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Safety, Tolerability, and Patient Acceptance of a Virtual Reality Exergame System for Shoulder Rehabilitation: A Prospective Non-Randomised Feasibility Study

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Abstract

Background: Shoulder pathologies, including glenohumeral instability, rotator cuff tears, and frozen shoulder, place a substantial burden on healthcare systems and often require prolonged and demanding rehabilitation. Patient adherence to physiotherapy protocols is frequently limited by low motivation, perceived difficulty, psychological barriers, and more broadly, by mobility- or distance-related barriers to accessing rehabilitation services. The purpose of this study was to assess the feasibility, safety, tolerability and patient acceptance of MoRehabXR, a custom-built virtual reality (VR) exergame system designed to support first-phase shoulder rehabilitation across three distinct pathologies.

Methods: This was a prospective, single-centre, open-label, single-arm, non-randomised feasibility study. The prespecified target was 15 completers (five per pathology group). Eighteen outpatients initiated the study across three shoulder pathology groups: glenohumeral instability following stabilization surgery (n = 6), rotator cuff tear after surgical repair (n = 7), and frozen shoulder (n = 5). The protocol comprised four supervised VR sessions using an HTC Vive Pro system with upper-body tracking. Outcomes included cybersickness, perceived risk, and intrinsic motivation inventory, and were analysed descriptively. Inter-session and inter-patient variability were also computed.

Results: Protocol completion was 83.3% (15/18), with three participants discontinuing early, resulting in five completers per group. No serious adverse events or adverse events requiring session interruption were reported among the 18 participants who initiated the study. Post-session patient-reported assessments used 7-point Likert scales. Cybersickness (1.25 ± 0.64) and perceived risk (1.21 ± 0.56) were low across all groups. Interest was high (6.08 ± 1.12), competence moderate-to-high (5.34 ± 1.29), pressure low (2.01 ± 1.78), and effort moderate (4.22 ± 2.12). Inter-session variability was low (0.47), while inter-patient variability was slightly higher (0.68).

Conclusions: In this small, supervised cohort, MoRehabXR demonstrated preliminary feasibility and short-term tolerability, with high interest and low perceived pressure. These findings supported progression to a planned randomised controlled trial, which is currently awaiting regulatory approval.

Trial registration: Registration details blinded for peer review.

Keywords: shoulder rehabilitation, gamification, exergame, patient motivation, virtual reality, glenohumeral instability, rotator cuff tears, frozen shoulder.

Key messages regarding feasibility

• **What uncertainties existed regarding feasibility?** Whether patients across three shoulder pathologies could complete repeated supervised VR rehabilitation sessions safely and with acceptable cybersickness, perceived risk, and motivational responses.

• **What are the key feasibility findings?** Eighteen participants initiated the protocol and 15 (83.3%) completed all four sessions. No serious adverse events or adverse events requiring interruption occurred, and all predefined feasibility criteria were met.

• **What are the implications for the main study?** The findings supported progression to a randomised controlled trial comparing MoRehabXR with standard rehabilitation, which is planned and currently awaiting regulatory approval.

1. Background

Shoulder pain affects approximately 19-31% of the general population monthly [1]. Among the most prevalent shoulder conditions requiring prolonged rehabilitation are rotator cuff tears, glenohumeral instability, and frozen shoulder [2]. Despite the critical role of physiotherapy in shoulder rehabilitation, adherence remains a persistent challenge [3–7]: adherence to home exercise programs ranges from 48% to 70%, and non-adherence represents a major barrier to optimal recovery [5,6].

Multiple modifiable and non-modifiable factors influence adherence, including low self-efficacy, insufficient social support, pain, perceived difficulty of exercises, and patient beliefs about treatment effectiveness [5,8,9]. Beyond psychological and motivational barriers, geographic and mobility-related factors may also limit access to rehabilitation: patients living farther from physiotherapy centres have a significantly higher risk of early discontinuation, as do those requiring additional assistance to attend appointments [10]. These barriers highlight the need for rehabilitation technologies that

may ultimately support more accessible care pathways [11]. However, before any home-based use can be considered, such systems must first demonstrate safety and tolerability under supervised clinical conditions.

Gamification offers a promising avenue for addressing these barriers. By directing patients' attention toward gameplay rather than the demanding movements required, perceived difficulty is reduced through a phenomenon known as external focus [12,13]. Virtual Reality (VR) technologies extend this benefit further, immersing users in digitally created worlds through head-mounted displays and sensor systems that enable real-time interaction with virtual environments. This immersion can produce embodiment—the sensation of inhabiting the virtual character's body as one's own [14,15].

Integrating motion tracking with VR may enable real-time therapeutic adjustments and more personalized rehabilitation [4]. In their review, Gumaa & Youssef [16] also reported that VR therapy may support the assessment of joint function and balance and help document patient progress.

However, despite these potential benefits, VR-assisted musculoskeletal rehabilitation remains uncommon due to substantial technical complexity. Effective implementation demands: (i) compelling game design, (ii) intuitive yet reliable hardware, (iii) sophisticated motion analysis seamlessly integrated with therapeutic constraints, and (iv) skilled 3D artists and software engineers to ensure both aesthetic appeal and functional efficiency. A deficiency in any of these elements risks creating an unpleasant or counterproductive experience. In addition, cybersickness [17] remains a key tolerability concern in immersive VR and must be assessed as a potential adverse effect.

This prospective non-randomised feasibility study evaluated the feasibility, safety, tolerability and patient acceptance of *MoRehabXR*, a custom-built VR-assisted rehabilitation system designed to support early controlled mobility exercises during first-phase rehabilitation for three common shoulder pathologies: glenohumeral instability, rotator cuff tears, and frozen shoulder. Specifically, we assessed whether patients could complete repeated supervised VR sessions safely, with low cybersickness and perceived risk, and whether they reported a positive rehabilitation experience.

These feasibility objectives were intended to inform progression to a subsequent randomised controlled trial evaluating clinical efficacy.

2. Methods

Study Design and Population

This prospective, single-centre, open-label, single-arm, non-randomised feasibility study was conducted at a specialist shoulder clinic between December 2024 and January 2026. Patients were recruited from specialist shoulder consultations if they met the general eligibility criteria and pathology-specific criteria for one of three diagnostic categories: glenohumeral instability treated by surgical stabilization, rotator cuff tears treated by surgical repair, or frozen shoulder treated conservatively.

Eligible participants were adults aged ≥18 years who were able to understand the study information, provide written informed consent, attend four supervised rehabilitation sessions over 2–4 weeks, and had a clinical indication for shoulder rehabilitation for one of the three target pathologies. Patients were excluded in case of language, cognitive, or legal barriers preventing informed consent or questionnaire completion; pregnancy; inability to comply with the rehabilitation protocol or follow-up; active shoulder infection; pathology-specific contraindications to the planned rehabilitation pathway; or contraindications to immersive VR use, including uncontrolled epilepsy, severe vestibular disorder, severe uncorrected visual impairment, prior intolerance to immersive VR, or inability to safely wear and use the headset and tracking equipment.

For glenohumeral instability, patients were eligible if they had undergone Latarjet stabilization for one or more of the following indications: traumatic initial dislocation in an athlete aged <20 years with high recurrence risk, recurrent instability (≥2 documented dislocations) after failed conservative treatment (minimum 3 months of supervised physiotherapy), locked dislocation requiring surgical reduction, failed previous stabilization surgery, high-risk sport or

occupational exposure, critical glenoid bone loss (>15–20% of glenoid width on preoperative computed tomography), or bipolar bone loss resulting in an off-track Hill-Sachs lesion. Patients were enrolled two weeks postoperatively, corresponding to the first phase of standard post-Latarjet rehabilitation [18]. Patients with multidirectional instability (instability in two or more directions), Ehlers-Danlos syndrome, or other connective tissue disorders [19] were excluded.

For rotator cuff tears, patients were eligible if they had undergone arthroscopic rotator cuff repair for one or more of the following indications: small to massive reparable tears according to Lädermann's classification (full-thickness tear of at least two complete tendons and grade 2 Patte retraction [20] of at least one tendon [21]) with failure of conservative treatment (minimum six months of supervised physiotherapy and analgesic management) or acute traumatic tears in patients aged <60 years [22,23]. Patients were enrolled six weeks postoperatively, corresponding to the protective phase of standard post-rotator cuff repair rehabilitation [24,25]. Patients with irreparable tears, Goutallier grade D fatty infiltration, severe muscle atrophy, or superior humeral head migration with acromiohumeral distance <7 mm were excluded.

For frozen shoulder, patients were eligible if they had primary idiopathic or secondary frozen shoulder, defined by severe shoulder pain and restriction of both active and passive shoulder motion in which radiographs of the glenohumeral joint are essentially unremarkable [26]. Patients with glenohumeral arthritis, calcific tendinitis, or other structural shoulder pathology on imaging were excluded.

Ethics approval and patient consent

This study was conducted in accordance with the Declaration of Helsinki and prior approval of the local ethics committee was obtained (BASEC 2022-00166). Reporting was guided by the CONSORT extension for pilot and feasibility trials[27], adapted for this non-randomised single-arm study in accordance with Lancaster and Thabane[28]. All patients provided written informed consent to participate in the study. The study was retrospectively registered in a public clinical trial registry (ClinicalTrials.gov, NCT06963983; first posted 9 May 2025).

Equity, Diversity, and Inclusion

The study included women and men across a range of ages. The research team included one woman and four men from different career stages and clinical or scientific disciplines. Data on race, socioeconomic status, and other social determinants of health were not collected.

Equipment and Setup

The rehabilitation system comprised a commercially available head-mounted display (HMD) with six-degrees-of-freedom tracking (HTC Vive Pro; HTC Corporation, Taoyuan, Taiwan), two hand controllers (version 2.0), five body-mounted trackers (version 2.0), four Lighthouse base stations, and a computer to run and monitor the exergame. The tracking accuracy of this configuration for upper-limb motion analysis has been previously evaluated [29]. Room-scale calibration followed standard manufacturer specifications [30].

Patients were equipped with the HMD, a tracker on a belt, and bilaterally with a hand controller, a tracker on the arm, and a tracker on the forearm (see Figure 1). Our custom-built software *MoRehabXR* (developed in Unity 2022.3.24f1; San Francisco, CA, USA) ran the rehabilitation protocol.



Figure 1: User equipped for a VR session.

Anatomical Calibration and Session Initiation

At the start of a session, the therapist was presented with a control interface on the monitor in which patient information was collected. This included a patient identifier, the affected side undergoing therapy, the pathology, the patient's current progression level, and their preference for one of two virtual environments (a comfortable chalet in the mountains or a bungalow over the sea). For returning patients, the system auto-populated historical data and proposed the next appropriate game level.

Following form validation, the chosen virtual environment loaded, and the therapist initiated anatomical calibration, used to align the virtual avatar and joint angle computations with the patient's anatomy. This anatomical calibration process, which typically took approximately 2-3 minutes, has been previously evaluated as part of the technical assessment of the upper-limb tracking configuration [29]. Patients remained stationary while the therapist digitized 12 bilateral anatomical landmarks using a hand controller: acromial processes, greater trochanters, humeral epicondyles (medial and lateral), and radial and ulnar styloid processes. The controller was then returned to the patient, and a final button press initiated the exergame.

Gamified Rehabilitation

The exergame projects the user into the chosen virtual environment and presents them with a large table supporting a maze (Figure 2). In that maze, a small, animated mouse ("Mousy") tries to reach a block of cheese at the other end of the labyrinth, but many obstacles block her way (Figure 3). The aim of the game is to move the tabletop so that obstacles roll out of the way and platforms are appropriately raised or lowered, allowing Mousy to find her way to the cheese (see video in Supplementary material). The manipulation of the tabletop is performed by capturing the movements of the affected limb and translating them into input controls. Because the system was intended for first-phase rehabilitation, all control motions were selected to remain compatible with early rehabilitation constraints. The control motions vary by pathology to respect post-surgical precautions and target relevant functional movements:

- For glenohumeral instability and frozen shoulder patients: (i, ii) wrist pronation and supination (table roll left/right); (iii, iv) shoulder protraction and retraction (table pitch forward/backward); (v) shoulder elevation (raising platforms within the maze); and (vi) elbow flexion (lowering the platforms).
- For rotator cuff tear patients: (i, ii) shoulder internal and external rotation (table roll left/right); (iii, iv) elbow flexion and extension (table pitch forward/backward); and (v) shoulder anterior elevation (raising platforms, which descend passively).

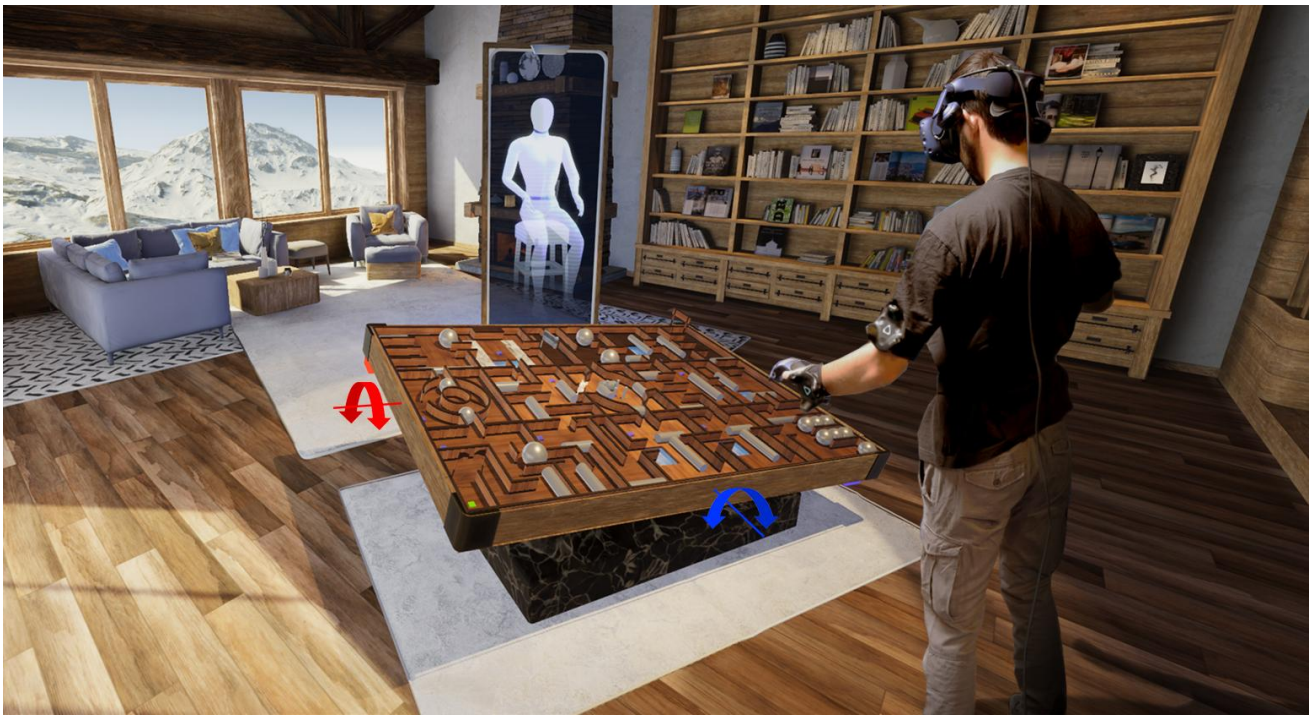

Figure 2: User in a virtual chalet solving a maze in VR while using shoulder movements as input. In front of the user, a holographic coach provides guidance. The blue arrow indicates tabletop roll left/right, and the red arrow indicates tabletop pitch forward/backward.

A standard maze comprised 15 modules in a 5 × 3 layout, each containing multiple obstacles. The game progression was organized into successive levels. Patients first completed a tutorial, during which a range-of-motion calibration was performed, and a virtual coach introduced the game mechanics using simple demonstrative mazes. Based on this calibration, the movement thresholds required to control the tabletop were automatically set at 80% of the patient's

maximum amplitude, allowing the movements to remain achievable while respecting early rehabilitation constraints. Patients then progressed through three initiation levels with increasing complexity and decreasing coach guidance, followed by 30 full mazes ordered by increasing difficulty. At each subsequent rehabilitation session, the range-of-motion calibration was repeated to adjust the movement thresholds to the patient's current capacity, and the patient resumed progression from the last maze reached in the previous session.

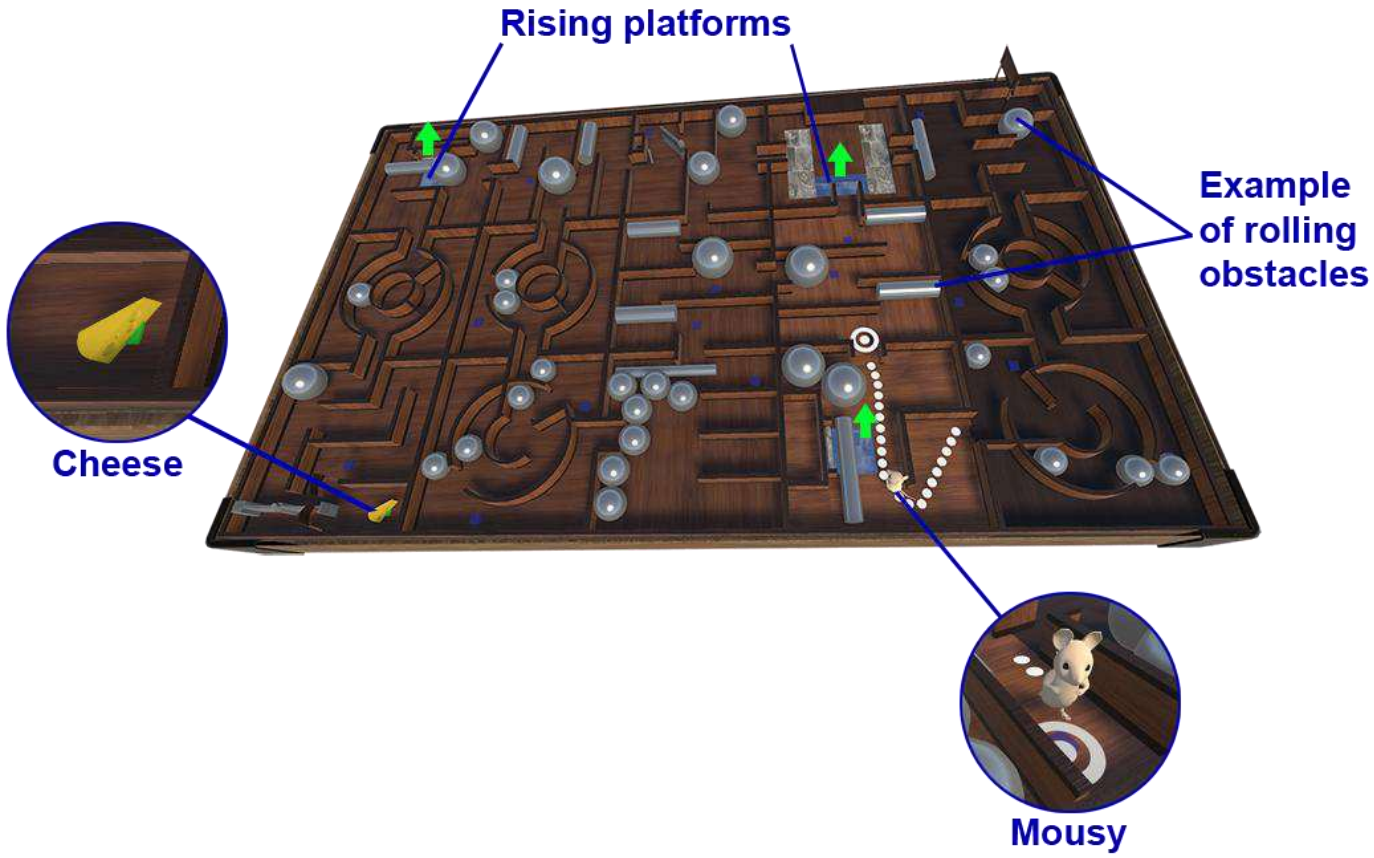

Figure 3: The maze includes: (i) Mousy, a white animated mouse, and her cheese; (ii) several metallic rolling obstacles; and (iii) rising platforms hidden underwater, with their motion indicated by green arrows.

The therapist monitored the session through a computer interface displaying the patient's avatar from multiple perspectives: frontal, superior, lateral, and first-person. The interface also displayed real-time upper-limb joint angles,

reported according to the International Society of Biomechanics (ISB) recommendations[31], together with the movement thresholds used to validate sufficient movement amplitude.

Data Collection and Adverse Event Monitoring

The protocol comprised four supervised VR sessions over 2–4 weeks. Sessions lasted approximately 20–25 minutes, including anatomical calibration (~3 minutes), range-of-motion calibration (~3 minutes), a tutorial when needed, and active gameplay (~15 minutes). All sessions were supervised by the same physiotherapist.

Adverse events were prospectively monitored and classified as: (1) serious adverse events (SAEs), defined as events requiring medical intervention, hospitalization, or protocol discontinuation, such as shoulder dislocation, severe pain exacerbation, syncope, fall, or severe VR-related disorientation; and (2) non-serious adverse events, defined as transient symptoms not requiring intervention, such as mild shoulder discomfort, transient dizziness, mild cybersickness, eyestrain, nausea, or visual discomfort. All adverse events were documented in real time by the supervising physiotherapist.

At the conclusion of every session, patients independently completed a computerized questionnaire, with all items rated on a 7-point Likert scale and drawn from the following instruments: (i) a shortened cybersickness questionnaire derived from the Simulator Sickness Questionnaire (SSQ) [17]; (ii) Avatar Embodiment [14]; (iii) reduced Intrinsic Motivation Inventory (IMI) [32,33], yielding four subscales (Interest, Competence, Effort, Pressure); and (iv) three custom questions assessing perceived risk during the tasks. For patient comfort, all questionnaires were administered in French (see Supplementary Materials for an English translation). Reverse-scoring procedures and questionnaire items are detailed in the Supplementary Materials.

To reduce measurement bias, questionnaire items were presented in randomised order, sessions followed a standardized procedure, and movement thresholds were automatically derived from each patient's range-of-motion calibration.

Primary and Secondary Outcomes

Primary outcomes were feasibility, safety, and tolerability of the VR-assisted rehabilitation protocol, assessed by protocol completion, adverse events requiring interruption, cybersickness symptoms, and perceived risk.

Secondary outcomes included patient acceptance, assessed through intrinsic motivation subscales, avatar embodiment as an exploratory VR-experience measure, and observed score variability.

Feasibility Criteria and Success Thresholds

Based on prior VR rehabilitation feasibility studies [34–36], the following pragmatic a priori success criteria were established to evaluate the feasibility, safety, and patient acceptance of *MoRehabXR*:

- Protocol completion rate: at least 80% of enrolled patients complete all four supervised VR sessions without serious adverse events requiring protocol discontinuation [34,36].
- Safety and tolerability: mean cybersickness and perceived risk scores remain ≤2.0 on the 7-point Likert scale, consistent with minimal symptom burden reported in controlled VR therapeutic environments [35,36].
- Patient engagement: mean intrinsic motivation interest scores ≥5.0/7 and mean perceived pressure scores ≤3.0/7, reflecting high engagement and low psychological burden associated with gamified VR interventions [37,38].
- Inter-session variability: inter-session variability (within-patient standard deviation) <1.0 across patient-reported outcome measures[39].

These pragmatic thresholds were defined prospectively to provide objective benchmarks for determining whether *MoRehabXR* supports progression to a subsequent randomised controlled trial of clinical efficacy.

Sample Size

The prespecified target sample size was 15 participants completing the four-session protocol, with five completers in each of the three pathology groups. The ethics-approved protocol specified this target of five completers per pathology group. Because the study was designed to assess protocol completion, short-term safety and tolerability, patient acceptance, and repeated-session variability across the three pathology-specific implementations, rather than clinical efficacy or between-pathology differences, no efficacy-based power calculation was performed. The target was pragmatic and intended to provide five complete four-session trajectories per pathology for descriptive evaluation of these feasibility objectives [40] . Recruitment continued until five completers were obtained in each pathology group, resulting in 18 participants initiating the study.

Statistical Analysis

Descriptive statistics were used exclusively. Results are reported as means (μ) and standard deviations (σ). We additionally calculated aggregated means and standard deviations by individual pathology and across all pathologies combined. For each session, questionnaire scores were calculated as the mean of the relevant constituent items. Participant-level scores were obtained by averaging session scores across the four completed sessions, and group and overall scores were calculated from these participant-level values.

To evaluate score variability, we computed two variability indices for each instrument:

- *Inter-session variability* (within-patient variability) was calculated for each patient as the standard deviation of their four session scores:

$$\sigma_{i,p}^{pat} = \sqrt{\frac{1}{S-1}\sum_{s=1}^{S}\left(m_{i,s,p}^{pat} - \mu_{i,p}^{pat}\right)^2}$$

where $m_{i,s,p}^{pat}$ represents the measurement for instrument *i*, session *s*, and patient *p* with pathology "*pat*"; $\mu_{i,p}^{pat}$ is the mean across sessions for that patient; and *S* is the total number of sessions.

- *Inter-patient variability* (between-patient variability) was computed for each instrument as the standard deviation of patient means within each pathology group:

$$\sigma_i^{pat} = \sqrt{\frac{1}{P^{pat} - 1} \sum_{p=1}^{P^{pat}} \left(\mu_{i,p}^{pat} - \bar{\mu}_i^{pat} \right)^2}$$

where $\bar{\mu}_i^{pat} = \frac{1}{P^{Pat}} \sum_{p=1}^{P^{Pat}} \mu_{i,p}^{pat}$ is the grand mean across all patients for pathology *"pat"*.

Participant flow, baseline characteristics, protocol completion, and adverse events were reported for all 18 participants who initiated the study. Patient-reported outcome analyses were performed on the 15 participants who completed all four VR sessions. No imputation was performed. All statistical analyses were performed using Python 3.13.11 (Python Software Foundation, Wilmington, DE, USA).

Use of Artificial intelligence

During the preparation of this work, the authors used OpenAI ChatGPT (GPT-6.0) to improve the English language, revise grammar and style, and enhance the clarity of the manuscript. After using this tool, authors carefully reviewed and edited the content and take full responsibility for the final version of the manuscript.

3. Results

Eighteen outpatients initiated the study and were distributed across three diagnostic categories (Figure 4):

- Glenohumeral instability (n = 6): patients recruited 2 weeks after surgical stabilization using the Latarjet technique.
- Rotator cuff tears (n = 7): patients recruited 6 weeks after surgical repair.
- Frozen shoulder (n = 5): patients recruited at treatment initiation.

Fifteen participants completed all four sessions (83.3%) and comprised the cohort for patient-reported outcome analyses (n = 5 per pathology). The three participants discontinued because work-related scheduling constraints prevented

continued attendance; all three also discontinued their usual physiotherapy at the same institution. Baseline characteristics of all 18 participants are summarized in Table 1.

Table 1. Baseline patient characteristics.

Characteristic	Glenohumeral Instability (n = 6)	Rotator Cuff Tears (n = 7)	Frozen Shoulder (n = 5)	Total (n = 18)
Age, years (μ ± σ)	24 ± 3	53 ± 9	54 ± 5	45 ± 15
Sex, n (%) male	6 (100)	4 (57)	1 (20)	11 (61)
Affected side, n (%) right	3 (50)	6 (86)	0 (0)	9 (50)
Dominant side affected, n (%)	3 (50)	6 (86)	0 (0)	9 (50)
Baseline pain (VAS 0-10), μ ± σ	2.4 ± 1.2	5.6 ± 1.4	6.9 ± 1.1	4.9 ± 2.2

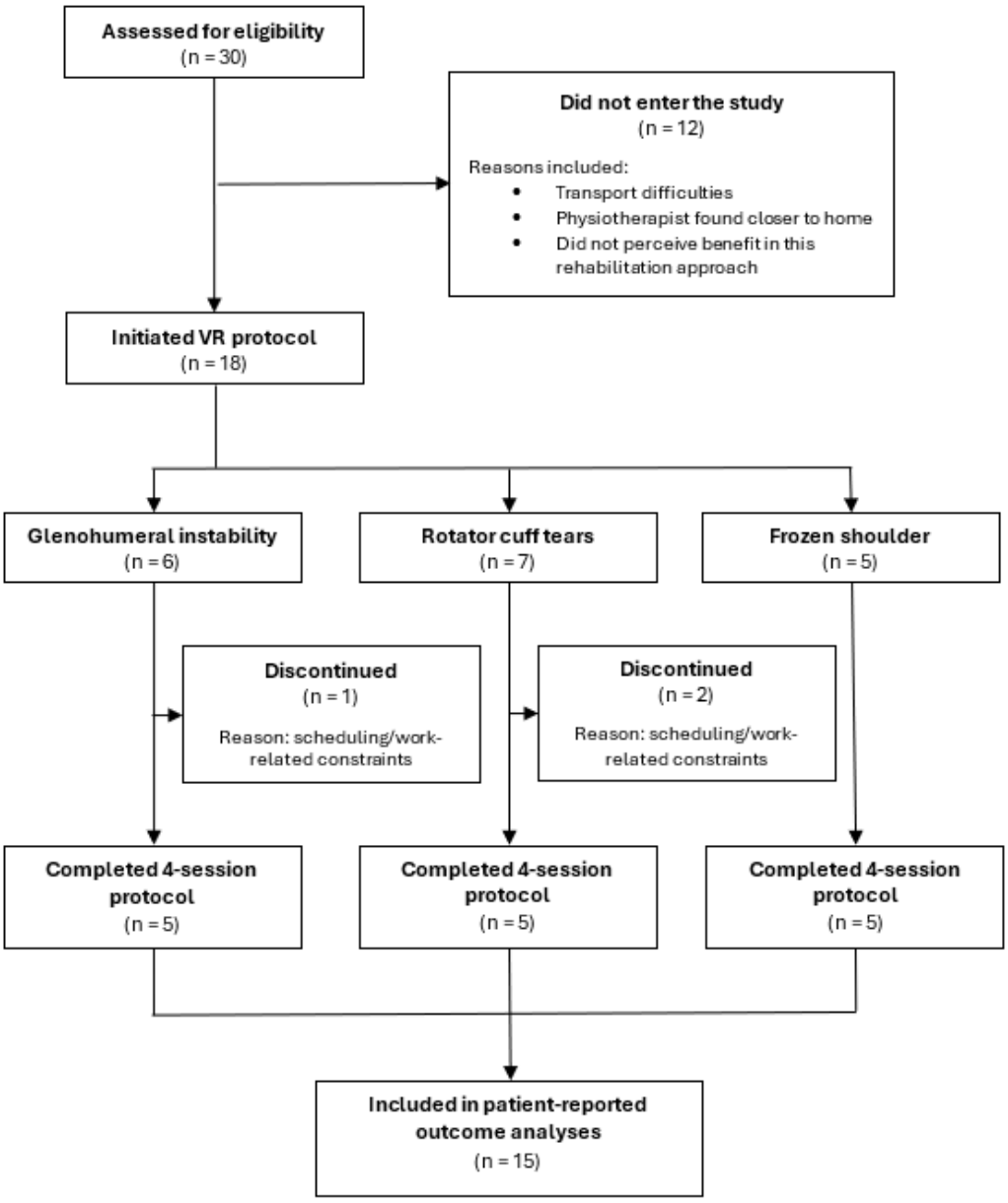

Figure 4: Participant flow diagram for this prospective non-randomised feasibility study.

Safety and Tolerability

The predefined safety and tolerability criteria were met. Among the 18 participants who initiated the VR protocol, no serious adverse events or adverse events requiring interruption were reported. Three patients reported mild, transient shoulder discomfort during gameplay that resolved spontaneously within five minutes without requiring session interruption. No participants experienced falls, dizziness requiring seated rest, or pain requiring analgesic administration during VR sessions. Among the 15 completers, overall perceived risk (1.21 ± 0.56) and cybersickness (1.25 ± 0.64) scores were low (Table 2). Descriptively, the frozen shoulder group had the highest mean general discomfort (1.50 ± 0.50) and perceived risk (1.43 ± 1.05) scores.

Table 2. Cybersickness and perceived risk by pathology (μ ± σ).

	Glenohumeral Instability	Rotator Cuff Tears	Frozen Shoulder	Aggregated
Cybersickness	1.17 ± 0.54	1.05 ± 0.31	1.53 ± 1.07	1.25 ± 0.64
Perceived risk	1.03 ± 0.18	1.17 ± 0.46	1.43 ± 1.05	1.21 ± 0.56

Among cybersickness subscales, eyestrain followed a similar pattern, with scores of 2.10 ± 1.65 in frozen shoulder patients, 1.70 ± 0.69 in glenohumeral instability, and 1.00 ± 0.00 in rotator cuff tear patients. Difficulty concentrating was also numerically higher in the frozen shoulder group (1.80 ± 0.48; glenohumeral instability: 1.05 ± 0.11; rotator cuff tears: 1.20 ± 0.33). Headache, nausea, and stomach awareness remained close to the minimum across all groups (Table 3).

Table 3. Cybersickness subscale scores by pathology (μ ± σ).

	Glenohumeral Instability	Rotator Cuff Tears	Frozen Shoulder	Aggregated
Difficulty concentrating	1.05 ± 0.11	1.20 ± 0.33	1.80 ± 0.48	1.35 ± 0.46
Eyestrain	1.70 ± 0.69	1.00 ± 0.00	2.10 ± 1.65	1.60 ± 1.06
General discomfort	1.25 ± 0.35	1.05 ± 0.11	1.50 ± 0.50	1.27 ± 0.38
Headache	1.00 ± 0.00	1.05 ± 0.11	1.00 ± 0.00	1.02 ± 0.06

Nausea	1.00 ± 0.00	1.00 ± 0.00	1.25 ± 0.56	1.08 ± 0.32
Stomach awareness	1.00 ± 0.00	1.00 ± 0.00	1.50 ± 0.47	1.17 ± 0.35

Embodiment

Embodiment scores were positive (overall: 5.78 ± 1.33) for all pathologies (glenohumeral instability: 5.78 ± 1.69; rotator cuff tears: 6.56 ±0.81; frozen shoulder: 4.99 ± 1.49), with low to average standard deviations.

Intrinsic Motivation

Interest scores were high overall (6.08 ± 1.12) and met the predefined engagement criterion (≥5.0/7). Competence was moderate to high (5.34 ± 1.29). Effort was moderate overall (4.22 ± 2.12) and showed the largest inter-patient dispersion (σ = 1.21). Perceived pressure was low (2.01 ± 1.78), met the predefined criterion (≤3.0/7), and showed wide variability (Table 4).

Table 4. Intrinsic Motivation Inventory subscales by pathology (μ ± σ).

	Glenohumeral Instability	**Rotator Cuff Tears**	**Frozen Shoulder**	**Aggregated**
IMI Interest	6.04 ± 1.43	6.86 ± 0.48	5.33 ± 1.43	6.08 ± 1.12
IMI Competence	5.85 ± 1.39	5.81 ± 1.27	4.36 ± 1.21	5.34 ± 1.29
IMI Effort	3.40 ± 2.21	4.62 ± 2.39	4.63 ± 1.76	4.22 ± 2.12
IMI Pressure	1.52 ± 1.71	1.94 ± 1.83	2.56 ± 1.80	2.01 ± 1.78

Score Variability

The predefined inter-session variability criterion was met, with values remaining below 1.0 across all instruments and pathologies (overall mean: 0.47; Table 5). Inter-patient variability was slightly higher (overall mean: 0.68; Table 6).

Table 5. Inter-session variability (σ) by instrument and pathology.

	Glenohumeral Instability	Rotator Cuff Tears	Frozen Shoulder	Aggregated*
IMI Interest	0.42	0.16	0.48	0.35
IMI Competence	0.56	0.67	0.69	0.64
IMI Effort	0.57	0.93	0.46	0.65
IMI Pressure	0.73	0.73	0.83	0.76
Embodiment	0.50	0.24	0.63	0.46
Cybersickness	0.14	0.10	0.27	0.17
Perceived risk	0.04	0.20	0.44	0.23
Average	**0.42**	**0.43**	**0.54**	**0.47**

*Aggregated values represent the mean of participant-level inter-session standard deviations across all 15 completers.

Table 6. Inter-patient variability (σ) by instrument and pathology.

	Glenohumeral Instability	Rotator Cuff Tears	Frozen Shoulder	Aggregated*
IMI Interest	1.09	0.21	1.09	0.90
IMI Competence	0.93	0.62	0.34	0.67
IMI Effort	1.02	1.44	1.14	1.21
IMI Pressure	0.20	0.85	0.56	0.60
Embodiment	1.18	0.66	0.68	0.87
Cybersickness	0.15	0.09	0.33	0.22
Perceived risk	0.07	0.21	0.38	0.25
Average	**0.66**	**0.58**	**0.65**	**0.68**

*Aggregated values represent the pooled sample standard deviation across the three pathology groups.

4. Discussion

Principal Findings

This feasibility study suggests that *MoRehabXR* was feasible and well tolerated during supervised first-phase shoulder rehabilitation across three distinct shoulder pathologies. All four predefined feasibility criteria were successfully met: protocol completion exceeded predefined thresholds (83.3% vs ≥80%), safety and tolerability criteria were satisfied, engagement scores exceeded target values, and inter-session variability remained within predefined limits. These findings support the short-term feasibility of supervised VR-assisted shoulder rehabilitation and progression to the planned randomised controlled trial, which is currently awaiting regulatory approval.

Safety and Cybersickness

The low cybersickness burden (overall: 1.25 ± 0.64) is consistent with prior VR rehabilitation studies [41–43]. The higher eyestrain observed in the frozen shoulder group (2.10 ± 1.65) was influenced by one patient with insufficiently corrected visual impairment identified retrospectively. Difficulty concentrating was also numerically higher in this group (1.80 ± 0.48), but these subgroup observations should be interpreted cautiously. Notably, nausea and stomach awareness remained close to the minimum score in all groups, which may relate to the static virtual environment and absence of self-motion. Regarding musculoskeletal tolerability, the mild transient shoulder discomfort reported by three patients may have been related to the absence of a structured warm-up phase before gameplay. Future protocol iterations should therefore consider including a brief standardized warm-up before VR exercises.

Patient Acceptance and Motivation

The high interest scores (6.08 ± 1.12) and low perceived pressure (2.01 ± 1.78) were notable. These findings reflect short-term motivational responses during supervised sessions[44]. Perceived competence was moderate to high (5.34 ± 1.29). Effort scores showed wide inter-patient variability (σ = 1.21), which may reflect clinical heterogeneity and differences in functional impairment or postoperative pain.

Embodiment

The embodiment scores (5.78 ± 1.33) were overall positive but presented a large inter-patient variability (σ =0.87). Informal patient feedback suggested that many patients were too absorbed in gameplay to attend to their virtual body representation, while others who noticed the avatar reported positive embodiment. This suggests that the Gonzalez-Franco & Peck instrument, designed for general VR research, may be less suited for task-focused rehabilitation contexts. A future iteration should employ an instrument targeting body ownership and agency during functional movement, or alternatively, measure embodiment conflict (disruption between virtual and physical body states) rather than embodiment presence.

Comparison with Existing VR Shoulder Rehabilitation Studies

Previous studies have evaluated VR-based rehabilitation specifically for shoulder pathologies [45–49]. The present study extends this work by assessing a unified VR platform across three distinct shoulder conditions with pathology-specific movement adaptations. The low cybersickness scores observed in our cohort (1.25 ± 0.64) are consistent with generally favourable tolerability reported in previous VR rehabilitation studies [50] and may relate to the static virtual environment, which avoided self-motion and associated vestibular-visual conflicts. The high interest scores (6.08 ± 1.12) align with previous findings that gamification may enhance engagement in upper limb rehabilitation[37].

Health System Implications

If clinical efficacy is confirmed, VR-assisted rehabilitation could ultimately support more accessible care pathways, including semi-autonomous home-based therapy with remote monitoring[7]. Automated difficulty progression and objective motion tracking could also be evaluated for their potential to reduce clinician burden. The gamified approach may improve long-term adherence, but this requires evaluation in future studies.

Limitations

This study's primary limitation is its small feasibility sample of five completers per pathology, which was not powered to assess clinical efficacy or between-pathology differences and did not include objective functional outcomes. The strict eligibility criteria further limit generalizability. Patient-reported outcome analyses were restricted to completers, introducing potential attrition bias. The four-session duration precluded assessment of long-term engagement, learning effects [51], or delayed adverse events. The absence of a non-VR rehabilitation comparator prevents attribution of observed motivation scores to the VR component specifically versus the attention and novelty of any additional intervention.

Cybersickness was assessed using a shortened questionnaire derived from the SSQ and adapted to a 7-point Likert scale, which limits direct quantitative comparison with studies reporting standard SSQ scores. All questionnaires were

administered in French without formal cross-cultural validation, which may limit their validity and comparability with international literature.

Clinical Implications

This study supports the preliminary feasibility and short-term tolerability of supervised VR-assisted shoulder rehabilitation across post-surgical and non-surgical populations using a gamified protocol. The observed motivation scores were favourable, with high interest and low perceived pressure during supervised sessions. If clinical efficacy is confirmed, future studies could evaluate simplified systems for remote or semi-autonomous rehabilitation with therapist monitoring.

Future Directions

A randomised controlled trial with an adequately powered sample size comparing *MoRehabXR* with standard care, with a focus on clinical endpoints (range of motion, pain scores, return-to-function timelines), is planned and currently awaiting regulatory approval. The planned trial is intended to incorporate longer follow-up, objective adherence metrics, and refined functional mobility assessment tools.

Beyond efficacy testing, the combination of VR exergames with modern motion tracking technologies may enable the passive collection of extensive patient motion data. Leveraging these data offers several future developments: (i) enhancing real-time in-game feedback and movement guidance; (ii) enabling dynamic, automated difficulty adjustment tailored to individual capability trajectories; (iii) documenting the temporal evolution of motor function through logged kinematic records; and (iv) supporting earlier clinical review through automated detection of unexpected changes in movement patterns.

5. Conclusions

MoRehabXR demonstrated preliminary feasibility and short-term tolerability in a small, supervised cohort across three shoulder pathologies. The gamified VR protocol was well tolerated and associated with high interest and low perceived pressure. These findings supported progression to the planned randomised controlled trial, currently awaiting regulatory approval.

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Authors' contributions

MM: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing; AL: Conceptualization, Investigation, Resources, Writing – review & editing,

Project administration, Supervision, Funding acquisition; YSD: Conceptualization, Software, Writing – review & editing; AS: Conceptualization, Investigation, Writing – review & editing; CC: Conceptualization, Methodology, Formal analysis, Resources, Project administration, Supervision, Funding acquisition, Writing – original draft, Writing – review & editing. All authors read and approved the final manuscript.

Competing interests

Alexandre Lädermann serves as a paid consultant for Arthrex, Stryker, and Medacta, and receives royalties from Stryker and Medacta. He is a co-founder of FORE, Med4Cast, LastPatient, and BeeMed, and holds equity in Follow Health. The other authors declare that they have no competing interests.

Consent for publication

Written informed consent for publication of the images and supplementary video material was obtained from the individuals shown.

Trial registration

This study was retrospectively registered on ClinicalTrials.gov (NCT06963983; first posted 9 May 2025).

Availability of data and materials

The participant-level data generated and analysed during the current study are not publicly available and are not available for secondary sharing. The questionnaires used in the study are provided in the Supplementary Materials.

List of abbreviations

AE: adverse event; HMD: head-mounted display; IMI: Intrinsic Motivation Inventory; ISB: International Society of Biomechanics; RCT: randomised controlled trial; SAE: serious adverse event; SSQ: Simulator Sickness Questionnaire; VAS: visual analogue scale; VR: virtual reality.

Supplementary Materials

A video showing the VR setup and exergame is available in the supplementary materials.

The following supplementary material presents the questionnaires administered to participants during the study, provided here as English versions. Items marked with (R) were reverse scored as 8 minus the original response.

Short form of the Intrinsic Motivation Inventory

Question	1	2	3	4	5	6	7
Interest/Enjoyment							
I enjoyed doing this activity very much.	☐	☐	☐	☐	☐	☐	☐
This activity was fun to do.	☐	☐	☐	☐	☐	☐	☐
I thought this was a boring activity. (R)	☐	☐	☐	☐	☐	☐	☐
This activity did not hold my attention at all. (R)	☐	☐	☐	☐	☐	☐	☐
I would describe this activity as very interesting.	☐	☐	☐	☐	☐	☐	☐
I thought this activity was quite enjoyable.	☐	☐	☐	☐	☐	☐	☐
While I was doing this activity, I was thinking about how much I enjoyed it.	☐	☐	☐	☐	☐	☐	☐
Perceived Competence							
I think I am pretty good at this activity.	☐	☐	☐	☐	☐	☐	☐
I think I did pretty well at this activity, compared to other patients.	☐	☐	☐	☐	☐	☐	☐

After working at this activity for a while, I felt pretty competent.	☐	☐	☐	☐	☐	☐	☐
I am satisfied with my performance at this task.	☐	☐	☐	☐	☐	☐	☐
I was pretty skilled at this activity.	☐	☐	☐	☐	☐	☐	☐
This was an activity that I could not do very well. (R)	☐	☐	☐	☐	☐	☐	☐
Effort/Importance							
I put a lot of effort into this.	☐	☐	☐	☐	☐	☐	☐
I did not try very hard to do well at this activity. (R)	☐	☐	☐	☐	☐	☐	☐
I tried very hard on this activity.	☐	☐	☐	☐	☐	☐	☐
It was important to me to do well at this task.	☐	☐	☐	☐	☐	☐	☐
I did not put much energy into this. (R)	☐	☐	☐	☐	☐	☐	☐
Pressure/Tension							
I did not feel nervous at all while doing this. (R)	☐	☐	☐	☐	☐	☐	☐
I felt very tense while doing this activity.	☐	☐	☐	☐	☐	☐	☐
I was very relaxed in doing these. (R)	☐	☐	☐	☐	☐	☐	☐
I was anxious while working on this task.	☐	☐	☐	☐	☐	☐	☐
I felt pressured while doing these.	☐	☐	☐	☐	☐	☐	☐

Scale anchor: 1 = Not at all true; 7 = Very true.

Perceived risk questionnaire

Question	1	2	3	4	5	6	7
I felt physically safe during this session. (R)	☐	☐	☐	☐	☐	☐	☐
I was concerned about getting injured during this session.	☐	☐	☐	☐	☐	☐	☐
Someone might get injured by performing this activity.	☐	☐	☐	☐	☐	☐	☐

Scale anchor: 1 = Not at all true; 7 = Very true.

Cybersickness questionnaire

Question	1	2	3	4	5	6	7
Headache	☐	☐	☐	☐	☐	☐	☐
Difficulty concentrating	☐	☐	☐	☐	☐	☐	☐

General discomfort	☐	☐	☐	☐	☐	☐	☐
Eyestrain	☐	☐	☐	☐	☐	☐	☐
Nausea	☐	☐	☐	☐	☐	☐	☐
Stomach awareness	☐	☐	☐	☐	☐	☐	☐

Scale anchor: 1 = Not at all true; 7 = Very true.

Avatar Embodiment

Question	1	2	3	4	5	6	7
I felt as if the virtual arm I saw when looking at myself in the mirror was another person's arm. (R)	☐	☐	☐	☐	☐	☐	☐
It felt like I could control the virtual arm as if it was my own arm.	☐	☐	☐	☐	☐	☐	☐
The movements of the virtual arm were caused by my movements.	☐	☐	☐	☐	☐	☐	☐
I felt as if the virtual arm was moving by itself. (R)	☐	☐	☐	☐	☐	☐	☐
I felt as if my left arm was located where I saw the virtual left arm.	☐	☐	☐	☐	☐	☐	☐

Scale anchor: 1 = Not at all true; 7 = Very true.

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