMG driven AR/MR interventions—Thøgersen et al,[16] Annapureddy et al,[19] and Prahm et al[20]—demonstrated 30–50 % reductions in pain alongside high usability and strengthened agency over the phantom limb. Keesom et al[23]'s qualitative follow-up further confirmed that patients experienced improved control, embodiment, and satisfaction with the treatment. In several of these reports, however, follow-up assessments revealed partial pain relapse over weeks to months, indicating that ongoing or booster immersive VR/AR sessions may be necessary to sustain therapeutic benefit.

Across the non-immersive and immersive trials, participants also reported broad gains in psychosocial and quality-of-life measures alongside pain relief. The studies documented uniformly high ratings of realism, immersion, and overall satisfaction with the VR/AR experience. Ambron et al[18] noted mood improvements and increased motivation for rehabilitation after repeated sessions, and Annapureddy et al[19] observed statistically significant boosts in patient specific functional scores (PSFS) and self-reported exercise adherence.

Table 4 - Study characteristics for publications utilizing immersive VR/AR systems.

Author (year) Study Design;	Sample (N); Type of Amputation (ULA or LLA)	VR vs. AR	AR/VR Modality	Outcome measures	Primary Findings
Murray et al[22] Prospective study	N= 5 ULA	VR	Participants wore a head-mounted display that presented a virtual limb in the space of the missing limb. Movements of the intact limb were tracked and mirrored to control the virtual limb, creating the illusion of movement in the phantom limb.	Qualitative data: participants' experiences, perceptions of pain relief, and the psychological impact of the intervention.	1) Participants reported subjective reductions in PLP, with some noting significant relief during and after sessions. The immersive experience facilitated a sense of control over the phantom limb, contributing to pain alleviation. 2) The intervention provided emotional and psychological benefits, including increased agency and reduced distress associated with PLP.
Cole et al[14] Prospective study	n=14 7 ULA 7 LLA	VR	Movements of the missing limb were controlled by surface EMGs: participants with ULAs performed a virtual grabbing/moving task, while LLA participants performed a bass drum movement.	Drug history, SF-MPQ, VAS	1)Mean PLP scores dropped by 35 % (± 12 % SD) during each VR session compared to baseline (mean reduction 2.1 ± 0.7 points on a 0–10 scale; $p = 0.002$). 2) Pain levels returned to within 5 % (± 10 % SD) of baseline within 24 hours after each session, indicating the effect was statistically significant only during immersion ($p < 0.01$) with no carryover effect at 24 hours ($p = 0.48$).
Rutledge et al[12] Prospective study	n=14 13 LLA 1 ULA	VR	Physical control: participants attached their prostheses to a bicycle pedaler which tracked their motion to a virtual biking avatar.	PCL-M, PHQ-9, PLPQ, SF-12, TAPES	1) Pre- to post-treatment pain scores fell significantly ($t_{13} = 2.7$; $p = 0.02$; Cohen's $d = 0.53$), indicating a moderate analgesic effect. 2) Unpleasant non-painful sensations also decreased significantly ($t_{13} = 4.4$; $p = 0.001$; Cohen's $d = 1.7$), demonstrating a large reduction in overall phantom discomfort.

Kulkarni et al[13] Prospective study	n=9 ULA	VR	Mirrored virtual limb: participants used the virtual limb to complete a 3D ball task.	Duration of PLP episodes, number of PLP episodes, NRS	1)After 3 sessions, mean NRS pain fell from 6.11 to 3.56 but did not reach significance (t_8 = 2.1; p = 0.05). There were no significant changes in episode frequency (χ^2 = 3.43; df = 2; p = 0.18) or duration (χ^2 = 22.50; df = 16; p = 0.13). 2) At one year follow-up, pain scores remained below baseline (6.11 vs. 5.56) without statistical significance (t_8 = 1.35; p = 0.21), and neither episode frequency (χ^2 = 8.00; df = 3; p = 0.05) nor duration (χ^2 = 20.25; df = 12; p = 0.06) showed significant long-term changes.
Osumi et al[11] Prospective study	n= 19 13 ULA	VR	Mirrored virtual limb: participants used the virtual limb to participate in three separate dexterity activities- reaching, grasping, and bimanual coordination.	OI, SF-MPQ	1) Bimanual coupling effects improved markedly (p < 0.0001), indicating significant restoration of phantom-limb movement representation. 2) Phantom-limb pain intensity decreased by 38.9 % (p = 0.02). 3) The percentage increase in ownership index (OI) correlated significantly with the percentage decrease in SF-MPQ scores (r = 0.54; p = 0.008).
Thøgersen et al[16] Prospective study	n=7 ULA	AR	Surface EMGs: participants used the virtual limb controlled by EMG signals to complete dexterity tasks.	DPD, fMRI, MPI-D, NRS, SF-MPQ, TS, VAS	1) Significant 41% reduction in PLP via NRS pain severity scores in patients (mean change: 0.93, p=0.022, d=1.334). 2) Significant 52% reduction in SF-MPQ pain between the first and seventh sessions (mean Δ = −1.88; p = 0.032; d = 1.14), although post-session pain ratings remained statistically unchanged. 3) Functional MRI during a lip-pursing task revealed a significant post-training decrease in the contralateral primary somatosensory cortex (S1) activation (−52, −14, 42; p = 0.011), while ipsilateral S1 clusters remained stable. 4) The magnitude of S1 activity reduction correlated with the observed decreases in NRS pain severity, indicating a neural substrate for the clinical analgesia.

Ambron et al[18] Prospective study	n= 7 LLA	Immersive VR	A head-mounted display provides a three-dimensional view of the environment, with a display of both intact legs controlled by the participant´s movements. Participants controlled a virtual avatar with two legs using motion tracking of their intact and residual limbs.	VAS, HADS, SF-12, FAI, PCS	1)Pain Reduction: Mean VAS pain score decreased from 44.5 (SE=7.6) to 26.9 (SE=8.1), a 39.6% reduction (p=0.015). 2) The results showed a decrease in the pain interference in the daily life scale of 28% (p=0.03). HADS depression scores showed a 60% reduction (p=0.06), and anxiety scores decreased by 36% (p=0.06) post-limb treatment. 3) Pain reductions were maintained at 1, 4, and 8 weeks post-treatment in most participants
Annapureddy et al[19] Prospective study	N=8 LLA	AR	Utilized the Mixed Reality System for Managing Phantom Pain (Mr. MAPP), which employs a sensor and an head-mounted display to create a real-time mirrored image of the intact limb onto the amputated side. Participants engaged in three interactive "exergames" targeting lower limb movements.	MPQ, BPI, PSFS	1)The results showed a significant decrease in mean current pain intensity from 1.75 to 1.125 out of 5 (p = 0.011). MPQ showed significant reductions in constrictive pain subclass and evaluative pain subclass. Exercise diary indicated a modest but significant immediate post-session pain reduction (from 2.92 to 2.71 out of 10; p = 0.0013). 2) Functional Improvement: PSFS scores improved significantly from 4.28 to 6.22 out of 10 (p = 0.006). 3) Participants reported enhanced ability to perform specific daily activities.
Keesom et al[23] Prospective study	N= 21 LLA	AR/VR	Phantom motor execution treatment for chronic PLP, using myoelectric signals to control movements in extended-reality environments.	Qualitative data: Pain interference-sleep, daily activities, work.	1) Many experienced significant pain relief, though a few reported little or no effect. 2) Participants described significant negative impacts of PLP on sleep, concentration, mood, and social participation prior to treatment. 3) After treatment, many reported improved energy, increased social interaction, and a stronger sense of self.
Steckel et al[10] RCT	N= 21 LLA	VR	Virtual reality with a VR headset. Participants remained seated and observed an avatar performing lower limb exercises. The control group received no VR intervention, only usual care.	ABC, MPQ, SSQ	1) Balance scores (ABC scale) improved in the VR group (from 59.7% to 63.9%) and decreased in control group (from 54.3% to 47.4%)—not statistically significant, but a medium effect size was noted (Cohen's d =

					0.56). 2) No statistically significant differences were observed between groups in PLP and residual limb pain post-intervention. 3) Participants reported a high sense of presence in VR (mean = 7.08/10), and mild cybersickness overall.
Prahm et al[20] Prospective study	N= 8 ULA	AR	A gamified mixed reality application used to superimpose either an anthropomorphic arm or a tentacle on the residual limb. The virtual limb was controlled via EMG signals.	NRS, PRI, SUS, GEQ, PES	1) Results showed a significant reduction in PLP, with a median decrease of three points on the NRS, representing a 58% reduction and a 45% reduction in the PRI. These changes were statistically significant ($p < 0.001$). 2) The system was rated highly usable, with amputees scoring an average of 89.6% on the SUS. The GEQ indicated high immersion with no adverse effects. 3) Participants also demonstrated a strong sense of agency over the virtual limb, regardless of whether it was an arm or tentacle.

ABC: Activities-specific Balance Confidence Scale; AR: Augmented Reality; BPI: Brief Pain Inventory; DPD: Daily Pain Diary; Drug history; fMRI: Functional Magnetic Resonance Imaging; FAI: Frenchay Activities Index; GEQ: Game Experience Questionnaire; HADS: Hospital Anxiety and Depression Scale; LLA: Lower Limb Amputation; LL A episodes duration; MPI-D: West Haven–Yale Multidimensional Pain Inventory; MPQ: McGill Pain Questionnaire; NRS: Numerical Rating Scale; OI: Ovalization Index; PCS: Pain Catastrophizing Scale; PCL-M: PTSD Checklist – Military Version; PHQ-9: Patient Health Questionnaire-9; PLPQ: Phantom Limb Pain Questionnaire; PRI: Pain Rating Index; PSFS: Patient-Specific Functional Scale; RCT: Randomized Clinical Trial; SF-12: 12-Item Short Form Survey; SF-MPQ: Short-Form McGill Pain Questionnaire; SSQ: Simulator Sickness Questionnaire; SUS: System Usability Scale; TAPES: Trinity Amputation and Prosthetic Experience Scale; TS: Telescoping Sliders; ULA: Upper Limb Amputation; VAS: Visual Analogue Scale; VR: Virtual Reality; WPD: Weighted Pain Distribution.

Discussion

A significant proportion of individuals with an amputee leg or arm experience persistent and, in some cases, debilitating pain in the missing limb, a condition known as PLP. Although various treatments can offer temporary relief, it is widely acknowledged that most current therapies fail to deliver lasting benefit for most individuals with PLP.[24]

A variety of sensorimotor-based strategies have been tested in small clinical studies, with mirror therapy remaining the most widely investigated and intuitively straightforward approach. VR-based therapies have built on that foundation in two principal ways: some systems simply mimic mirror therapy-displaying a mirrored view of the intact limb in a fully virtual scene- like Kulkarni et al e Osumi et al, while others provide myoelectric or motion-capture control of the amputated extremity's avatar via surface EMG on the residual limb.[16,20] Compared with a static physical mirror, these VR implementations offer several important advantages: they can be embedded in engaging game like activities rather than repetitive motions, boosting patient motivation; they allow asynchronous, non-mirrored bimanual interactions, vastly expanding therapeutic possibilities.[7]

This review synthesizes the diverse and rapidly expanding literature on AR/VR for the treatment of PLP. Notably, we observed a shift toward fully immersive head-mounted systems as their cost has fallen and availability has risen-thus removing a potential barrier to the clinical use of AR/VR therapeutics.

The included studies showed for, both non-immersive and immersive AR/VR interventions, clinically meaningful reductions in phantom-limb pain across mirror-therapy–style platforms, motion-capture games, and EMG-driven phantom-motor execution systems. Equally important, several studies documented parallel gains in mood, confidence, and functional ability, and reported high levels of user satisfaction and device usability. Among the four RCTs, Abbas et al,[8] Lendaro et al[9] and Steckel et al[10] showed significant reduction in PLP intensity, while Rothgangel et al[7] reported PLP reductions across all three arms but no between-group differences reached significance.

This review has several limitations related to the current available evidence of AR/VR in PLP management. Methodological heterogeneity-in type of treatment, outcome measures, and follow-up intervals-limits our ability to determine which specific elements are most responsible for long-term benefits in pain, mood, and function. Moreover, few studies have compared immersive versus non-immersive formats directly. Small sample sizes and inconsistent outcome measures further constrain cross-study comparisons and warrant cautious interpretation of the existing data.

Finally, future research must adopt multicenter, randomized designs with harmonized intervention (e.g., uniform session frequency and duration), consistent follow-up intervals, and common primary endpoints such as the Numerical Rating Scale and validated quality-of-life instruments.

Conclusion

AR/VR therapies for phantom-limb pain appear to offer meaningful, and in some cases long-lasting, reductions in pain intensity as well as improvements in function, mood, and patient satisfaction. However, the existing studies display considerable heterogeneity in intervention type, treatment dose, and outcome measures. Larger, well-powered RCTs using standardized protocols, uniform endpoints, and direct comparisons between AR/VR-based therapies and existing PLP treatments—such as mirror therapy, graded motor imagery, and pharmacological approaches- will be essential to clarify their relative efficacy and create optimal treatment algorithms.

Authors' Contributions

Catarina Fonseca (first author): Conceived and designed the review; performed literature search, selection, and analysis; drafted the manuscript; critically revised it for important intellectual content; gave final approval of the version to be published; and is accountable for all aspects of the work, ensuring integrity and accuracy in all parts.

Marta Gil: Assisted in the literature search and data extraction; contributed to the interpretation of findings; critically revised several sections of the manuscript for important intellectual content; approved the final version; and is accountable for their specific contributions.

Mariana Soutinho: Contributed to the conceptual framing of the review; helped refine the analysis and the discussion; critically reviewed the manuscript; provided final approval; and is accountable for the contributions made.

João Diniz: Participated in drafting parts of the manuscript (e.g., methodology and discussion); critically revised the text; approved the final version; and takes responsibility for their contributions.

Maria João Cotter and **Lúcia Dias** (final reviewers): Conducted the final round of proofreading and editing for clarity, style, and coherence; approved the final version; and are accountable for the accuracy and integrity of their editorial work.

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