From Prototypes to Comparable Evidence: A Design–Mechanism–Measurement View of AR Gamified Rehabilitation

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Abstract

Augmented Reality (AR) gamification shows growing promise as an approach to the design of rehabilitation tools, but evidence on intervention effectiveness remains difficult to synthesise and compare across systems and studies. As part of a broader scoping review, we analyse 21 papers that report on AR gamified rehabilitation and examine how design choices, mechanisms, and measurement practices are connected in those studies. Our analysis reveals a recurring Design – Mechanism – Measurement (D-M-M) misalignment: systems increasingly combine heterogeneous AR delivery and sensing pipelines with gamified feedback, yet intervention mechanisms are rarely specified as testable pathways, and evaluations more often emphasise usability and feasibility of tools than indicators of rehabilitation change. We argue that future work should report AR gamified rehabilitation as an explicit intervention logic and make minimal D-M-M claims linking core design ingredients to hypothesised mechanisms and aligned measures. The next phase of this work will extend the same analytic lens across the wider review corpus to examine whether this pattern is specific to rehabilitation or reflects broader reporting tendencies in AR gamified physical activity research.

CCS Concepts

• **Human-centered computing** → **Mixed / augmented reality**; **Ubiquitous and mobile computing**; *Empirical studies in HCI*; Interactive systems and tools; • **Applied computing** → *Health informatics.*

Keywords

Augmented Reality, Gamification, Rehabilitation, Digital health, Design-Mechanism-Measurement, Sensing and Tracking

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1 Introduction

Augmented Reality (AR) is gaining momentum in rehabilitation to support motor practice, guidance, and feedback across a range of therapeutic contexts. From an HCI perspective, AR rehabilitation is not simply a "technology add-on" to conventional therapy; it is an *interactive system* organised around a closed loop of sensing, state updating, and feedback that shapes subsequent action [6]. Crucially, many AR rehabilitation systems also integrate gamification – the use of game design elements in non-game contexts – to make repetitive practice more tolerable, engaging, and sustainable [11, 22].

Yet, despite increasing proliferation of prototypes and trials, the evidence base remains difficult to compare, reproduce, and translate into actionable design guidance for clinicians and developers. Existing studies frequently describe what was built and some outcome measures, but less consistently articulate why a given AR and gamification configuration is expected to work, or how evaluation should test those claims. As a result, design features, hypothesised mechanisms, and measurement choices are often reported as separate elements rather than as a coherent intervention logic or theoretical approach.

This paper argues that progress in AR gamified rehabilitation would benefit from stronger alignment between design, mechanisms, and measurement. As an initial analytic step within a broader ongoing scoping review of AR gamified physical activity interventions, we report a focused analysis of 21 papers on AR gamified rehabilitation. Rather than revisiting effectiveness alone, we focus on how existing studies (1) specify AR and gamification designs, (2) articulate the behavioural and psychological mechanisms they intend to influence, and (3) operationalise outcomes in evaluation.

2 Prior work

Recent reviews have examined AR in rehabilitation, particularly in domains such as stroke recovery, hand function, gait, and limb training, and generally report promising effects on performance- or function-related outcomes. For example, Chang et al. [7] reviewed AR for lower-limb rehabilitation and suggested promising effects on functional outcomes, Pereira et al. [23] synthesised AR and VR application in hand rehabilitation, and Gorman and Gustafsson [12] provided a narrative review of AR for post-stroke rehabilitation, highlighting both practical potential and definitional challenges around what counts as "AR". Related review work has also examined gamification in rehabilitation and e-health more broadly, often focusing on the integration of game elements and their reported benefits [23, 24].

However, they differ in scope and analytic emphasis. Systematic reviews tend to synthesise functional effectiveness and commonly report improvements in rehabilitation outcomes[7, 23], while scoping and narrative reviews more often describe system characteristics and practical considerations, such as sensing and feedback pipelines, device constraints, and deployment conditions, and highlight challenges such as heterogeneous study designs and inconsistent terminology around what constitutes "AR" [12].

What remains less visible across these review stands is how design choices, hypothesised mechanisms, and measurement practices are connected within individual studies.

3 Method

This paper reports a focused subset analysis drawn from a broader scoping review (n=109) that is currently ongoing of AR interventions that incorporate gamification in physical activity contexts. The broader scoping review followed PRISMA-ScR procedures for identification, screening, and extraction workflow, systematically searched five databases:*ACM Digital Library, Scopus, PubMed, IEEE Xplore, and Web of Science*, covering studies published between January 2015 and December 2025 [27].

We constructed a rehabilitation subset for the present paper in order to examine one analytically coherent application cluster in greater depth. Studies were included when the AR gamified interventions aimed at restoring or improving functioning (e.g., mobility, balance, limb function, ADL) for people with health conditions, injuries, or disabilities; typically in clinical or therapeutic contexts [15, 30]. Studies focusing on general fitness, sports training, or non-clinical skill training were excluded unless rehabilitation was the explicitly stated purpose. Applying these criteria yielded 21 studies for the focused analysis reported in this paper. For this focused analysis, we examined extracted data on AR modality, gamification structure, sensing implementation, theory and mechanism reporting, and evaluation measures. We then compared how these elements were reported across studies, paying particular attention to whether proposed mechanisms of change were explicitly connected to design features and measurement choices. The recurring alignment issues identified through this comparison are developed in the findings and discussion sections.

4 Findings

4.1 Overview of the rehabilitation subset

15 studies in our data set reported an explicit evaluation design and outcome results, while six reported formative studies with user data but without complete outcome evaluation. Clinically, the evidence concentrates on neurological rehabilitation, most commonly post-stroke populations (n=7), with smaller clusters addressing Parkinson's disease and cerebral palsy. Intervention targets were similarly clustered around upper-limb function (n=7) and gait/balance/mobility-orientated tasks (n=5). Sample sizes were generally modest (Median=14; range=3–48). Most evaluations were conducted in a single session (n=13), with seven multi-session deployments. The evidence base, to conclude, is dominated by brief exposure windows and small samples, which constrains what can be concluded about sustained adherence or longer-term functional change.

4.2 Design landscape

AR modality and platform distribution. A range of AR modalities was used among the rehabilitation subset. Head-worn AR was most common (n=9; HMD n=7; smart-glasses n=2). Camera-based AR formed the second major cluster (n=8; marker-based & marker-less based), typically deployed on laptop or Android smartphones. Rather than converging on a single platform model, the subset reflects multiple delivery configurations for supporting rehabilitation tasks.

Gamification patterns. Gamification designs were dominated by simple and repeatable structures. Fixed goal structures dominated (n=17) relative to adaptive goals (n=4). Feedback was most often visual-only (n=10) or multimodal (n=10), with audio-only feedback rare (n=1). Motivational framing was most frequently reward-based (n=13), whereas narrative-based framing appeared in only two studies, and competition-based framing appeared in one study; five studies did not clearly report motivational framing. Social interaction was largely absent: only one study reported a cooperative feature.

Sensor and tracking configurations. Sensor and tracking pipelines were highly heterogeneous and frequently combined multiple components. To better support cross-study comparisons, table 1 re-frames this heterogeneity as six mutually exclusive primary pipelines and links each pipeline to the evaluation signals. This re-framing highlights that different pipelines constrain what can be meaningfully measured "in the loop": pose- and depth-based pipelines can yield kinematic proxies, such as joint-angle range, movement smoothness, and gait parameters; marker-based pipelines support spatial accuracy/alignment error and task execution metrics; and robot-/projection-based setups can expose end-effector error and force/assistance traces. While most systems used sensing to enable closed-loop feedback and task adaptation, only a subset explicitly operationalised sensor and log streams as comparable outcome indicators, like gait kinematics, tracking-quality metrics, dose/adherence logs, and eye-tracking signals, leaving substantial variation in how evaluation signals are defined and reported.

4.3 Mechanism & Theory

We distinguish between theory and mechanisms. Here, theory refers to a named explanatory framework used to justify design choices, whereas mechanisms refer to articulated, measurable pathways linking design features to change – often expressed as design → process/mediator → outcome. Across the rehabilitation subset, explicit mechanism specification was limited: few studies articulated such measurable pathways in measurable terms. Instead, "engagement", "motivation", or "improved performance" were commonly invoked as assumed explanations, rather than as mechanism components to be operationalised and examined empirically.

Theory use was also inconsistent: most studies did not explicitly report any guiding theory or framework (n=14). When theory was

Table 1: Primary sensing/tracking pipeline in the rehabilitation subset

Primary pipeline	n	Evaluation signals (examples)
HMD inside-out SLAM / spatial mapping	6	Gait & mobility kinematics [28]; model/estimation validity [28];in-task joint/performance logs [1, 26]
RGB markerless pose/motion (2D / 3D)	5	Practice dose & adherence logs [13];gait metrics [13];eye tracking (fixations/saccades) [4];
Mobile visual SLAM / sensor-fusion AR	3	Path/trajectory recordings [29]; task success criteria [29]; game logs[31].
Fiducial / image-target marker tracking	3	Tracking quality score [9]; task completion time; error count[9]; session completion counts [16];
RGB-D skeletal tracking	2	Movement success rate [5]; time correctness [5].
Projection-based and robotic / haptic loop	2	Task completion time; end-effector–target distance/error; cognitive-loading misses [21]; task performance metrics [20].

referenced (n=7), it more often functioned as a high-level rationale than as an evaluable model that would guide the selection of mechanism-relevant indicators. Notably, the sensing pipelines described in 4.2 could, in principle, support mechanism operationalisation by producing objective proxies aligned with common claims, such as practice dose as an adherence proxy, movement quality as a skill acquisition proxy, or error event as a feedback-uptake proxy. Yet, these links were seldom made explicit.

4.4 Measurement Practices

Most studies used mixed measurement approaches (n=15), typically combining self-report with objective performance logs or task metrics. Objective-only evaluations were less common (n=4), and self-report-only designs were rare (n=2). Notably, the primary evidence reported was most often user experience and usability (n=15), whereas fewer studies foregrounded physical activity or behavioural outcomes (n=4).

Standardized self-report instruments were used inconsistently. The System Usability Scale (SUS) appeared in five studies, while other instruments were used sporadically. Motivation- or affect-adjacent measures were comparatively rare. Objective measurement commonly relied on in-task or in-system metrics such as scores, time, or accuracy, but operational definitions varied across studies. In contrast, sensor-derived rehabilitation metrics – like dose proxies or movement quality features – were less consistently specified as explicit outcome variables, even though rich sensing and tracking pipelines were described in Section 4.2. Clinical or functional tests were present but comparatively infrequent, and were typically concentrated in the small subset that treated health outcomes as primary endpoints.

5 Discussion

5.1 What the rehabilitation subset reveals: a D–M–M misalignment pattern

From the rehabilitation subset, we observed a consistent pattern: design choices are increasingly sophisticated, but mechanisms of intervention action are rarely specified as testable pathways, and measurement tends to prioritise feasibility and user experience over mechanism-aligned outcomes. This should not obscure a genuine strength of AR gamified rehabilitation: many systems combine a rich sensing and tracking pipeline with real-time feedback and task adaptation, enabling a closed-loop form of guidance and error correction that conventional screen-based tools cannot easily provide [17].

However, the central issue is that technical richness is rarely translated into a shared explanatory layer. Across studies, mechanism language remained largely aspirational rather than operationalised, while evaluation more readily demonstrated that systems were usable and acceptable than how specific design choices contributed to rehabilitation-relevant change. This D-M-M misalignment is not unique to AR gamified rehabilitation. Similar critiques have emerged in digital health behaviour change and serious games: interventions frequently report positive acceptability or engagement outcomes while leaving the mediating processes underspecified, limiting theory-building and transfer [18]. In gamified health interventions, "gamification elements" are often enumerated without articulating the psychological mechanisms they aim to activate, or without measuring those mediators explicitly [2, 8]. Furthermore, AR adds a further layer of complexity: the sensing and interaction loop itself becomes part of the intervention logic, yet loop parameters are rarely discussed in mechanistic terms.

5.2 Why the gap matters: comparability, replicability, and design transfer

The practical consequence of under-specified mechanisms is that cross-study learning becomes difficult. When two systems both report "improved engagement" [10, 25] but differ in tracking fidelity, feedback timing, task demands, and reward structures, it becomes unclear what actually produced the effect. This weakens evidence accumulation in two ways. First, it reduces comparability: results cannot be meaningfully pooled or contrasted because "AR + gamification" represents many different bundles of design decisions. Second, it impairs replicability and transfer: without a clear pathway, researchers and clinicians cannot identify which components are essential for whom and under what constraints across populations, settings, and rehabilitation tasks.

Measurement choices further reinforce this gap. Our findings show that evaluations more often foreground acceptability, usability, and short-term performance than mechanism-aligned indicators of rehabilitation. Such prioritisation is understandable in early-stage system work, and usability is a legitimate determinant of adherence and safety in rehabilitation contexts [3]. Yet, when feasibility and UX dominate without a minimal set of mechanism-aligned measures, the literature tends to reward deployable prototypes over explanatory evidence. This mirrors longstanding concerns in behaviour change research, where interventions are evaluated for outcomes but not for how they achieved them, limiting cumulative scientific progress[19].

5.3 Towards alignment: actionable guidance for design, mechanism, and measurement

Our evidence map suggests that AR gamified rehabilitation should be treated and reported as an intervention logic – a closed feedback loop – rather than as a bundle of features. Systems in the subset often combine multiple sensing and tracking pipelines and adaptive goals; yet, the causal story connecting these design choices to change is rarely made explicit. This makes it difficult to compare systems that appear similar on the surface (AR+gamification) but differ substantially in feedback timing, tracking fidelity, task adaptation, and motivational framing.

To improve alignment, we argue that papers should articulate a minimal design-mechanism-measurement (D-M-M) claim:

- Design: name the primary active ingredient in the intervention logic, whether this is a game element (e.g., goals, rewards, social interaction) or a loop property (e.g., feedback timing, tracking fidelity, task adaptation)
- Mechanism: state which process this ingredient is intended to influence, such as perceived presence, self-efficacy, feedback uptake, or motor learning.
- Measurement: indicate the minimum evidence that could plausibly reflect that mechanism, ideally including at least one mediator or objective proxy (e.g., practice dose, movement quality, error events) alongside a behavioural or rehabilitation-relevant indicator where feasible.

For example, if adaptive visual feedback is presented as a primary design ingredient, the study should clarify whether it is expected to improve movement correction, feedback uptake, or practice quality, and what evidence would plausibly reflect this, such as error reduction, adjustment latency, or change in movement quality over repeated trials. Even in early-stage system work, such minimal claims would make it easier to understand what a system is trying to change and how that change is being examined.

Adapting alignment prompts would not only improve the clarity of reporting but also support more meaningful comparisons, replication, and measurement decisions under common practical constraints, such as limited clinical access or small samples. More broadly, AR gamified rehabilitation could build on adjacent reporting traditions that emphasise intervention active ingredients and logic models [14, 24], while treating sensing and interaction fidelity as part of the intervention logic rather than background implementation detail.

5.4 Extending the D-M-M lens to a broader research programme

A key next step is to examine whether the D-M-M misalignment identified in the rehabilitation subset also appears across other application clusters in the wider review, including general wellbeing and physical activity, sports, and skill training. Extending the same analytic lens across the full corpus will make it possible to distinguish which alignment problems are more specific to rehabilitation and which reflect broader reporting patterns in AR gamified intervention research.

In the next phase of the review, we will refine and apply a common cross-category coding frame for three linked dimensions: first, the primary design ingredients of each intervention, including AR modality, feedback structure, adaptation logic, motivational framing, and social features; second, the extent to which studies articulate measurable mechanisms rather than invoking broad terms such as engagement or motivation; and third, how outcomes are operationalised, particularly whether sensing and in-system log data are treated as mechanism-relevant evidence or remain background implementation detail. This next step will support a comparative evidence map showing where alignment is currently strongest, where measurement remains weakest, and which forms of sensing and feedback appear most promising for mechanism-informed evaluation.

Beyond synthesis alone, this broader analysis is intended to inform subsequent design work. More specifically, it can help derive candidate alignment prompts and reporting expectations for future formative and prototype-stage AR interventions, where design decisions are often made before mechanisms and measures are fully specified. In this sense, the present rehabilitation subset should be understood not as an endpoint but as an initial analytic step toward a more transferable design agenda for AR gamified physical activity research.

6 Conclusions

AR gamified rehabilitation offers a clear promise by coupling action, context, and real-time feedback in ways that can support engaging and adaptive practice. Yet our rehabilitation subset reveals a recurring Design–Mechanism–Measurement (D–M–M) misalignment: mechanisms are rarely framed as testable pathways, and evaluations more often foreground feasibility and user experience than aligned indicators of rehabilitation change. We present this pattern as an initial analytic finding from a broader ongoing scoping review. Future work should therefore report AR gamified rehabilitation as an explicit intervention logic and make minimal D–M–M claims linking primary design ingredients to hypothesised mechanisms and aligned measures.

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