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Systematic Review

Remote Rehabilitation and Virtual Reality Interventions Using Motion Sensors for Chronic Low Back Pain: A Systematic Review of Biomechanical, Pain, Quality of Life, and Adherence Outcomes

Marina Garofano [1,*], Rosaria Del Sorbo [1,*], Mariaconsiglia Calabrese [1], Massimo Giordano [1], Maria Pia Di Palo [1], Marianna Bartolomeo [1], Chiara Maria Ragusa [1], Gaetano Ungaro [2], Gianluca Fimiani [3], Federica Di Spirito [1], Massimo Amato [1], Michele Ciccarelli [1], Claudio Pascarelli [4], Giuseppe Scanniello [3], Placido Bramanti [5] and Alessia Bramanti [1]

[1] Department of Medicine, Surgery and Dentistry, University of Salerno, Via S. Allende, 84081 Baronissi, Italy; macalabrese@unisa.it (M.C.); mgiordano@unisa.it (M.G.); mariapia140497@gmail.com (M.P.D.P.); mbartolomeo@unisa.it (M.B.); chiaramragusa@hotmail.com (C.M.R.); fdispirito@unisa.it (F.D.S.); mamato@unisa.it (M.A.); mciccarelli@unisa.it (M.C.); abramanti@unisa.it (A.B.)

[2] University Hospital "San Giovanni di Dio e Ruggi d'Aragona", Via San Leonardo, 84125 Salerno, Italy; gaungaro@unisa.it

[3] Department of Computer Science, University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, Italy; gfimiani@unisa.it (G.F.); gscanniello@unisa.it (G.S.)

[4] Department of Engineering for Innovation, University of Salento, 73100 Lecce, Italy; claudio.pascarelli@unisalento.it

[5] Faculty of Psychology, University eCampus, 22060 Novedrate, Italy; bramanti.dino@gmail.com

* Correspondence: mgarofano@unisa.it (M.G.); rdelsorbo@unisa.it (R.D.S.)

Abstract: Background: Chronic low back pain (CLBP) is a leading cause of disability, impacting quality of life (QoL), function, and work productivity. Traditional rehabilitation faces challenges in accessibility and adherence. Remote rehabilitation and virtual reality (VR) interventions using motion sensors offer real-time movement tracking, biofeedback, and personalized exercises. This systematic review evaluates their effectiveness in pain reduction, functional improvement, adherence, and QoL. Methods: A systematic search was performed across PubMed, Scopus, Web of Science, and PEDro (2015–2025), including randomized controlled trials, observational, and feasibility studies on adults with CLBP undergoing sensor-based digital rehabilitation. The primary outcomes included pain, functional mobility, and movement biomechanics; secondary outcomes included adherence, QoL, and cost-effectiveness. Eight studies involving 7166 participants were included. Overall, sensor-based remote rehabilitation and VR interventions demonstrated positive effects on pain, function, and adherence. Pain reductions ranged from modest short-term decreases to over 60% in long-term programs (e.g., −68.5% in VAS). Functional improvements included lumbar ROM gains up to +9.9° and better movement control. Adherence was consistently high, with some programs reporting completion rates between 73% and 90%, particularly those incorporating gamification or real-time feedback. Selected studies also showed QoL improvements (e.g., +9.10 points on SF-36) and reductions in work impairment by over 60%. A few trials reported significant decreases in inflammatory markers (e.g., CRP −1.16 mg/L, TNF-α −8.9 pg/mL). Conclusions: Motion sensor-based remote rehabilitation and VR interventions show promising results in pain management, mobility, and adherence for individuals with CLBP. Gamification and biofeedback features enhance engagement, addressing a key challenge of conventional rehabilitation. However, more long-term RCTs and economic evaluations are needed to confirm their effectiveness and cost-efficiency.

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1. Introduction

Low-back pain (LBP) refers to pain or discomfort situated between the lower rib margin and the upper boundary of the gluteal region, with or without radiating symptoms in the legs [1]. When LBP persists for at least 12 weeks, lacks a clear underlying pathology, and varies in intensity, it is classified as chronic and nonspecific [2,3]. Chronic low back pain (CLBP) is one of the most common musculoskeletal disorders worldwide, and it is estimated that a significant percentage of the adult population will experience CLBP at least once in their lifetime [3–5]. Traditionally, the treatment of CLBP has included drug therapies, therapeutic exercise, physiotherapy, and psychological interventions for pain management [6–8]. In recent years, innovative technologies have been incorporated into the rehabilitation of CLBP with the aim of improving the effectiveness of interventions, increasing patient adherence and providing more personalized and accessible treatment options [9–11]. Among these, telerehabilitation, virtual reality (VR), machine learning (ML), and wearable sensors are transforming clinical practice. Several studies, including those by Lara-Palomo et al. [12] and Raiszadeh et al. [13], have shown that telerehabilitation is comparable to traditional physiotherapy in terms of pain reduction and improvement in functional disability [12,14]. VR is used to create immersive environments that facilitate the performance of therapeutic exercises with high levels of engagement, reduce fear of movement (kinesiophobia), and improve proprioception compared to conventional methods [15–17]. Initially developed for engineering applications, VR has been widely adopted in healthcare—particularly in musculoskeletal rehabilitation, and also for CLBP—where it shows promise in improving patient motivation and optimizing functional outcomes [18]. ML algorithms offer new ways to personalize treatment by analyzing data collected from patients to predict rehabilitation progress and optimize treatment strategies [19–21]; additionally, they play a crucial role in movement assessment by identifying pathological movement patterns [22,23]. Finally, wearable sensors such as accelerometers, gyroscopes, and magnetometers, which capture detailed information about the body's dynamics in real time, allow continuous and objective monitoring of movement, providing accurate data on motor performance and enabling real-time feedback [24–27]. Despite the growing use of these technologies, current evidence remains fragmented, with many studies addressing them separately and using inconsistent outcome measures. A comprehensive synthesis of their combined application, particularly wearable sensors within telerehabilitation programs, is still lacking. This systematic review aims to synthesize the available evidence on the effectiveness of wearable motion sensors and telerehabilitation technologies in managing movement-related outcomes for individuals with low back pain. Specifically, it will assess their impact on key clinical parameters such as pain reduction, improved function and mobility, enhanced quality of life (QoL), and optimized patient management. Additionally, this review will identify the main methodological limitations of existing studies and explore future perspectives for the large-scale implementation of these technologies in clinical practice.

2. Materials and Methods

2.1. Study Protocol

The current study protocol was designed in accordance with the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews) [28], ensuring a rigorous methodologi-

cal approach prior to the literature search and data analysis with a specific focus on the research questions and the clinical effectiveness of innovative technologies, including telerehabilitation, VR, ML, and wearable sensors, in the rehabilitation of CLBP. The analysis focuses on the effects of these technologies in terms of pain reduction, functional improvement, enhanced QoL, and treatment adherence, evaluating their impact on rehabilitation pathways and therapeutic strategies. Before starting the literature search and data analysis, the related study protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) database of systematic reviews (identification number: CRD42024608097). The formulation of the research question and the strategy and criteria for study selection were developed using the PICO model [29]. The study question focused on the following:

Population (P): Adults (≥18 years) with low back pain.

Intervention (I): Remote rehabilitation utilizing motion tracking and sensor-based movement monitoring technologies.

Comparison (C): Conventional in-person rehabilitation or no rehabilitation.

Outcomes (O):

Main outcome(s): Evaluation of clinically relevant movement and biomechanical parameters, including lumbar and trunk range of motion (ROM), postural control, movement kinematics, and motor coordination.

Additional outcome(s): Pain, cost-effectiveness, adherence, accessibility, any healthcare outcome measures, and QoL.

2.2. Search Strategy and Study Selection

The literature search was conducted electronically across four databases: PubMed, Scopus, WOS, and PEDro. The database screening was carried out independently by three reviewers (A.B., R.D.S., Marina Garofano) from January 2015 to 1 February 2025, using the following keywords combined with Boolean operators: low back pain, movement analysis, motion tracking, movement monitoring, motion capture, telerehabilitation, remote rehabilitation, and virtual rehabilitation. Complete search strategies are provided in Appendix A. The collected citations were recorded, duplicates were eliminated using EndNote, and the titles and abstracts obtained were independently screened by two reviewers (A.B., R.D.S). The full texts of potentially relevant papers and ambiguous abstracts were reviewed independently by the same authors (A.B., R.D.S.), who resolved disagreements through discussion and consensus and, if necessary, with the involvement of a third reviewer (Marina Garofano).

The inclusion criteria were as follows:

- Source: studies published in the English language from 2015 to 1 February 2025;
- Study design: randomized controlled trial (RCT), observational studies, feasibility studies;
- Study population: Adults (>18) with low back pain (no gender restrictions);
- Study intervention: Remote rehabilitation with the use of movement sensors;
- Study outcomes: Evaluation of movement and biomechanical parameters, including "movement", "motor activity", "movement analysis", "motion tracking", "movement monitoring", "biomechanics", and "kinematics"; and "motion capture", pain, cost-effectiveness, adherence, accessibility, any healthcare outcome measures, and QoL.

The exclusion criteria were as follows:

- Source: studies published before 2015 or after 1 February 2025;
- Study intervention: Studies not involving remote rehabilitation, studies not utilizing movement sensors for assessment or intervention, or interventions focusing solely on pharmacological or surgical treatments.

- Study outcomes: studies not reporting movement-related or biomechanical outcomes; studies without measurable clinical outcomes related to pain, cost-effectiveness, adherence, accessibility, healthcare impact, or QoL.

2.3. Data Extraction and Collection

Two authors (Marina Garofano and R.D.S.) independently screened the titles and abstracts retrieved from the database searches to determine their eligibility based on the inclusion criteria. Studies were included or excluded upon mutual agreement. In cases of disagreement regarding a manuscript's inclusion based on abstract evaluation, discrepancies were resolved through discussion and consensus. If consensus was not reached, a third reviewer (A.B.) was consulted for the final decision. The data extraction process followed established methodologies and was structured to align with the research questions of this review. Extracted data included: (a) author, year, and country; (b) study design; (c) participants; (d) mean age; (e) intervention; (f) control group; (g) technological solution; (h) primary outcomes; (i) secondary outcomes; (j) key results. This systematic approach ensured a rigorous and consistent collection of relevant data, facilitating a comprehensive synthesis of evidence to address the research questions.

2.4. Quality Assessment

Three independent reviewers assessed the methodological quality of the studies in this review, using validated tools for risk of bias analysis. The Risk of Bias 2 (ROB-2) [30] tool was used for RCTs Table 1, while Risk of Bias in Non-randomized Studies (ROBINS-I) [31] was used for non-randomized studies Table 2. The methodological aspects addressed in this evaluation are selection of participants, presence of confounding factors, accuracy in classification of the intervention, fidelity to the intended procedure, handling of missing data, selection of reported outcomes, and reliability in measuring them. The risk of bias was classified into four categories:

Table 1. Cochrane risk of bias tool for the risk of bias in individual studies.

Study	Bias Arising from the Randomization Process	Bias Due to Deviations from Intended Interventions	Bias Due to Missing Outcome Data	Bias in Measurement of the Outcome	Bias in Selection of the Reported Result	Overall
Matheve et al., 2018 [32]	Low	Low	Low	Some concerns	Low	Low
Matheve et al., 2020 [33]	Low	Low	Low	Some concerns	Low	Low
Mueller et al., 2022 [34]	High	High	Some concerns	High	Some concerns	High
Nambi et al., 2023 [35]	Low	Low	High	High	High	High
Shi et al., 2024 [36]	Low	Low	High	High	Some concerns	High

Table 2. ROBINS-I Tool for non-RCTs; abbreviations: PY (Probably Yes), P (Possibly), PN (Probably No), N (No).

Study	Bias Due to Confounding	Bias in Selection of Participants	Bias in Classification of Interventions	Bias Due to Deviations from Intended Interventions	Bias Due to Missing Data	Bias in Measurement of Outcomes	Bias in Selection of Reported Results	Overall Risk of Bias
Bailey et al., 2020 [37]	PY	P	PN	P	P	PY	PY	SERIOUS
Park et al., 2022 [38]	P	P	PN	P	PY	PY	PN	MODERATE
Shebib et al., 2019 [39]	PN	PN	PN	P	PY	P	P	LOW TO MODERATE

LOW, if all assessed domains were found to have a minimal risk of bias;

MODERATE, if at least one domain with intermediate risk was present, without evidence of high criticality;

SERIOUS, if at least one domain showed a high risk of bias, but no aspect critically compromised the reliability of the study;

HIGH, if the risk of bias was such that it called into question the overall validity of the study.

These analyses determined the level of reliability of the included studies and considered the impact of the risk of bias in interpreting the results of this systematic review.

3. Results

3.1. Study Selection and Characteristics

The study selection process followed the PRISMA 2020 guidelines [28]. A total of 4301 records were identified through database searches of PubMed (195 records), Scopus (328 records), Web of Science (3825 records), and PEDro (8 records). After removing 263 duplicate records with EndNote, 4038 records remained for screening. Following the screening, 4016 records were excluded based on the title and abstract, leaving 22 reports for retrieval. All reports were successfully retrieved and assessed for eligibility. Of these, 14 were excluded for various reasons, 3 articles were excluded because they did not address telerehabilitation, 5 did not involve the use of motion sensors, and 3 focused on VR without combining it with telerehabilitation and sensor use. Ultimately, eight studies met the inclusion criteria and were included in the systematic review. These studies were critically appraised to ensure they aligned with the research objectives and provided relevant data for analysis. This selection process is summarized in the PRISMA flow diagram (Figure 1), and in Table 3, there are the descriptive characteristics of the eight included studies, with a focus on: (a) author, year, and country; (b) study design; (c) participants; (d) mean age; (e) intervention; (f) control group; (g) technological solution; (h) primary outcomes; (i) secondary outcomes; and (j) key results.

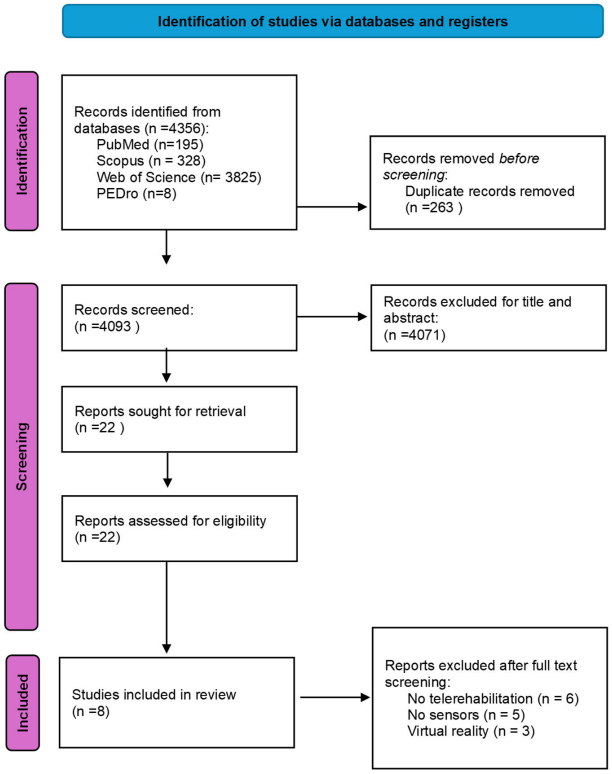


Figure 1. Flow diagram of study selection.

Table 3. Descriptive characteristics of the included studies.

Authors, Year, Country	Study Design	Participants (N, M/F)	Mean Age (SD)	Intervention	Control Group	Technological Solution	Primary Outcomes	Secondary Outcomes	Key Results
Bailey et al., 2020, USA [37]	Longitudinal Observational Study	6468 (M:1487, F:4981, CLBP)	42.58 (10.91)	12-week digital care program with sensor-guided exercise, CBT, and coaching	N/A	Bluetooth motion sensors & mobile app	Pain intensity (VAS)	Depression (PHQ-9), Anxiety (GAD-7), Work productivity (WPAI)	VAS pain −68.45%, Depression −57.5%, Anxiety −58.1%, Work productivity +61.5%
Matheve et al., 2018, Belgium [32]	RCT	108 (54 CLBP–M:24, F:30; 54 Healthy–M:36, F:18)	CLBP: 40 (17), Healthy: 37 (14)	Sensor-based postural feedback to improve movement control	Mirror feedback & No-feedback	Wireless inertial sensors & avatar interface	Lumbopelvic movement control (Kinematic analysis)	NPRS, RMDQ, TSK	Significant movement control improvement in sensor group ($p < 0.0001$)
Matheve et al., 2020, Belgium [33]	RCT	84 (42 IG–M:15, F:27; 42 CG–M:15, F:27)	IG: 44.1 (12.2), CG: 42.8 (13.4)	VR-based exercise therapy using motion sensors	Conventional exercise therapy	Valedo®Pro motion sensor & VR games	Movement control, Motor learning, Pain reduction (NPRS)	Functional performance, TSK, RMDQ	VR + motion sensor improved movement control & pain reduction ($p < 0.01$)
Mueller et al., 2022, Germany [34]	Randomized cross-over pilot trial	13 CLBP (M:5, F:8)	41 (16)	Game-based real-time biofeedback training via trunk exergame	Cross-over design with rest periods	Sensor-based trunk exergame	Maximum angle in lateral flexion	Angle reproduction & secondary movement planes	No primary movement change but improved control in secondary planes ($p = 0.02$)
Nambi et al., 2023, Saudi Arabia [35]	RCT	60 (30 IG, 30 CG, CNLBP, all male)	IG: 21.6 (2.1), CG: 22.1 (1.9)	VR-based trunk exercises with a moving game chair	Isokinetic & core stabilization exercises	Pro-Kin system with VR feedback	Pain intensity (VAS), Muscle CSA (MRI/ultrasound)	Inflammatory biomarkers (CRP, TNF-α, IL-2, IL-4, IL-6)	Significant pain reduction & muscle CSA increase, VRE improved biomarkers
Park et al., 2022, Korea [38]	Retrospective Case-Control Study	176 (104 IG–M:41, F:63; 72 CG–M:51, F:21)	IG: 36.7 (8.03), CG: 38.3 (7.04)	Mobile exercise coaching app using AI motion tracking	Video-streaming exercise group	Smartphone AI motion tracking	QoL (SF-36), Pain intensity (VAS)	Exercise adherence, Treatment satisfaction	Higher QoL (SF-36: +9.10 vs. +1.09), Greater pain reduction (−0.96 vs. −0.26 VAS)
Shebib et al., 2019, USA [39]	RCT	177 (113 IG–M:71, F:42; 64 CG–M:33, F:31)	43 (11)	12-week digital care program with sensor feedback & CBT	Digital education articles only	Wearable sensors & virtual coaching	Disability (ODI, Korff Pain & Disability Scale)	Pain (VAS), Adherence, Surgery interest	Pain −52–64%, Disability −31–55%, High adherence (90%)
Shi et al., 2024, China [36]	RCT	54 (27 IG–M:12, F:14; 27 CG–M:9, F:18)	IG: 43.5 (10.2), CG: 42.9 (9.8)	Telerehabilitation with motion sensors for remote tracking	Outpatient-based exercise therapy	HIRS motion tracking system	Disability (ODI)	Pain (NPRS), FABQ, QoL (SF-36)	Significant pain & function improvement, no difference vs. conventional rehab

Abbreviations: CBT: Cognitive Behavioral Therapy, CG: Control Group, CLBP: Chronic Low Back Pain, CNLBP: Chronic Non-specific Low Back Pain, CRP: C-Reactive Protein, FABQ: Fear-Avoidance Beliefs Questionnaire, F: Female, GAD-7: Generalized Anxiety Disorder-7, HIRS: Healbone Intelligent Rehabilitation System, IG: Intervention Group, IL-2, IL-4, IL-6: Interleukins (inflammatory biomarkers), M: Male, MRI: Magnetic Resonance Imaging, NLBP: Non-specific Low Back Pain, NPRS: Numeric Pain Rating Scale, ODI: Oswestry Disability Index, PHQ-9: Patient Health Questionnaire-9 (Depression), QoL: Quality of Life, RCT: Randomized Controlled Trial, RMDQ: Roland-Morris Disability Questionnaire, SF-36: 36-Item Short Form Health Survey, TNF-α: Tumor Necrosis Factor-alpha, TSK: Tampa Scale of Kinesiophobia, VAS: Visual Analog Scale, VRE: Virtual Reality Exercise, WPAI: Work Productivity and Activity Impairment Questionnaire.

3.2. Participant Demographics

The studies included in this systematic review analyzed a diverse population of adults with CLBP, with a total of 7166 participants across all studies. Sample sizes varied, ranging from small pilot trials (n = 13) [34] to large-scale observational studies (n = 6468) [37]. The mean age of participants differed across studies, with younger cohorts in sports-related interventions (e.g., soccer players, mean age ~22 years) [17] and older populations in telerehabilitation-based programs (mean age ~43–45 years) [36,39]. Gender distribution was often unbalanced, with some studies predominantly including female participants [37], while others had a more equal representation of males and females [33,36]. Clinical characteristics varied, with most participants experiencing nonspecific or CLBP [32–34,36,37,39],

Meanwhile, some studies specifically targeted subpopulations such as office workers or athletes [17,38]. The demographic variability across studies underscores the generalizability of findings to a broad population of individuals with CLBP undergoing digital rehabilitation interventions.

3.3. Outcome Measures

The studies included in this systematic review assessed a range of outcome measures to evaluate the effectiveness of digital rehabilitation interventions for CLBP. Primary outcomes commonly focused on movement-related parameters, including biomechanical assessments (e.g., range of motion, motor control, and movement kinematics) [17,32–34] and pain intensity, typically measured using the Visual Analog Scale (VAS) or Numeric Pain Rating Scale (NPRS) [17,32–34,36–39]. These biomechanical and movement-based outcomes hold substantial clinical relevance, as they are directly linked to functional impairment, postural instability, and movement inefficiencies commonly observed in individuals with chronic low back pain. Improvements in parameters such as lumbar range of motion, trunk stabilization, and motor coordination are essential for restoring mobility, reducing compensatory patterns, and preventing long-term disability. Several studies also evaluated functional disability through standardized tools such as the Oswestry Disability Index (ODI) and the Roland–Morris Disability Questionnaire (RMDQ) [32,33,36,39]. Secondary outcomes included measures of treatment adherence, QoL (e.g., SF-36, EQ-5D), psychological factors (e.g., depression, anxiety, and fear-avoidance beliefs) [33,36,37], and cost-effectiveness [38,39]. Some studies incorporated wearable motion sensors and ML algorithms to provide real-time movement tracking and biofeedback, allowing for more precise assessment of motor learning and rehabilitation progress. The diversity of outcome measures highlights the multidimensional impact of digital rehabilitation strategies, assessing not only pain relief but also functional improvements, engagement, and broader health-related benefits.

3.4. Biomechanical Assessment

Biomechanical assessment was a fundamental outcome in several studies included in this systematic review, utilizing wearable motion sensors, VR-based systems, and telerehabilitation platforms to objectively measure spinal movement, posture, and motor control. Matheve et al. [32] investigated the impact of sensor-based postural feedback on lumbopelvic movement control, demonstrating a significant improvement in lumbar ROM. Compared to mirror feedback, the sensor-based intervention resulted in an estimated ROM difference of 9.9° (95% CI, 6.1–13.7°; $p < 0.0001$), and compared to no feedback, the difference was 10.6° (95% CI, 6.8–14.3°). The corresponding effect sizes were large (Cohen's d ≈ 1.3 for sensor vs. mirror and ≈ 1.4 for sensor vs. control), highlighting the superior efficacy of real-time feedback via wireless inertial sensors. Similarly, Matheve et al. [33] analyzed a VR-based rehabilitation program using motion sensors (Valedo®Pro) during

pelvic tilt exercises. Participants in the VR group performed a high number of controlled pelvic tilts (mean = 98.1, SD = 15.6), comparable to that of the control group (mean = 100), indicating consistent motor execution. Participants in the VR group exhibited greater engagement and motivation, reinforcing the potential of gamified rehabilitation to enhance compliance. Mueller et al. [34] explored game-based real-time biofeedback training in a randomized cross-over pilot trial. While no significant changes were observed in trunk lateral flexion range or reproduction accuracy ($p > 0.05$), a small yet significant reduction in trunk extension/flexion range (thoracic segment: mean decrease = 0.9°, $p = 0.02$, d = 0.20) was noted, suggesting reduced compensatory movement and improved control in secondary planes. These findings support the hypothesis that even a single session of sensor-based exergaming may elicit acute improvements in movement efficiency. Nambi et al. [17] examined the effects of a VR-based trunk exercise system using a moving game chair on spinal muscle morphology. After four weeks, significant increases in trunk muscle Cross-Sectional Area (CSA) were reported in the VRE group, with the right psoas major increasing from 8.6 ± 0.4 cm^2 to 9.5 ± 0.3 cm^2 and the multifidus from 5.6 ± 0.6 cm^2 to 7.1 ± 0.5 cm^2 ($p < 0.001$). These changes, although less pronounced than those observed in the isokinetic training group, were accompanied by small-to-moderate effect sizes (e.g., multifidus CSA d = 1.5 right, 1.11 left), suggesting improved muscle engagement and motor recruitment through VR-mediated repetitive movement. Overall, these findings underscore the effectiveness of advanced motion-tracking technologies in delivering precise and objective biomechanical assessments, which are fundamental for optimizing rehabilitation strategies in CLBP management (Table 4).

Table 4. Biomechanical Parameters.

Study	Technology Used	Biomechanical Parameters Assessed	Key Findings	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Matheve et al., 2018 [32]	Wireless inertial motion sensors	Lumbar and hip ROM, postural control	Significant improvement in lumbar ROM (+9.9°) with sensor-based feedback vs. mirror ($p < 0.0001$)	Cohen's d ≈ 1.3–1.4; CI: 6.1°–13.7°, 6.8°–14.3°	Large effect
Matheve et al., 2020 [33]	VR-based motion tracking (Valedo®Pro)	Movement control, motor learning	High number of controlled pelvic tilts (mean = 98.1, SD = 15.6); improved engagement and attentional focus, supporting motor learning potential	CI not reported; no direct effect size	Suggests motor learning
Mueller et al., 2022 [34]	Trunk exergame with real-time feedback	Trunk movement control, flexion/extension angles	Reduction in thoracic flexion/extension range ($\Delta = -0.9°$, $p = 0.02$), suggesting improved motion control	Cohen's d = 0.20; CI not reported	Small (acute) improvement

Table 4. *Cont.*

Study	Technology Used	Biomechanical Parameters Assessed	Key Findings	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Nambi et al., 2023 [35]	VR-based trunk ex. (Pro-Kin system)	Muscle CSA, spinal mobility	Increase Right psoas major CSA ($8.6 \pm 0.4 \rightarrow 9.5 \pm 0.3$ cm²); increase in multifidus CSA ($5.6 \pm 0.6 \rightarrow 7.1 \pm 0.5$ cm²); both $p < 0.001$	Multifidus d = 1.5 (R), 1.11 (L); CI not reported	Moderate–Large improvement

Abbreviations: CI: Confidence Interval, CSA: Cross-Sectional Area, d: Cohen's d (effect size), L: left, R: right, ROM: Range of Motion, SD: Standard Deviation, VR: Virtual Reality, VRE: Virtual Reality Exercise.

3.5. Pain

Pain reduction was a primary outcome across all included studies, with most using the VAS or the NPRS for assessment. Sensor-based rehabilitation programs showed significant pain improvements, particularly in long-term interventions. Bailey et al. [37] reported a 68.45% VAS pain reduction after a 12-week digital care program integrating sensor-guided exercises and remote coaching. This corresponded to a standardized mean difference of 1.37 (95% CI: 1.33–1.40), indicating a large and clinically meaningful effect. Similarly, Shebib et al. [39] found among participants who completed the program that VAS pain scores decreased by 62% (from 43.6 to 16.5) and VAS impact on daily life decreased by 64% (from 37.3 to 13.4), with effect sizes ranging from −23.7 points (95% CI: −31.9 to −15.5; $p < 0.001$). A total of 81% reached a minimally important change in VAS, confirming robust clinical benefit. Matheve et al. [32] evaluated the effects of sensor-based postural feedback on movement control in CLBP patients but did not observe significant changes in pain intensity. NPRS scores remained stable across conditions (baseline: 4.5–4.9; post-intervention mean differences: −0.4 to −0.1), indicating that while movement control improved (ROM differences: 9.9–10.6°, $p < 0.0001$), pain was not directly reduced in the short term. In a follow-up study, they [33] reported significant hypoalgesic effects from a single session of VR-based pelvic tilt exercises: pain intensity decreased during (Cohen's d = 1.29, 95% CI: 0.82–1.76) and immediately after (Cohen's d = 0.85, 95% CI: 0.40–1.29) the session. Additionally, time spent thinking of pain was significantly reduced (d = 1.31, 95% CI: 0.84–1.78), confirming the analgesic potential of interactive and gamified VR interventions.

Mueller et al. [34] investigated game-based real-time feedback training using trunk exergames in a cross-over pilot study. Although the intervention improved trunk motion efficiency and reduced compensatory movements ($p = 0.02$; d = 0.20), no significant pain reduction was observed: VAS decreased from 3.3 ± 2.5 to 2.6 ± 2.5, but this change was not statistically significant ($p > 0.05$). VR-assisted interventions also demonstrated pain relief benefits. Nambi et al. [17] reported significant pain reduction after four weeks of VR-based trunk training: VAS dropped from 7.2 ± 0.4 to 1.8 ± 0.3 ($p = 0.001$). Compared to isokinetic training, the VRE group had a mean difference of 0.7 (95% CI: 0.38–1.07); and compared to conventional training, they had a mean difference of 3.0 (95% CI: 2.68–3.31). The effect size was very large (Cohen's d = 5.37), indicating a robust clinical effect. In a study comparing a motion-detecting exercise coaching app with standard video-based exercise, Park et al. [38] compared a machine-learning-based motion-detecting mobile exercise coaching app with standard video-based coaching. After a 14-day program, the intervention group showed a

significantly greater reduction in VAS scores for lower back pain (-0.96 ± 1.82) compared to the control group (-0.26 ± 0.71), with $p < 0.01$ between groups. The improvement was correlated with higher adherence and real-time visual/audio feedback, although the absolute pain reduction was modest. Finally, Shi et al. [36] evaluated the effectiveness of an 8-week telerehabilitation program using a smartphone app and integrated sensors. Although both groups (telerehabilitation and outpatient) showed significant within-group improvements in NPRS (−4.65 points), there were no statistically significant between-group differences (mean difference: −0.39, 95% CI: −2.10 to 1.31; $p = 0.64$), confirming that telerehabilitation was non-inferior to standard care in pain reduction. Overall, these findings suggest that wearable sensors and movement-tracking strategies, combined with VR and telerehabilitation technologies, are effective in reducing pain in individuals with CLBP. However, short-term interventions, such as exergames, may require additional sessions to achieve significant and sustained pain relief (Table 5).

Table 5. Pain.

Study	Pain Outcome Measures	Key Results	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Bailey et al., 2020 [37]	VAS	68.45% reduction in pain after 12 weeks of intervention	Cohen's d = 1.37 (95% CI: 1.33–1.40)	Large effect
Matheve et al., 2018 [32]	NPRS	No significant change in pain post-intervention	Not reported	No effect
Matheve et al., 2020 [33]	NPRS	Significant pain reduction during (−1.66) and immediately after VR session ($p < 0.01$)	Cohen's d = 1.29 (95% CI: 0.82–1.76); d = 0.85 (95% CI: 0.40–1.29)	Large short-term effect
Mueller et al., 2022 [34]	VAS	No significant reduction in pain (3.3 ± 2.5 pre, 2.6 ± 2.5 post; $p > 0.05$)	Cohen's d = 0.20	Small effect
Nambi et al., 2023 [35]	VAS	Significant reduction in pain after 4-week intervention ($p < 0.05$)	Cohen's d = 5.37; mean difference vs. conventional = 3.0 (95% CI: 2.68–3.31)	Very large effect
Park et al., 2022 [38]	VAS	Greater pain reduction in MDMECA group (−0.96 vs. −0.26; $p < 0.01$)	Not reported; between-group difference = 0.70 ($p < 0.01$)	Modest group difference
Shebib et al., 2019 [39]	VAS	52–64% reduction in pain post-intervention ($p < 0.001$)	Cohen's d not reported; $\Delta = -23.7$ points (95% CI: −31.9 to −15.5)	Large effect
Shi et al., 2024 [36]	NPRS	Significant within-group improvement; no significant between-group difference ($p = 0.64$)	Between-group $\Delta = -0.39$ (95% CI: −2.10 to 1.31); Cohen's d not reported	Non-inferior to outpatient care

Abbreviations: NPRS: Numeric Pain Rating Scale, VAS: Visual Analog Scale.

3.6. Quality of Life

Two studies in this review evaluated the impact of digital rehabilitation interventions on QoL using SF-36, a standardized measure. Park et al. [38] found a significant improve-

ment in SF-36 scores in participants using a motion-detecting mobile exercise coaching app (+9.10, $p < 0.01$), while the control group showed minimal changes (+1.09, $p = 0.37$). Conversely, Shi et al. [36] observed no statistically significant between-group differences in SF-36 score improvements after 8 weeks of telerehabilitation compared to conventional outpatient rehabilitation. While both groups showed within-group QoL improvements, the mean difference between groups at 8 weeks was −0.38 (95% CI: −8.69 to 7.92; $p = 0.93$), indicating non-inferiority but no superiority of telerehabilitation (Table 6).

Table 6. QoL.

Study	QoL Outcome Measures	Results	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Park et al., 2022 [38]	SF-36	Motion-detecting mobile app: +9.10, $p < 0.01$ (significant improvement); Control group: +1.09, $p = 0.37$ (minimal change)	Cohen's d ≈ 0.83; CI not reported	Large effect
Shi et al., 2024 [36]	SF-36	No significant difference, both interventions led to improvement	Effect size not reported; between-group difference Δ = −0.38 (95% CI: −8.69 to 7.92; $p = 0.93$)	No significant difference

Abbreviations: SF-36: 36-Item Short Form Health Survey.

3.7. Adherence

Adherence to remote rehabilitation programs utilizing motion sensors varied across the included studies, with completion rates ranging from 53.1% to 100%. High adherence was observed in interventions that incorporated real-time feedback, structured coaching, and gamification elements. Shebib et al. [39] reported 90% engagement among participants who completed a 12-week digital care program, with an average of 3.8 sensor-guided workouts per week. Similarly, Bailey et al. [37] found a 73.04% completion rate, with higher engagement (exercise sessions, coaching interactions) correlating with better outcomes in pain reduction and QoL. Conversely, interventions with less interactivity or structured support showed lower adherence rates. Park et al. [38] reported that 53.1% of participants completed a 14-day mobile coaching program, significantly higher than the 31.0% completion rate in the control group using standard video-based exercise. Shi et al. [36] further highlighted adherence differences between telerehabilitation-based and conventional exercise programs. The telerehabilitation group (TBEG) demonstrated higher adherence (89%) compared to the conventional outpatient group (81%), suggesting that remote monitoring and motion-tracking technology can enhance compliance with rehabilitation protocols. Finally, Mueller et al. [34] reported 100% adherence in a single-session trunk exergame trial, though this high rate may reflect the short intervention duration rather than long-term engagement trends. Overall, adherence appears to be positively influenced by real-time feedback, structured support, and gamification, whereas less interactive interventions may struggle with participant retention. These findings highlight the need for motivational strategies and personalized rehabilitation approaches to optimize adherence in remote rehabilitation for low back pain (Table 7).

Table 7. Adherence.

Study	Completion/Adherence Rate	Key Findings	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Shebib et al., 2019 [39]	90% engagement (3.8 workouts/week)	High adherence with structured support and coaching	Not determined	Not determined
Bailey et al., 2020 [37]	73.04% completion rate	Higher engagement correlated with better pain and QoL outcomes	Not reported	Not reported
Park et al., 2022 [38]	53.1% (mobile app) vs. 31.0% (video-based group)	Real-time motion tracking improved adherence	Not reported	Not reported
Shi et al., 2024 [36]	89% (telerehabilitation) vs. 81% (outpatient)	Remote monitoring enhanced adherence	Not reported	Not reported
Mueller et al., 2022 [34]	100% adherence	Likely due to short intervention duration	Not reported	Not reported

Abbreviations: QoL: Quality of life.

3.8. Any Healthcare Measures

The healthcare outcome measures reported across the included studies varied but primarily focused on pain, which we have already analyzed, and also on psychological well-being, inflammatory biomarkers, and functional disability. Regarding mental health, some improvements were also observed; Bailey et al. [37] reported a 57.5% reduction in depression symptoms and a 58.1% decrease in anxiety levels after 12 weeks of a digital care program. Additionally, reductions in Fear-Avoidance Beliefs Questionnaire (FABQ) scores were noted, with Shi et al. [36] reporting a decrease of 31.92 points (SD 15.07) in the telerehabilitation group and 40.15 points (SD 13.38) in the conventional rehabilitation group ($p = 0.12$), while Matheve et al. found no significant post-intervention differences in FABQ scores (37.0 ± 5.6 vs. 36.2 ± 6.9 at baseline) and also in Tampa Scale of Kinesiophobia (TSK) scores (TSK: 37.0 ± 5.6 in the intervention group vs. 36.2 ± 6.9 in the control group at baseline) [33] (Table 8).

In terms of biological outcomes, Nambi et al. [17] found significant reductions in inflammatory biomarkers in the virtual reality exercise (VRE) group. Specifically, CRP levels decreased from 1.56 ± 0.3 mg/L to 0.4 ± 0.08 mg/L ($p = 0.001$) and TNF-α from 16.6 ± 0.7 pg/mL to 7.7 ± 0.5 pg/mL ($p = 0.001$). The effect sizes were very large, with Cohen's d = 6.66 for CRP and d = 4.54 for TNF-α, indicating extremely strong anti-inflammatory effects. Similar results were observed for other inflammatory markers, such as IL-2 (d = 1.81), IL-4 (d = 1.16), and IL-6 (d = 4.57). These findings support the hypothesis that VR-based rehabilitation may elicit robust systemic anti-inflammatory responses in patients with chronic low back pain, possibly mediated by neuromuscular activation and elevated metabolic demands during interactive tasks (Table 9).

Functional disability is measured through standardized tools such as the ODI and RMDQ. Shebib et al. [39] reported a notable reduction in ODI scores from 19.7 at baseline to 13.5 after a 12-week digital care program, representing a 31.5% improvement in disability. The mean difference between groups was −6.9 points (95% CI: −10.5 to −3.3, $p < 0.001$), indicating a large effect. In contrast, the control group, which only received digital educational content, showed no significant change (18.9 to 19.7). Similarly, Shi et al. [36] found a decrease in ODI scores of 16.42 points (SD 7.30) in the telerehabilitation group compared to 13.18 points (SD 8.48) in the conventional rehabilitation group. However, the difference between groups at 8 weeks was not statistically significant (mean difference: −3.24, 95%

CI: −8.65 to 2.17, $p = 0.24$), suggesting noninferiority but no clear superiority. Regarding the RMDQ, Matheve et al. evaluated the impact of sensor-based postural feedback on movement control in CLBP patients, but no significant post-intervention differences in RMDQ scores were observed both in a 2018 [32] study (baseline: 6.6 ± 3.3 in the sensor group, 7.5 ± 4.9 in the mirror feedback group, and 7.7 ± 3.5 in the control group) and 2020 study [33] (RMDQ baseline: 11.4 ± 3.8 in the intervention group vs. 10.9 ± 4.3 in the control group) (Table 10).

Table 8. Psychological Well-Being.

Study	Outcome Measures	Key Findings	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Bailey et al., 2020 [37]	Depression Symptoms (PHQ-9)	57.5% reduction in depression symptoms after 12 weeks of digital care program.	Not reported	Not reported
Bailey et al., 2020 [37]	Anxiety Symptoms (GAD-7)	58.1% reduction in anxiety levels after 12 weeks of digital care program.	Not reported	Not reported
Shi et al., 2024 [36]	Fear-Avoidance Beliefs (FABQ)	31.92 points decrease in FABQ (telerehabilitation group). $p = 0.12$.	Not reported	Not reported
Matheve et al., 2020 [33]	Fear-Avoidance Beliefs (FABQ)	No significant change in FABQ scores (VR-based rehabilitation group).	Not reported	Not reported
Matheve et al., 2020 [33]	Fear of Movement (TSK)	No significant change in TSK scores (VR-based rehabilitation group).	Not reported	Not reported

Abbreviations. FABQ: Fear-Avoidance Beliefs Questionnaire, GAD-7: Generalized Anxiety Disorder-7, PHQ-9: Patient Health Questionnaire-9 (Depression), TSK: Tampa Scale of Kinesiophobia, VR: Virtual Reality.

Table 9. Inflammatory Biomarkers.

Study	Outcome Measures	Key Findings	Effect Size (Cohen's d)/Confidence Interval (CI)	Interpretation
Nambi et al., 2023 [35]	CRP (mg/L)	Significant decrease in CRP levels from 1.56 to 0.4 mg/L ($p = 0.001$) after VR-based rehabilitation.	Cohen's d: 6.66	Large effect
Nambi et al., 2023 [35]	TNF-α (pg/mL)	Significant decrease in TNF-α levels from 16.6 to 7.7 pg/mL ($p = 0.001$) after VR-based rehabilitation	Cohen's d: 4.54	Large effect

Abbreviations: CRP: C-Reactive Protein, TNF-α: Tumor Necrosis Factor-alpha, VR: Virtual Reality.

Table 10. Functional Disability.

Study	Outcome Measures	Key Findings	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Shebib et al., 2019 [39]	ODI	31.5% improvement in disability (ODI reduction from 19.7 to 13.5).	Not reported; between-group mean difference = −6.9 (95% CI: −10.5 to −3.3; $p < 0.001$)	Large clinical effect
Shi et al., 2024 [36]	ODI	16.42 points decrease in ODI (telerehabilitation group, $p = 0.24$); 13.18 points decrease in ODI (conventional rehabilitation group, $p = 0.24$).	Not reported; between-group difference = −3.24 (95% CI: −8.65 to 2.17; $p = 0.24$)	No significant difference
Matheve et al., 2018 [32]	RMDQ	No significant change in RMDQ scores (baseline: 6.6 ± 3.3 in the sensor group, 7.5 ± 4.9 in the mirror feedback group, and 7.7 ± 3.5 in the control group)	Not reported	Not reported
Matheve et al., 2020 [33]	RMDQ	No significant change in RMDQ scores (baseline: 11.4 ± 3.8 in the intervention group vs. 10.9 ± 4.3 in the control group)	Not reported	Not reported

Abbreviations: ODI: Oswestry Disability Index, RMDQ: Roland-Morris Disability Questionnaire.

3.9. Economic Perspective

The economic perspective was addressed in a limited number of studies included in this systematic review. Bailey et al. [37] reported significant economic benefits associated with a 12-week digital rehabilitation program that combined sensor-guided exercises, cognitive–behavioral support, and remote coaching. Participants experienced a 61.5% reduction in work impairment, as measured by the Work Productivity and Activity Impairment (WPAI) questionnaire, with scores improving from 34.12 ± 26.37 to 12.24 ± 15.58, indicating notable recovery in occupational performance and potential indirect cost savings related to CLBP. Similarly, Shebib et al. [39] highlighted a 52% decrease in surgery interest following participation in a digital care program, suggesting possible reductions in healthcare expenditures by limiting the need for invasive procedures. Regarding willingness to pay, Park et al. [38] evaluated participants' financial acceptability of a motion-detecting mobile exercise coaching application. Although no significant differences were observed between groups, the majority of participants indicated a willingness to pay less than USD 5 per month for the service (45.2% in the intervention group vs. 38.9% in the control group, $p = 0.59$), reflecting a moderate perceived economic value of digital rehabilitation technologies (Table 11).

Table 11. Economic Outcomes.

Study	Economic Outcomes	Key Findings	Effect Size (Cohen's d)/ Confidence Interval (CI)	Interpretation
Bailey et al., 2020 [37]	Work Productivity (WPAI)	61.5% reduction in work impairment (WPAI score from 34.12 ± 26.37 to 12.24 ± 15.58)	Not reported	Not reported
Shebib et al., 2019 [39]	Surgery Interest	52% reduction in surgery interest; potential healthcare cost savings	Not reported	Not reported
Park et al., 2022 [38]	Willingness to Pay	Majority willing to pay < $5/month (45.2% in intervention group; $p = 0.59$)	Not reported	Not reported

Abbreviations: WPAI: Work Productivity and Activity Impairment.

3.10. Discussion

This systematic review aimed to evaluate the effectiveness of remote rehabilitation interventions using motion sensors for individuals with LBP, focusing on key outcomes such as movement improvement, pain reduction, QoL, adherence, healthcare, and economic aspects. The findings suggest that sensor-based digital rehabilitation strategies, often combined with VR, mobile applications, and remote coaching, can provide clinically meaningful improvements across multiple domains of patient care.

From a functional perspective, several studies demonstrated that motion-tracking technologies enhance biomechanical outcomes by improving lumbopelvic movement control, reducing compensatory movements, and promoting motor learning, essential to ensure that movement modifications are retained and successfully transferred to daily life, supporting long-term outcomes in musculoskeletal rehabilitation [40–42]. Additionally, the rapid advancement of markerless and wearable systems has significantly expanded the potential of motion analysis beyond clinical settings, allowing for remote, non-invasive, and automated monitoring of posture and movement [40,43]. Interventions incorporating real-time biofeedback through wearable sensors showed significant improvements in ROM and movement efficiency, highlighting the potential of these technologies to support targeted and personalized rehabilitation approaches. Furthermore, VR-based programs, in particular, contributed to increased engagement and motivation, factors known to enhance adherence and optimize rehabilitation outcomes [44–46].

Pain reduction emerged as a consistent benefit across most included studies, with sensor-guided interventions achieving moderate to large decreases in pain intensity over both short and long-term programs. In general, these benefits are observed across various digital interventions, highlighting their potential in chronic pain management [47]. The Cochrane review by Hayden et al. [48] similarly underscored that structured exercise programs yielded clinically meaningful pain relief compared to no treatment or usual care, particularly when interventions were sustained over time. These findings align with previous research emphasizing the importance of continuous feedback and interactive platforms in sustaining patient participation and addressing chronic musculoskeletal pain [49–52]. However, short-duration interventions, such as single-session exergames, were less effective in producing significant pain relief, suggesting that prolonged and structured programs are necessary to achieve lasting benefits [32,34]. Regarding QoL, the evidence was more limited but promising; improvements were primarily noted in studies utilizing interactive

mobile coaching applications, while other interventions showed comparable effects to conventional therapies [36,38]. This variability highlights the need for further high-quality trials to understand the specific contribution of digital rehabilitation to broader health-related QoL metrics. Adherence was generally high across studies, particularly in programs integrating gamification, real-time feedback, and remote supervision. High adherence rates are critical for the success of home-based rehabilitation and are directly linked to improved clinical outcomes. Studies suggest that serious games designed with user-centered principles and motivational strategies, such as real-time feedback and progressive challenges, significantly enhance engagement and adherence [53]. Additionally, multimodal digital care programs have demonstrated high completion rates and engagement, even among socioeconomically disadvantaged groups, reinforcing the importance of accessible and patient-centered rehabilitation strategies [54]. Traditional physiotherapy, by contrast, often suffers from high dropout rates due to factors such as lack of motivation, accessibility barriers, and low patient engagement, highlighting the need for innovative digital solutions to support long-term participation [55,56]. An important limitation of this systematic review lies in the heterogeneity of the included studies, which varied substantially in terms of intervention type (e.g., virtual reality platforms, wearable sensor-based feedback, and mobile coaching applications), program duration (ranging from single-session to 12-week interventions), participant demographics (including age, gender distribution, and clinical profiles), and outcome measurement tools. These differences reflect the diverse landscape of digital rehabilitation approaches for chronic low back pain and underscore the challenge of drawing uniform conclusions. While such heterogeneity limits the comparability of results and precluded formal subgroup analysis due to the small number of included studies (n = 8), it also provides a comprehensive overview of current practices and innovation trends in this domain. Future research should prioritize standardized intervention protocols, consistent outcome measures, and stratified study designs to enable more rigorous comparative analyses and meta-analytic synthesis. Moreover, subgroup analyses based on clinical characteristics (e.g., baseline disability level, age groups, or type of digital platform used) will be essential to better understand which interventions are most effective for specific patient populations.

From an economic perspective, only a few studies directly have addressed cost-related outcomes. Bailey et al. [37] reported a significant reduction in work impairment, reflecting potential indirect cost savings through improved productivity. A Cochrane review [48] highlighted that CLBP leads to a significant number of lost work hours, with 65% of patients still experiencing pain after one year, but exercise-based interventions were linked to lower absenteeism and improved productivity, reinforcing their economic benefits. Similarly, Shebib et al. [39] identified a decreased interest in surgical intervention, suggesting downstream healthcare cost reductions. However, despite these encouraging signals, formal health economic evaluations remain scarce. This limits the ability to draw definitive conclusions regarding the cost-effectiveness and financial sustainability of digital rehabilitation strategies for CLBP. Future studies should incorporate robust economic analyses to assess direct healthcare costs, indirect societal costs, and long-term value.

Overall, this review highlights the promising role of wearable sensors, telerehabilitation, and VR technologies in managing CLBP, with reported improvements in pain, movement control, and adherence. However, some findings, particularly those from small-scale or pilot studies with a higher risk of bias [17,34], should be interpreted with caution. These studies, while innovative, may overestimate treatment effects due to methodological limitations such as lack of blinding or small sample sizes. Future high-quality trials are needed to confirm these preliminary results and to standardize outcome reporting, particularly for biomechanical and adherence-related endpoints.

3.11. Comparison of Digital Rehabilitation Modalities and Implementation Challenges

This review included a range of digital rehabilitation modalities, each with unique characteristics influencing their clinical impact. VR-based interventions provided immersive and gamified environments that enhanced motivation and engagement [32,33]. These programs were particularly effective in improving movement control and reducing pain, especially when coupled with motion-tracking technologies. However, VR systems often require dedicated hardware and infrastructure, which may limit their scalability and accessibility in low-resource settings.

AI-driven mobile coaching applications, on the other hand, offered greater flexibility and ease of access by delivering real-time exercise feedback through smartphones [38]. These interventions showed beneficial effects on pain and quality of life and may be especially suited to patients requiring minimal technical support or remote supervision. While more scalable, these tools may provide less detailed biomechanical feedback than sensor-based systems.

Telerehabilitation platforms with wearable sensors allowed for precise movement analysis, objective tracking of rehabilitation progress, and personalized remote supervision [34,36,37,39]. These approaches demonstrated positive outcomes in terms of adherence, functional improvement, and psychological well-being. Nonetheless, long-term data on sustainability and outcomes beyond the intervention period remain limited.

Taken together, the comparative analysis suggests that each modality has strengths suited to specific patient needs, technological resources, and rehabilitation goals. Future studies should directly compare these approaches to determine optimal implementation strategies for chronic low back pain management.

However, beyond clinical effectiveness, several practical challenges must be considered for the successful implementation of digital rehabilitation strategies. Digital literacy remains a key barrier, especially among older adults or individuals with low technological familiarity, who may struggle to engage with mobile apps, VR systems, or sensor-based platforms [57]. Additionally, limited internet access or unstable connectivity, particularly in rural or underserved regions, may delay the continuity of remote rehabilitation [58]. The acceptance and readiness of healthcare professionals also influence adoption: lack of training, skepticism toward digital tools, and concerns about data security may reduce uptake in clinical practice [59], particularly in the field of musculoskeletal rehabilitation, which has traditionally relied on direct physical contact with patients [60]. In addition, ethical and regulatory issues, such as ensuring informed consent, data privacy, and compliance with telehealth legislation, must be carefully addressed to support the responsible integration of these technologies into clinical care [61].

Addressing these challenges is essential to ensure that digital rehabilitation becomes a truly accessible, inclusive, and sustainable solution for chronic low back pain.

4. Conclusions

This systematic review underscores the growing role of remote rehabilitation and VR interventions using motion sensors in managing CLBP. The findings demonstrate that these innovative digital approaches offer significant benefits in multiple domains, including improved movement control, pain reduction, treatment adherence, and suggestive evidence of improvements in QoL. Motion sensors, particularly when integrated with real-time feedback, gamification, and remote supervision, facilitate a more engaging and personalized rehabilitation experience, which is crucial for maintaining long-term participation and optimizing outcomes. VR-based interventions have also shown promise in enhancing proprioception, reducing kinesiophobia, and increasing motivation compared to conventional therapies. Furthermore, adherence to digital rehabilitation programs was

consistently high, particularly in interventions incorporating structured coaching and interactive elements, addressing a well-known limitation of traditional physiotherapy, which often suffers from high dropout rates. The economic impact of these technologies, although supported by preliminary findings, suggests potential cost savings through reduced work impairment, improved productivity, and lower healthcare utilization. The integration of wearable sensors and ML tools further expands the potential for real-time monitoring and adaptive treatment, paving the way for more precise and individualized rehabilitation protocols. Overall, the reviewed evidence highlights the transformative potential of digital rehabilitation for CLBP, offering a viable alternative or complement to conventional physiotherapy. These interventions not only provide clinically meaningful improvements but also increase accessibility, particularly for patients with limited access to in-person rehabilitation services. Moving forward, the continued development and refinement of digital rehabilitation technologies, alongside structured implementation strategies, will be key to optimizing their effectiveness and ensuring widespread adoption in clinical practice.

Limitations and Research Gaps

This review highlights promising results, but several limitations must be considered. The study heterogeneity, including variations in sample sizes, intervention protocols, and follow-up durations, limits direct comparisons. Many studies had short intervention periods and potential biases, particularly in blinding and adherence reporting. Additionally, long-term effects remain unclear due to limited follow-up data. The lack of large-scale RCTs and formal cost-effectiveness analyses prevents definitive conclusions on the financial sustainability of digital rehabilitation. Future studies should adopt standardized reporting frameworks to enhance reproducibility and comparability across trials. Multicentric RCTs are also needed to improve external validity and representativeness of patient populations. Moreover, incorporating robust cost-effectiveness evaluations will be essential to inform health policy decisions and guide the allocation of resources. While pain and biomechanical improvements were well-documented, psychosocial factors and long-term adherence received less attention. Future research should focus on standardized methodologies, longer follow-up periods, and AI-driven personalized rehabilitation models. Exploring multidisciplinary approaches that integrate digital rehabilitation with behavioral strategies could further enhance engagement and long-term outcomes. Addressing these gaps will help optimize the effectiveness and integration of motion sensor-based rehabilitation for CLBP.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are included in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Search Strategy

Database	Search Strategy	Filters applied	Date of Search
PubMed	#1: Low Back Pain [Mesh] OR # 2: Back Pain, Low OR Back Pains, Low OR Low Back Pains OR Pain, Low Back OR Pains, Low Back OR Low Back Ache OR Ache, Low Back OR Aches, Low Back OR Back Ache, Low OR Back Aches, Low OR Low Back Aches OR Low Backache OR Backache, Low OR Backaches, Low OR Low Backaches OR Lower Back Pain OR Back Pain, Lower OR Back Pains, Lower OR Lower Back Pains OR Pain, Lower Back OR Pains, Lower Back OR Lumbago OR Low Back Pain, Mechanical OR Mechanical Low Back Pain OR Low Back Pain, Posterior Compartment OR Low Back Pain, Postural OR Postural Low Back Pain OR Low Back Pain, Recurrent OR Recurrent Low Back Pain # 3: # 1 OR #2 AND #4: rehabilitation OR physical therapy modalities OR home exercises AND # 5: motion detection OR motion analysis OR motion capture OR motion detection OR movement analysis OR motion tracking OR movement tracking OR sensor OR camera OR video OR User-Computer Interface[MeSH Terms] OR serious game OR exergame OR kinect OR wii OR virtual reality OR feedback OR biofeedback #6: #3 AND #4 AND #5	Publication years: 2015–2025, Filters: Clinical Trial, English, Adult: 19+ years	1 February 2025
Scopus	TITLE-ABS-KEY(“Low Back Pain” OR “Back Pain, Low” OR “Back Pains, Low” OR “Low Back Pains” OR “Pain, Low Back” OR “Pains, Low Back” OR “Low Back Ache” OR “Ache, Low Back” OR “Aches, Low Back” OR “Back Ache, Low” OR “Back Aches, Low” OR “Low Back Aches” OR “Low Backache” OR “Backache, Low” OR “Backaches, Low” OR “Low Backaches” OR “Lower Back Pain” OR “Back Pain, Lower” OR “Back Pains, Lower” OR “Lower Back Pains” OR “Pain, Lower Back” OR “Pains, Lower Back” OR “Lumbago” OR “Low Back Pain, Mechanical” OR “Mechanical Low Back Pain” OR “Low Back Pain, Posterior Compartment” OR “Low Back Pain, Postural” OR “Postural Low Back Pain” OR “Low Back Pain, Recurrent” OR “Recurrent Low Back Pain”) AND TITLE-ABS-KEY(“rehabilitation” OR “physical therapy modalities” OR “home exercises”) AND TITLE-ABS-KEY(“motion detection” OR “motion analysis” OR “motion capture” OR “movement analysis” OR “motion tracking” OR “movement tracking” OR “sensor” OR “camera” OR “video” OR “User-Computer Interface” OR “serious game” OR “exergame” OR “kinect” OR “wii” OR “virtual reality” OR “feedback” OR “biofeedback”)	Publication years: 2015–2025,	1 February 2025

Database	Search Strategy	Filters applied	Date of Search
Web of Science	TS = ("Low Back Pain" OR "Back Pain, Low" OR "Back Pains, Low" OR "Low Back Pains" OR "Pain, Low Back" OR "Pains, Low Back" OR "Low Back Ache" OR "Ache, Low Back" OR "Aches, Low Back" OR "Back Ache, Low" OR "Back Aches, Low" OR "Low Back Aches" OR "Low Backache" OR "Backache, Low" OR "Backaches, Low" OR "Low Backaches" OR "Lower Back Pain" OR "Back Pain, Lower" OR "Back Pains, Lower" OR "Lower Back Pains" OR "Pain, Lower Back" OR "Pains, Lower Back" OR "Lumbago" OR "Low Back Pain, Mechanical" OR "Mechanical Low Back Pain" OR "Low Back Pain, Posterior Compartment" OR "Low Back Pain, Postural" OR "Postural Low Back Pain" OR "Low Back Pain, Recurrent" OR "Recurrent Low Back Pain") AND TS = ("rehabilitation" OR "physical therapy modalities" OR "home exercises") AND TS = ("motion detection" OR "motion analysis" OR "motion capture" OR "movement analysis" OR "motion tracking" OR "movement tracking" OR "sensor" OR "camera" OR "video" OR "User-Computer Interface" OR "serious game" OR "exergame" OR "kinect" OR "wii" OR "virtual reality" OR "feedback" OR "biofeedback")	Publication years: 2015–2025, Document types: Article, Language: English	1 February 2025
PEDro	Simple search: Telerehabilitation, low back pain		1 February 2025

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