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Effectiveness of biofeedback-assisted asynchronous telerehabilitation in musculoskeletal care: A systematic review

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Abstract

Background: Musculoskeletal conditions are the leading cause of disability worldwide. Telerehabilitation may be a viable option in the management of these conditions, facilitating access and patient adherence. Nevertheless, the impact of biofeedback-assisted asynchronous telerehabilitation remains unknown.

Objective: To systematically review and assess the effectiveness of exercise-based asynchronous biofeedback-assisted telerehabilitation on pain and function in individuals with musculoskeletal conditions.

Methods: This systematic review followed Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. The search was conducted using three databases: PubMed, Scopus, and PEDro. Study criteria included articles written in English and published from January 2017 to August 2022, reporting interventional trials evaluating exercise-based asynchronous telerehabilitation using biofeedback in adults with musculoskeletal disorders. The risks of bias and certainty of evidence were appraised using the Cochrane tool and Grading of Recommendations, Assessment, Development, and Evaluation (GRADE), respectively. The results are narratively summarized, and the effect sizes of the main outcomes were calculated.

Results: Fourteen trials were included: 10 using motion tracker technology ($N = 1284$) and four with camera-based biofeedback ($N = 467$). Telerehabilitation with motion trackers yields at least similar improvements in pain and function in people with musculoskeletal conditions (effect sizes: 0.19–1.45; low certainty of evidence). Uncertain evidence exists for the effectiveness of camera-based telerehabilitation (effect sizes: 0.11–0.13; very low evidence). No study found superior results in a control group.

Conclusions: Asynchronous telerehabilitation may be an option in the management of musculoskeletal conditions. Considering its potential for scalability and access democratization, additional high-quality research is needed to address long-term outcomes, comparativeness, and cost-effectiveness and identify treatment responders.

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Introduction

Musculoskeletal (MSK) conditions are characterized by "impairments in the muscles, bones, joints, and adjacent connective tissues leading to temporary or lifelong limitations in functioning and participation,"[1] being the number one cause of disability worldwide[1] (nearly 150 million years lived with disability).[2] Although this concept encompasses several diagnosis, the present work will focus on conditions with non-rheumatoid, non-metabolic, and non-autoimmune etiology. These conditions can produce significant limitations in mobility and functionality, compromising the ability to perform daily activities and work productivity. This, compounding to the frequently associated mental health distress, contributes to the reduced reported quality of life. The subsequent economic expenditure driven by direct healthcare-related and indirect costs exceeds those for heart disease and cancer,[3] imposing a tremendous societal impact.

Adequate treatments may substantially reduce this burden, with exercise and behavior-change strategies being widely recommended as first-line interventions in the management of these conditions.[4–7] Access to conservative care, namely, physical therapy, is frequently hampered by numerous barriers including geographic and travel constraints, lack of clinicians and healthcare facilities, and high costs associated with in-person care.[8,9]

Telerehabilitation, a subset of telemedicine, arose as an attempt to overcome these challenges and aims to facilitate access and improve adherence to treatment.[10] The recent COVID-19 pandemic highlighted the potential of telemedicine to ensure continued care delivery, in a situation where access to in-person care was severely limited.[11,12] The Centers for Disease Control and Prevention reported a 50% increase in telehealth visits from January to March 2020 compared with the same period in 2019, with an astounding 154% increase from March 23 to March 28.[13]

Previous systematic reviews assessed the effectiveness of telerehabilitation in patients with MSK conditions, addressing specifically pain and function improvement.[14–16] Cottrell et al.[14] conducted a systematic review with meta-analysis and concluded that telerehabilitation is as effective and comparable to conventional care for both function and pain in a variety of MSK conditions (including shoulder, hip, and knee arthroplasties, low back pain, neck pain, and osteoarthritis). Similar findings were reported in two other systematic reviews supporting its use for non-acute[16] and chronic[15] MSK conditions. However, these systematic reviews considered only synchronous interventions (where patients are accompanied by therapists in real time through video conferencing or telephone) including those in a hybrid format (i.e., telerehabilitation combined with in-person care) and excluded asynchronous interventions (where sessions displayed in a digital format are performed independently by the patient). Synchronous telerehabilitation may pose some limitations, particularly regarding the scalability of treatment and scheduling constraints, which has generated interest in asynchronous telerehabilitation.[17] Gava et al.[18] conducted a systematic review focused on telerehabilitation in participants with shoulder pain, gathering evidence from six randomized controlled trials (RCTs) (1 synchronous + 5 asynchronous). The authors reported low to very low certainty of evidence supporting the use of telerehabilitation to improve pain and disability.[18]

Recently, the development of innovative technologies has allowed the integration of important features to enable and optimize asynchronous care delivery.[12] Motion tracking systems have now been integrated into telerehabilitation interventions to provide real-time biofeedback during exercise. These encompass diverse technologies, such as wearable sensors with inertial measurement units, built-in smartphone sensors, and camera-based sensors. Such technologies guide patients during sessions and promote close remote monitoring on patient progress, thereby permitting individualized support and reinforcing accountability.[19,20] Additionally, movement digitalization with respective data storage in web platforms may assist therapists in patient monitoring and intervention data-driven adjustments.

Despite advances in biofeedback technologies and the clinical applicability of such strategies, no systematic review has assessed the evidence on asynchronous telerehabilitation with biofeedback, particularly on stand-alone MSK telerehabilitation (i.e., without in-person sessions).

The aim of this systematic review is to summarize the evidence and assess the effectiveness of exercise-based asynchronous telerehabilitation incorporating biofeedback systems on pain and function in patients with MSK

conditions, focusing on the last 5 years. The secondary objectives are to assess patient adherence and satisfaction with such programs.

Methods

Study design

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines[21] and the Cochrane Handbook for Systematic Reviews[22] (PRISMA checklist is provided in Appendix 1). Although the protocol of this systematic review was not registered, the review methodology was established prior to the conduct of the review and was not modified post hoc.

Search strategy

A systematic literature search was performed on PubMed, Scopus, and PEDro on published articles. A primary search was conducted on 27 April 2022, and subsequent searches were conducted on 29 April 2022 (Scopus), 2 May 2022 (PubMed), and 24 August 2022 (PEDro) to ensure a thorough appraisal and selection of relevant literature. In order to select studies with the most recent and innovative technological biofeedback solutions for MSK telerehabilitation, only articles published in the previous 5 years were considered (filter used: publication date after 1 January 2016). This time frame was chosen because of the dramatic changes in this technology that have occurred in the past several years; a subsequent search revealed only a single article published earlier.[23] The search strategy for each database consisted of free text words and Medical Subject Headings (MeSH) as reported in Appendix 2. All keywords were searched independently and then combined using relevant Boolean terms. Additionally, the reference list of included articles and of relevant previous systematic reviews were manually searched to guarantee that all relevant literature was included.

Selection criteria

The study selection criteria were defined based on the following PICOS:

- Participants: Adult patients (>18 years old) with MSK-related conditions, defined as those causing MSK-related pain or disability in either acute or chronic stages. Studies including pregnant patients, as well as those comprising conditions related to metabolic diseases (e.g., osteoporosis and diabetes), neurologic disorders (e.g., post-stroke), chronic widespread pain (e.g., fibromyalgia), cancer, and autoimmune causes including inflammatory arthropathies (e.g., rheumatoid arthritis) were excluded.
- Intervention: Exercise-based asynchronous telerehabilitation, defined by remote interventions where exercise sessions were performed independently by the patient, delivered via telecommunication technologies incorporating biofeedback systems for MSK care, with a minimum treatment time of 4 weeks (considered a sufficient time frame to obtain consistent results on the defined outcomes[24,25]). Hybrid modalities (i.e., combining telerehabilitation with in-clinic treatment) were excluded.
- Comparison: Control groups from eligible studies should include one of the following: placebo, standard care, no treatment (waiting list), and other active treatments (conservative care, in solo or with adjunctive telerehabilitation). Studies without control groups (i.e., single-arm interventional) were eligible.
- Outcome: Pain intensity and self-reported function. Secondary outcomes were patient adherence and satisfaction.
- Setting/study design: Home-based/outpatients (any country, but had to be written in English). Eligible study designs included controlled trials (randomized and non-randomized), before-after trials, and interventional single-arm longitudinal studies. Clinical trials without a control group were included due to the expected limited body of evidence to gather insights on studied interventions details, feasibility, patient's acceptability and engagement, and preliminary observed results.

Inclusion and exclusion criteria are summarized in Table 1.

Selection process and data extraction

Search results were examined by three individual researchers (D.J., B.W., and F.C.) based on the established inclusion and exclusion criteria listed above. Duplicates were removed before the studies were first screened using titles and abstracts. Full-text screening and quality assessment were performed by three authors independently (D.J., B.W., and F.C.). Any disagreements were resolved by consensus. Data extraction was performed into a Microsoft® Excel® template including first author, date of intervention, country, study design, industry funding/sponsorship, sample size, patient's demographics, MSK condition, type of telerehabilitation and comparator, intervention duration, follow-up period, adverse events and dropouts, outcome measures, and results. Outcome extracted data included post-intervention scores for each group and mean difference (MD) between groups, with respective SDs, and confidence intervals (CIs). When an included study did not report the aforementioned data in sufficient detail, the corresponding author was contacted via email to provide additional data.

Table 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
• Studies published after 1 January 2017 • Patients: adults (>18 years) with MSK-related complaints • Intervention: remote exercise-based asynchronous telerehabilitation (minimum 4-week duration) • Comparison: control or other interventions; pre-intervention data in single-arm studies • Outcome: pain and function • Setting/study design: controlled interventional trials (randomized and non-randomized), before-after trials, and single-arm interventional studies	• Non-peer-reviewed articles • Intervention duration shorter than 4 weeks • In-person or hybrid format with in-person treatment (interventional group) • Patients with non-MSK-related complaints, widespread pain, metabolic diseases, neurologic disorders, cancer, and autoimmune diseases • Patients during pregnancy • Written in language other than English

Abbreviation: MSK, musculoskeletal.

Evidence synthesis

Results were narratively synthesized according to the Synthesis Without Meta-analysis (SWiM) reporting guideline.[26] The narrative synthesis was grouped based on the underlying biofeedback technology incorporated (inertial motion sensors and camera-based biofeedback) and reported by MSK condition. For the synthesis methods, please see the "Statistical analysis" section.

Quality and risk of bias assessment

To assess the risk of bias (ROB), the Cochrane ROB tool (version 2.0)[31] was used for randomized controlled trials (RCT), whereas non-randomized trials were assessed using the ROB in Nonrandomized Studies of Interventions (ROBINS) tool.[32] The ROB assessed by the Cochrane ROB tool was rated as high, low, or having some concerns, while ROB in ROBINS was rated as critical, serious, moderate, or low.

The Grading of Recommendations, Assessment, Development and Evaluation (GRADE) approach was used to appraise the effectiveness quality of evidence.[33] The quality of evidence was initially considered as high, and downgraded one level for serious concerns and two levels for very serious concerns, based on five criteria: high ROB, inconsistency of results, indirectness of evidence, imprecision, and publication bias. Finally, the quality of evidence for each outcome was assessed according to four categories: high, moderate, low, or very low.

Since single-arm studies lack a control group, these were not considered on the effectiveness assessment and therefore their ROB and quality of evidence were not assessed.

Statistical analysis

A summary of effect size estimates was performed in a table format. Considering the different measurement scales used to assess either pain or function across studies, data were converted into standardized mean differences (SMDs) with 95% CI considering the first post-intervention result as the time frame to assess outcomes (independent of intervention length). These were calculated for each study by subtracting the post-intervention mean of the control group from the post-intervention mean of the intervention group and dividing by the pooled SD for the sample. A positive value denotes superior results in the intervention group compared to the control group. Some studies did not note the primary outcome or used other primary outcomes besides pain and function. In such cases we prioritized numerical pain rating scales or visual analogue scales (VAS) for pain, as they are the most recommended metrics, including by IMMPACT, ICHOM, and other groups.[27–30] For function, condition-specific patient-reported outcome measures were selected, as self-perception of functional limitations and disabilities is considered an important domain by the same groups mentioned above. Whenever available, intent-to-treat results were selected. Effect direction plots were produced to visually depict the range of the obtained effect estimates and CI.

A post hoc sensitivity analysis was performed to assess whether effect sizes for pain and function were different between industry-sponsored and non-industry-sponsored studies.

Results

Search results

The details on the literature search and screening/eligibility processes are depicted in Figure 1. From the initial screening, 141 papers were appraised in full text for eligibility, and 14 papers completely matched the inclusion/exclusion criteria.

Characteristics of the included studies

The details of the included studies, namely, MSK condition, interventions, outcomes, and main findings are presented in Table 2. Further details on the intervention of the studies are presented in Appendix 3 and on adverse events and reasons for dropouts in Appendix 4.

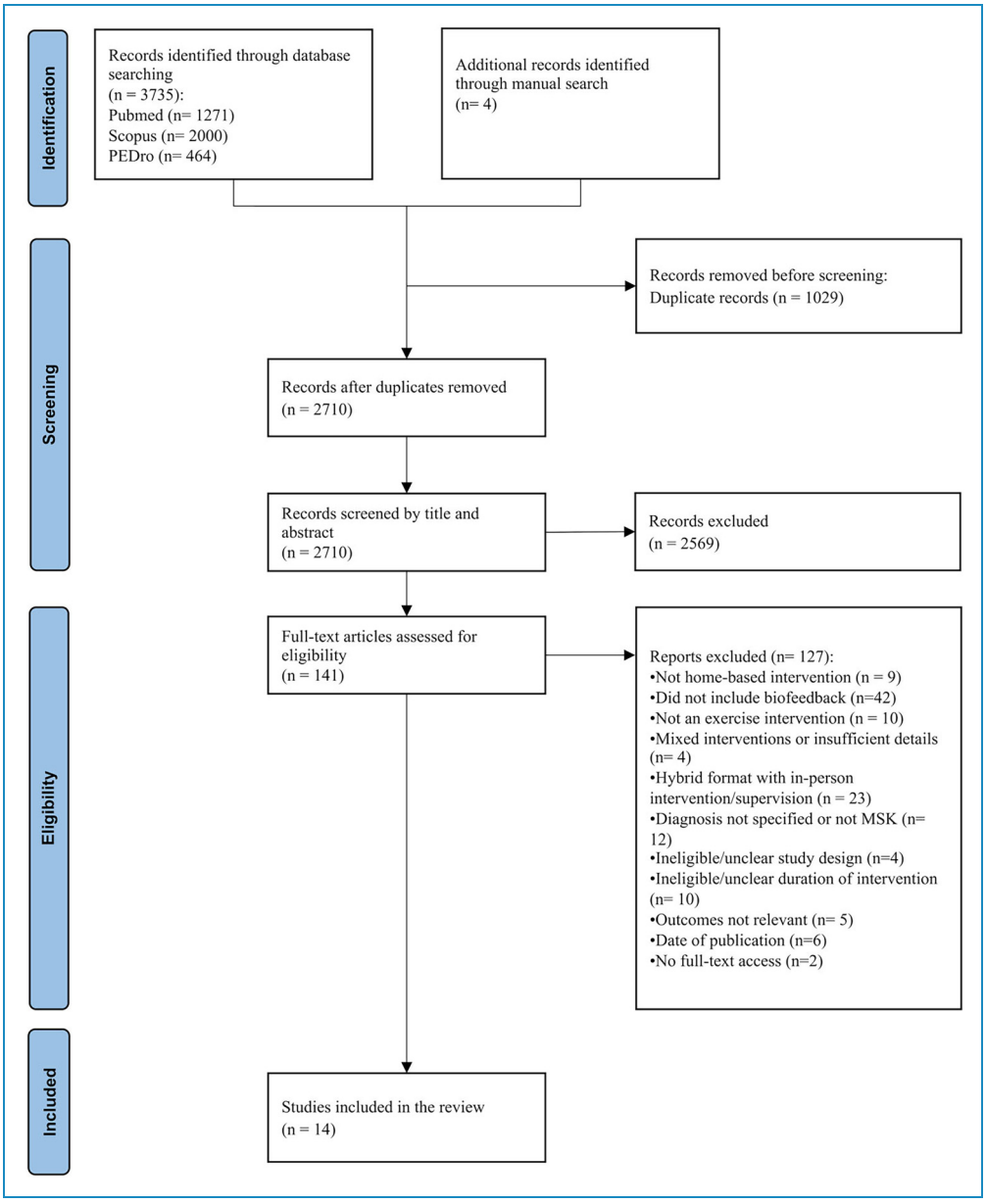

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow chart of study selection process.

All studies were published between 10 October 2017 and 8 January 2022. A total of 8 RCTs, 3 non-randomized control trials, and 3 single-arm studies were included, with sample sizes ranging from 12 to 343. Half of the studies ($N = 7/14$) included cohorts with a majority of females,[34–40] while four studies had a majority of males.[41–44] The mean ages differed between studies with three studies reporting cohorts with mean ages of 30–40 years,[39,42,43] eight with mean ages between 50 and 60 years,[34,36,37,40,41,44–46] and three with a mean age ≥60 years.[35,38,47]

Regarding the technology interface used for care delivery, nine studies reported on app-based interventions,[34–36,41–43,45–47] four were web-based interventions,[37,38,40,44] and one focused on virtual reality.[39] The majority of studies ($N = 10/14$) used wearable inertial motion sensors to provide biofeedback during exercise sessions,[34–36,39–43,46,47] and four studies used camera-based sensors.[37,38,44,45] Eight studies focused on interventions consisting only of exercise,[34,37–41,44,45] whereas the other six studies reported on multimodal programs combining exercise with education and cognitive-behavioral therapy.[35,36,42,43,46,47] The majority of the assessed studies (10/14) included simultaneously pain and function as outcomes (either primary or secondary).[35,38–43,45–47]

Although all studies acknowledged the ability of telerehabilitation systems to register and monitor adherence, only 11 studies provided metrics of adherence.[35,36,38,39,41–47] Most of these studies reported metrics solely about the

Table 2. Characteristics of the included studies.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Inertial motion sensor-based interventions												
Y. P. Chen et al. 2020, Taiwan	non-RCT $n = 15$ (CG = 7, IG = 8)	Frozen shoulder	54.6	35.7%	Shoulder exercises with wearable motion sensors + mobile app (Patient App) + mobile app (Doctor App); Tailored progression; Communication through text messages	Instructions on daily shoulder exercises + description of the condition, and advice on sleep, posture, and pain relief.	Intervention: 12 weeks Follow-up: 12 weeks	Primary outcome: not defined VAS for pain; QuickDASH Adherence: reported by the motion sensor device was calculated by dividing the number of exercises completed daily by the number of assigned exercise tasks daily; self-reported was by a 0–100% scale (the average exercise completion rate in the previous month)	12 weeks: IG: VAS pain: 5.3 (1.3) to 2.0 (0.6) QuickDASH: 30.6 (18.1) to 9.8 (12.4) Adherence: 26.9% (device) and 13.5% (self-reported) Dropout rate: 0% CG: VAS pain: 6.1 (1.8) to 3.3 (1.1) QuickDASH: 23.3 (7.2) to 19.1 (13.7) Adherence: 13.2% (self-reported) Dropout rate: 0%	The IG had significantly better QuickDASH and pain scores at 12 W. No significant within-group changes in QuickDASH at 12 W in the CG. Adherence was higher in the IG when considering objective data, and similar based on self-reported outcomes.	Potential for baseline confounding; Deviations from intended interventions due to patient's adherence; Participants were unblinded to group allocation	Government grant

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Y. Choi et al. 2019, Korea	RCT $n = 84$ (CG = 42, IG = 42)	Frozen shoulder	54.5	67.9%	Assistive passive shoulder exercises with a smartphone app + built-in motion sensors; Communication to increase adherence	Recommendations for a self-exercise program (gentle assistive passive movements)	Intervention: 12 weeks Follow-up: 12 weeks	Primary outcome: VAS for pain at each time point; Satisfaction: five-point Likert scale (1, "negative/ disagree" to 5, "positive/ strongly agree")	12 weeks: IG: VAS pain: 6.0 (2.2) to 1.8 (2.5) Satisfaction: 4.9 (0.5) Dropout rate: 0% CG: VAS pain: 5.8 (2.3) to 2.2 (1.7) Dropout rate: 0%	No differences between group were observed for pain scores.	Participants and investigators were unblinded to group allocation; The time frame for the pain outcome is not reported (e.g., if related to the last 24 h or last 7 days)	Government grant
Correia et al. 2019, Portugal	Non-RCT $n = 66$ (CG = 31, IG = 35)	Total hip arthroplasty	64.5	47.0%	Exercise, education, and CBT with a mobile app + wearable motion sensors; Tailored progression; Scheduled communication	Home-based supervised rehabilitation provided by a physical therapist	Intervention: 8 weeks Follow-up: 6 months	Primary outcome: timed up and go change between baseline and 8 weeks; Secondary outcomes: HOOS; Adherence: percentage of participants that did not comply with the number of sessions prescribed per week; Satisfaction: 0–10 scale (how likely to recommend the intervention)	8 weeks: IG: HOOS pain: 33.0 (13.0) to 100.0 (7.0) HOOS function: 29.0 (15.0) to 93.0 (11.0) Adherence: 5 patients (17%) did not comply with the prescribed frequency (five sessions/week) Satisfaction: 97.1% reported 10 or 9 Dropout rate: 14% CG: HOOS pain: 33.0 (35.0) to 98.0 (12.0) HOOS function: 28.0 (28.0) to 82.0 (14.0) Dropout rate: 6%	The IG had significantly better HOOS function scores compared to the CG group. No differences between groups were observed for HOOS pain.	Potential for baseline confounding; Participants were unblinded to group allocation	Industry sponsorship

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Correia et al. 2018, Portugal	Non-RCT $n = 69$ (CG = 31, IG = 38)	Total knee arthroplasty	68.5 (7.0)	78.3%	Exercise, education, and CBT with a mobile app + wearable motion sensors; Tailored progression; Scheduled and on-demand communication	Home-based supervised rehabilitation provided by a physical therapist	Intervention: 8 weeks Follow-up: 8 weeks	Primary outcome: timed up and go change between baseline and 8 weeks; Secondary outcome: KOOS; Total active treatment: total hours that patients dedicated to perform sessions; Satisfaction: 0–10 scale (how likely to recommend the intervention)	8 weeks: IG: KOOS pain: 33.0 (12.0) to 90.5 (10) KOOS function: 34.0 (19.0) to 90.5 (10.0) Total active treatment time: 31.5 h (18.0) Satisfaction: 93.3% reported 10 or 9 Dropout rate: 21% CG: KOOS pain: 47.0 (24.0) to 78.0 (14.0) KOOS function: 41.0 (18.0) to 76.0 (16.0) Total active treatment time: 24 h Dropout rate: 6%	The IG had significantly better KOOS pain and KOOS function scores compared to the CG. Total active treatment time was superior in the IG.	Potential for baseline confounding; Presence of missing data; Participants were unblinded to group allocation	Industry sponsorship

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Costa et al. 2022, USA	Single-arm trial $n=343$	MSK acute pain	51.1 (11.4)	59.8%	Exercise, education, and CBT with a mobile app + wearable motion sensors; Tailored progression; Scheduled and on-demand communication	-	Intervention: 8–12 weeks Follow-up: 12 weeks	Primary outcome: NPRS change between baseline and end of the intervention; Adherence: number of sessions performed per week; Satisfaction: 0–10 scale (how likely to recommend the intervention)	12 weeks: NPRS pain: 4.48 (1.41); change 2.88 (-0.25; 3.96) Adherence: 3.2 sessions/week (minimum three recommended) Satisfaction: 8.7/10 (1.26) Dropout rate: 12.0%	Significant within-group improvements regarding pain.	Lack of a control group	Industry sponsorship
Janela et al. 2022, USA	Single-arm trial $n=296$	Chronic shoulder pain	50.9 (11.6)	52.7%	Exercise, education, and CBT with a mobile app + wearable motion sensors; Tailored progression; Scheduled and on-demand communication	-	Intervention: 8–12 weeks Follow-up: 12 weeks	Primary outcome: QuickDASH change between baseline and end of the intervention; Secondary outcomes: NPRS; Adherence: number of sessions performed per week; Satisfaction: 0–10 scale (how likely to recommend the intervention)	12 weeks: NPRS pain: 4.56 [4.35; 4.77] to 2.06 [1.81; 2.32] QuickDASH: 26.07 [24.59; 27.55] to 12.62 [11.08; 14.15] Adherence: 2.7 exercise frequency (1.5) (out of three sessions/week recommended) Satisfaction: 8.7/10 (1.6) Dropout rate: 16.9%	Significant within-group improvements in both pain and QuickDASH.	Lack of a control group	Industry sponsorship

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Mecklenburg et al. 2018, USA	RCT $n = 162$ (CG = 61, IG = 101)	Chronic knee pain	46 (12)	43%	Exercise, education, CBT, weight loss, and psychosocial support with a tablet app + motion sensors + access to treatment as usual; Tailored progression by a personal coach; Communication (text messages) and regular reminders to perform exercise sessions	Three educational pieces regarding self-care for chronic knee pain + access to treatment as usual	Intervention: 12 weeks Follow-up: 12 weeks	Primary outcomes: KOOS pain subscale; KOOS-PS scores at 12 weeks; Adherence: number of sessions performed per week	12 weeks: IG: KOOS pain 41.0 (14.1) to 30.3 (17.1) KOOS-PS: 53.8 (12.3) to 44.6 (16.7) Adherence: 2.5 exercise frequency (out of three minimum sessions/week recommended) Dropout rate: 20.8% CG: KOOS pain 41.4 (16.5) to 38.4 (17.2) KOOS-PS: 54.5 (15.7) to 52.5 (16.2) Dropout rate: 11.5%	The IG had a significantly greater improvement in KOOS pain and Function compared to the CG.	Participants and investigators were unblinded to group allocation	Industry sponsorship

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Sarig Bahat et al. 2017, Australia	RCT $n = 90$ (CG1 = 30, CG2 = 30, IG = 30)	Chronic neck pain	48	70.0%	Virtual reality-based exercise; Tailored progression; Scheduled communication	Laser-oriented exercises or waiting list control group	Intervention: 4 weeks Follow-up: 3 weeks	Primary outcome: NDI; Secondary outcome: VAS for pain; Adherence: number of sessions performed per week	4 weeks: IG: VAS pain: 47.79 (20.9) to 31.10 (23.6) NDI: 32.88 (12.5) to 23.75 (15.7) Adherence: 3.5 exercise frequency (out of four sessions/week prescribed) Dropout rate: 16.7% CG1 (laser training): VAS pain: 52.47 (19.5) to 35.97 (22.9) NDI: 32.19 (13.3) to 26.88 (14.0) Adherence: 4.5 exercise frequency (out of four sessions/week prescribed) Dropout rate: 13.3% CG2 (waiting list): VAS pain: 45.78 (21.5) to 39.45 (22.0) NDI: 24.72 (10.7) to 23.60 (11.8) Dropout rate: 16.7%	The IG had significantly better pain scores compared to the CG. No differences between groups were observed for NDI. Adherence was superior in the CG.	Participants and investigators were unblinded to group allocation; Presence of missing data	Government grant

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Shebib et al. 2019, USA	RCT *n* = 177 (CG = 64, IG = 113)	Chronic low back pain	43 (11)	41.0%	Exercise, education, CBT, weight loss, and psychosocial support with a tablet app + motion sensors + access to treatment as usual; Tailored progression by a personal coach; Communication on-demand	Three digital educational articles + access to treatment as usual	Intervention: 12 weeks Follow-up: 12 weeks	Primary outcomes: MvK pain; ODI and Korff disability; Adherence: number of sessions performed per week	12 weeks: IG: MvK: 51.1 (17.8) to 33.8 (21.6) ODI: 21.7 (12.1) to 17.6 (12) Adherence: 3.0 exercise frequency (out of three minimum sessions/week recommended) Dropout rate: 22.1% CG: MvK: 51.4 (17.4) to 50.5 (21.4) ODI: 21 (9.66) to 21.1 (11.2) Dropout rate: 3.1%	The IG had significant greater improvements in both pain and ODI compared to the CG.	Participants and investigators were unblinded to group allocation	Industry sponsorship

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
A. Wijnen et al. 2020, Netherlands	Non-RCT $n = 42$ (IG = 15; CG1 = 15; CG2 = 12)	After total hip arthroplasty	59.3	64.3%	Exercises with a web-based app + motion sensors; Tailored progression; Scheduled communication	Usual care with no specific intervention (both groups)	Intervention: 12 weeks Follow-up: 6 months	Primary outcome: not defined; HOOS	12 weeks: IG: HOOS pain: 48.9 (12.8) to 94.0 (3.4) HOOS function: 52.7 (17.5) to 92.8 (8.5) Dropout rate: 0% CG 1: HOOS pain: 35.5 (14.8) to 87.9 (10.7) HOOS function: 34.0 (10.2) to 79.0 (11.3) Dropout rate: 0% CG 2: HOOS pain: 36.3 (18.4) to 78.5 (16.6) HOOS function: 37.1 (19.1) to 69.7 (14.8) Dropout rate: 0%	The IG had slightly better scores on both HOOS pain and HOOS function scales compared to the control groups.	Potential for baseline confounding; Participants were unblinded to group allocation	University grant

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Eichler et al. 2019, Germany	RCT $n = 111$ (CG = 55, IG = 56)	After total hip or knee replacement	54.9 (6.7)	51.7%	Exercises with a minicomputer app; Tailored progression; On-demand communication	No study-specific treatment after inpatient rehabilitation	Intervention: 12 weeks Follow-up: 12 weeks	Primary outcome: not defined; WOMAC index; Adherence: percentage of participants performing the prescribed sessions	12 weeks: IG: WOMAC index: 26.4 (18.5) to 11.5 (12.7) Adherence: 80% of participants performed sessions until the 7th week of the program Dropout rate: 14.3% CG: WOMAC Index: 24.8 (16.4) to 13.9 (14.3) Dropout rate: 29.1%	No significant differences between groups were observed for the WOMAC index.	Participants and investigators were unblinded to group allocation; Presence of missing data	Insurance grant
W. D. Marley et al. 2022, UK	RCT n = 64 (CG = 33, IG = 31)	After arthroscopic shoulder surgery	53.7	59.4%	Exergames with a system prescribed by a physical therapist; Tailored progression; Communication only in the case of problems	Standard physical therapy (on a weekly basis during 12 weeks)	Intervention: 12 weeks Follow-up: 12 weeks	Primary outcome: active shoulder range of motion change between baseline and 12-weeks; DASH; OSS	12 weeks: IG: DASH: 42.9 to 23.7 OSS: 27.1 to 35.6 Dropout rate: 3.2% CG: DASH: 38.1 to 17.9 OSS: 29.1 to 37.6 Dropout rate: 3.0%	No significant differences between group were observed for both DASH and OSS.	Participants and investigators were unblinded to group allocation; Unclear if participant's allocation was concealed	Industry sponsorship and government grant

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
Prvu Bettger et al. 2020, USA	RCT *n* = 306 (CG = 153, IG = 153)	Total knee arthroplasty	65	63%	Exercise with a virtual telehealth system; Tailored progression; Scheduled and on-demand communication	Usual care	Intervention: 12 weeks Follow-up: 12 weeks	Primary outcome: healthcare costs at 12-weeks; Secondary outcome: KOOS; Adherence: percentage of participants completing all the prescribed exercises; Satisfaction: 0–10 scale (likelihood of referring the intervention program)	12 weeks: IG: KOOS pain: 46.6 (13.0) to 78.4 (14.0) KOOS function: 51.7 (16.7) to 82.7 (13.6) Adherence: 88.3% performed all exercises Satisfaction: 83.3% scored 9 or 10 Dropout rate: 1.4% CG: KOOS pain: 45.0 (16.3) to 76.7 (17.5) KOOS function: 50.0 (17.2) to 80.9 (17.7) Adherence: 65.4% performed all exercises Dropout rate: 0.7%	No significant differences between groups were observed for both KOOS pain and KOOS function scores. Adherence was significantly higher in the IG.	Participants and investigators were unblinded to group allocation; Unclear if participant's allocation was concealed	Industry sponsorship

(continued)

Table 2. Continued.

Author, year of publication and country	Study design and sample size	Condition	Age[a]	% of Females	Intervention	Control	Intervention and Follow-up length	Outcome measure(s)	Outcomes[a]	Results	Comments	Funding
B. Steiner et al. 2020, Germany	single-arm trial ($n = 12$)	chronic shoulder conditions	52.3	41.7%	Exercises delivered via a web interface; Tailored progression; Communication unidirectional (by telephone) on-demand	-	Intervention: 16 weeks (4 W in-facility and 12 W home-based) Follow-up: 16 weeks	Primary outcome: satisfying technical functionality and user acceptance; Secondary outcomes: SPADI; VAS for pain; Adherence: number of days performing exercise (65 total sessions were prescribed); Satisfaction: 5-point Likert scale (1, "very satisfied" to 5, "not satisfied")	12 weeks (after discharge): SPADI (patients achieving 11 points MCID): 5/6 (83.3%) Adherence: all participants performed ≥69.2% of the total prescribed exercise sessions Satisfaction: 3.45/5 (1.13) Dropout rate: 14.3%	Five of 12 participants showed clinically relevant improvements on SPADI.	Lack of a control group Baseline and post-intervention scores were not reported	Industry sponsorship

Abbreviations: CG, control group; DASH, disabilities of the arm, shoulder, and hand; HOOS, Hip Dysfunction and Osteoarthritis Outcome Score; IG, interventional group; KOOS, Knee injury and Osteoarthritis Outcome Score; KOOS-PS, Knee injury and Osteoarthritis Outcome Score for Physical Functioning short-form; MCID, Minimal Clinically Important Difference; MSK, musculoskeletal; MvK, modified von Korff; NDI, Neck Disability Index; NPRS, numerical pain rating scale; ODI, Oswestry Disability Index; OSS, Oxford Shoulder Score; QuickDASH, Quick Disabilities for the Arm, Shoulder and Hand; RCT, randomized controlled trial; ROM, range of motion; SPADI, Shoulder Pain and Disability Index; TKR, total knee replacement; THR, total hip replacement; VAS, visual analogue scale; WOMAC, Western Ontario and McMaster Universities Osteoarthritis.

[a]Reported by mean (SD), median (IQR), or mean (95% confidence interval).

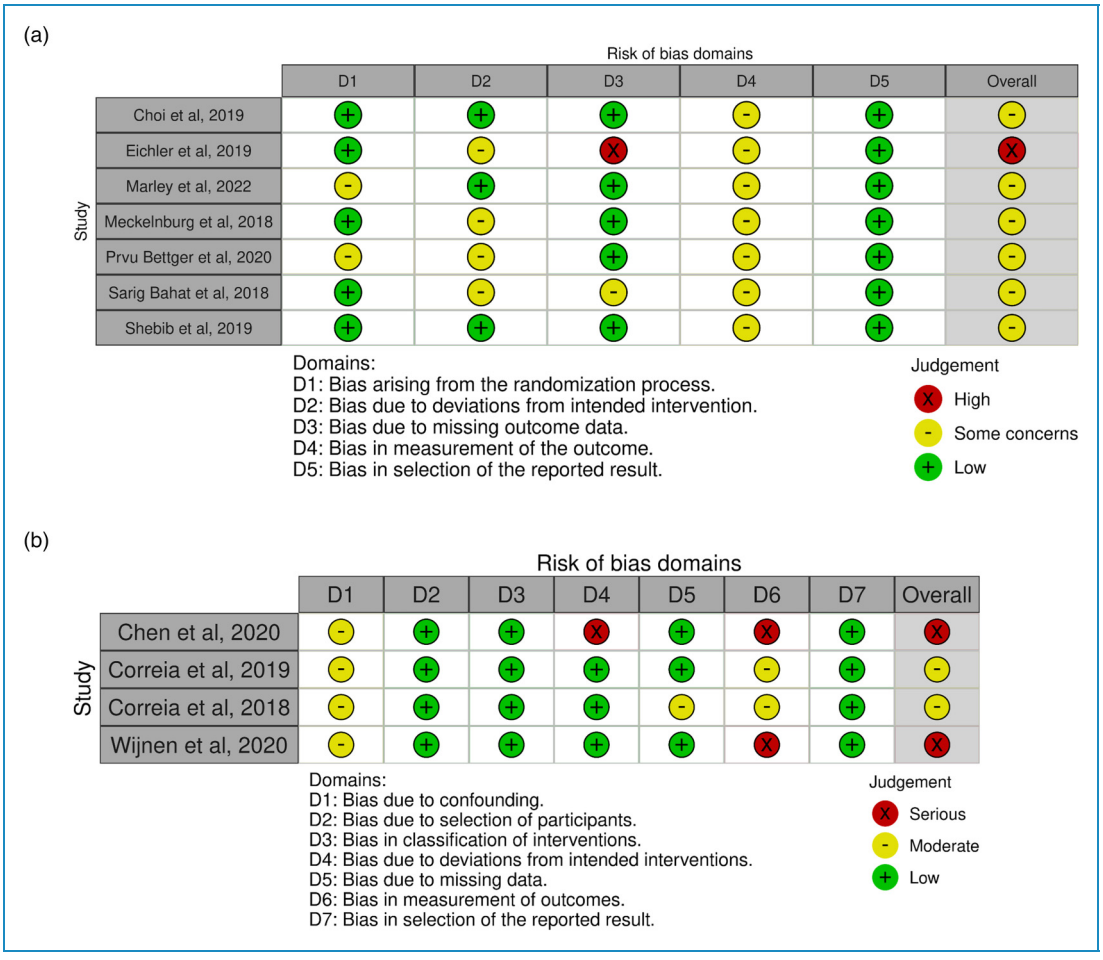

Figure 2. Risk of bias (ROB) assessment for (a) randomized trials (ROB 2.0) and (b) non-randomized trials. (ROBINS-I: ROB in non-randomized studies of interventions).

intervention group (7/11),[36,42–47] while the remaining four compared metrics between groups.[35,38,39,41] Satisfaction scores were provided by seven studies.[34–36,38,44,46,47]

All studies included some form of communication system between health professionals and patients, a majority (7/14) through scheduled contacts[35,36,38–40,46,47] and two focusing on ensuring adherence to exercise.[34,42] Three studies reported unidirectional communication (when the healthcare professionals decided it was needed),[37,41,44] while six also allowed the patients to reach out as needed.[35,36,38,43,45,46]

Methodological quality and risk of bias

The assessment of ROB for all studies is summarized in Figure 2. The main risks of bias found in the included studies were the lack of blinding in both participants and investigators, presence of missing data, and, in non-RCT, potential baseline confounding. It was also unclear if allocation was concealed in two RCTs.[37,38] From the included studies, nine were sponsored by industry.[35–38,42–44,46,47]

Evaluation of the included studies suggested high heterogeneity, mostly related to the diversity of included MSK conditions, the type of intervention, comparison groups, and outcome measures. Visual inspection of the forest plots, combined with the I^2 statistic (pain, 70%, $P < .0001$; function, 80%, $P < .0001$), confirmed this high heterogeneity,[22] precluding the performance of a meta-analysis.

Efficacy of the outcomes

The summary of findings and respective certainty of evidence are reported in Table 3. The reasons for downgrading the quality of evidence level are described in the table footnotes. Effect direction plots for pain and function are presented in Figure 3 to provide a visual display of the results.

Effect sizes were not calculated for three single-arm studies,[36,44,46] for one study that did not report sufficient outcome statistical data[37] and another study that did not report results for pain intensity and function individually,[45] in which these parameters could not be retrieved from the

Table 3. Summary of findings on pain and function outcomes.

Study		Sample size	Assessment time point	Comparison	Standardized mean difference (95% CI)	Risk of bias assessment	Overall certainty of evidence
Pain							
Inertial motion trackers biofeedback	Chen et al. 2020	14	12 weeks	Exercise instructions and education	1.37 (0.17, 2.58)	Serious	Low[a]
	Choi et al. 2019	84	12 weeks	Exercise instructions	0.19 (−0.24, 0.61)	Some concerns	
	Correia et al. 2019	66	8 weeks	In-person rehabilitation	0.28 (−0.21, 0.76)	Moderate	
	Correia et al. 2018	59	8 weeks	In-person rehabilitation	1.37 (0.80, 1.94)	Moderate	
	Mecklenburg et al. 2018	155	12 weeks	Education	0.47 (0.14, 0.81)	Some concerns	
	Sarig Bahat et al. 2017	60	4 weeks	Laser-oriented exercises	0.21 (−0.30, 0.72)	Some concerns	
	Shebib et al. 2019	177	12 weeks	Education	0.77 (0.46, 1.09)	Some concerns	
	Wijnen et al. 2020	27	12 weeks	Usual care	0.78 (−0.01, 1.58)	Serious	
Camera-based biofeedback	Prvu Bettger et al. 2017	280	12 weeks	Usual care	0.13 (−0.11, 0.36)	Some concerns	Very low[b]
Function							
Inertial motion trackers biofeedback	Chen et al. 2020	14	12 weeks	Exercise instructions and education	0.76 (−0.34, 1.86)	Serious	Low[a]
	Correia et al. 2019	66	8 weeks	In-person rehabilitation	1.17 (0.65, 1.70)	Moderate	
	Correia et al. 2018	69	8 weeks	In-person rehabilitation	1.45 (0.87, 2.03)	Moderate	
	Mecklenburg et al. 2018	155	12 weeks	Education	0.68 (0.34, 1.02)	Some concerns	
	Sarig Bahat et al. 2017	60	4 weeks	Laser-oriented exercises	0.21 (−0.30, 0.72)	Some concerns	
	Shebib et al. 2019	177	12 weeks	Education	0.30 (−0.01, 0.61)	Some concerns	

(continued)

Table 3. Continued.

Study		Sample size	Assessment time point	Comparison	Standardized mean difference (95% CI)	Risk of bias assessment	Overall certainty of evidence
	Wijnen et al. 2020	27	12 weeks	Usual care	1.36 (0.51, 2.22)	Serious	
Camera-based biofeedback	Prvu Bettger et al. 2017	280	12 weeks	Usual care	0.11 (−0.12, 0.35)	Some concerns	Very low[b]

GRADE working group grades of evidence:
High certainty: We are very confident that the true effect lies close to that of the estimate of the effect.
Moderate certainty: We are moderately confident in the effect estimate: The true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
Low certainty: Our confidence in the effect estimate is limited: The true effect may be substantially different from the estimate of the effect.
Very low certainty: We have very little confidence in the effect estimate: The true effect is likely to be substantially different from the estimate of effect.
[a]Downgraded one level due to high risk of bias in two non-RCT due to lack of concealment of allocation, deviations from intended interventions and in the measurement of outcomes, and one level for inconsistency ($I^2 > 50\%$ and $P < 0.1$)
[b]Downgraded two levels for indirectness and one level for publication bias.

authors. These studies were therefore not included in the "Summary of findings" table.

Telerehabilitation with inertial motion trackers biofeedback. Ten studies incorporated inertial motion trackers to provide biofeedback during exercise, including four RCTs,[34,39,42,43] four non-RCT,[35,40,41,47] and two single-arm interventional studies[36,46] (total patient sample size: $N =$ 1284). Intervention duration was similar across studies, ranging between 8 and 12 weeks, except for one study with a shorter treatment duration (4 weeks).[39]

Three non-RCT studies[35,40,47] focused on rehabilitation after **knee/hip arthroplasty**. Among these, two studies[35,47] included in-person exercise-based rehabilitation as comparison groups. These assessed the outcomes of a multimodal telerehabilitation comprising exercise, education, and cognitive behavioral therapy. One study ($N =$ 59)[35] found significantly superior outcomes for both pain and function in the digital group, while the other ($N =$ 66)[47] found differences between groups only for function (favoring telerehabilitation). For pain, the SMDs were 1.37 (95% CI: 0.80, 1.94) versus 0.28 (95% CI: −0.21, 0.76), respectively, while for function, the studies presented similar SMDs, 1.45 (95% CI: 0.87, 2.03), and 1.17 (95% CI: 0.65, 1.70), respectively. Both studies were appraised with moderate ROB, mainly related to the unblinding of participants and potential bias for baseline confounding. The third non-RCT study[40] only provided exercise in the telerehabilitation group, with no specific intervention in the two included control groups (recruited from different healthcare facilities). Slightly higher scores at post-intervention were observed in the digital group for both pain and function compared to controls. The effect size was calculated using data from the larger control group ($N = 30$), translating into an SMD of 0.75 (95% CI: 0.00, 1.49) for pain and 1.34 (95% CI: 0.54, 2.15) for function. This study was appraised with a high ROB due to potential baseline confounding and unblinding of participants to group allocation.

Chronic shoulder conditions were evaluated in three trials (one RCT, one non-RCT, and one single-arm study). Two studies[34,41] compared instructions for self-exercise to exercise-based telerehabilitation in participants with frozen shoulder. In an RCT conducted in 84 participants, Choi et al.[34] found no significant differences in pain between groups (SMD: 0.19; 95% CI: −0.24, 0.61), although there were some concerns regarding ROB mainly related to the unblinding of participants and investigators, and the unclear time frame for which the pain outcome was asked for participants (e.g., if related to the last 24 h or last 7 days). Function was not assessed in this study. In a small non-RCT ($N = 14$), Chen et al.[41] reported superior improvements for pain (SMD: 1.37; 95% CI: 0.17, 2.58) in the telerehabilitation group but similar improvements between groups for function (SMD: 0.76, 95% CI −0.35, 1.86). This study was appraised with serious ROB, as there was moderate risk of baseline confounding, possible deviations from intended interventions due to patient's adherence, and participants were unblinded. The single-arm study ($N =$ 296)[46] assessed a multimodal telerehabilitation intervention and presented significant within-group improvements for pain and function.

Two RCTs[42,43] compared a multimodal telerehabilitation program to education in patients with **chronic knee**[42] ($N = 162$) or chronic **low back pain**[43] ($N = 177$), with

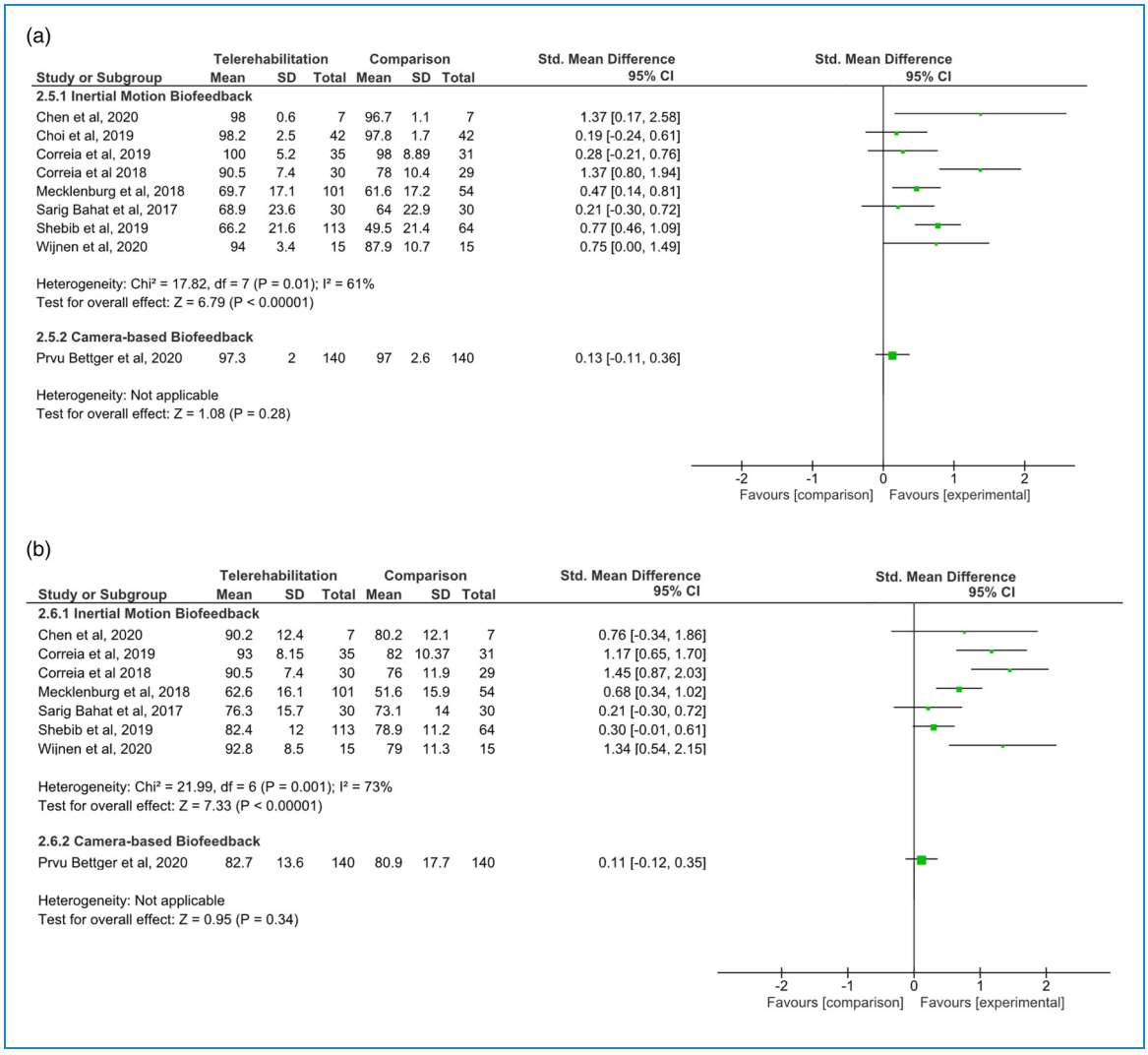

Figure 3. Effect direction plots. Telerehabilitation versus comparison groups with two sub-groups: inertial motion trackers biofeedback and camera-based biofeedback: (a) pain (b) function.

participants from both groups being allowed to access usual care. These studies reported greater improvements for both pain and function with telerehabilitation, presenting similar effect sizes for pain (SMD: 0.47, 95% CI: 0.14, 0.81 and SMD: 0.77, 95% CI: 0.46, 1.09), but different effects for function (SMD: 0.68; 95% CI: 0.34, 1.02 and SMD: 0.30; 95% CI: −0.01, 0.61), with the larger study finding a non-significant difference between groups. Both studies were rated with some concerns of ROB due to lack of blinding of participants and investigators.

An exercise-based intervention with virtual reality was investigated in an RCT composed of 90 participants with **chronic neck pain**.[39] This study included two control groups: an active control laser-oriented exercise intervention or a waiting list. Comparing the intervention group with the active comparator ($N = 60$), similar results were observed between groups for pain and function, presenting with equal effect sizes (SMD: 0.21; 95% CI: −0.30, 0.72 for both outcomes). This study presented some concerns of ROB due to participants and investigators unblinding and missing data.

The remaining study incorporating inertial motion trackers investigated a multimodal telerehabilitation approach in individuals with **acute MSK conditions.**[36] This was a single-arm study with a large sample size ($N = 343$) and found significant within-group improvements for pain.

Overall, no study found superior results for pain or function in any control group compared to telerehabilitation. These results suggest that telerehabilitation delivered through devices incorporating inertial motion trackers can yield similar or better results than other interventions in improving pain and function, albeit with a low certainty of evidence.

Telerehabilitation with camera-based biofeedback. Biofeedback-assisted telerehabilitation programs supported by camera vision were evaluated in four studies (three RCTs and one single-arm study, $N = 467$).

In a large RCT ($N = 280$), Bettger et al.[38] assessed an exercise-based telerehabilitation program **after knee arthroplasty** compared to usual care. No significant differences were observed between groups for pain (SMD: 0.13; 95% CI: −0.11, 0.36) or function (SMD: 0.11; 95% CI: −0.12, 0.35). This study was determined to contain some concerns of ROB: participants and investigators were unblinded, and it was unclear if participant's allocation was concealed. Another RCT[45] ($N = 111$) also assessed telerehabilitation based on exercise alone compared to no intervention and found no differences. However, this study did not report the results separately for pain and function.

The other RCT[37] compared an exercise program to standard physical therapy in 64 participants who underwent **shoulder arthroscopy**, reporting no significant differences in function between the two groups at 12 weeks. The SMD was not calculated for this study, and the study was rated as having some concerns of ROB, related to lack of blinding and uncertainty of allocation concealment.

Last, a small single-arm study[44] evaluated a telerehabilitation program based on exercise alone in 12 patients with **chronic shoulder conditions.** This study did not describe mean baseline or post-intervention function scores but reported that 83.3% of participants achieved a minimal clinically important difference.

Overall, whether camera-based telerehabilitation is effective in improving pain compared to other interventions remains uncertain due to the observed very low certainty of evidence.

Sensitivity analysis

In order to verify if conclusions were affected by study sponsorship, a sensitivity analysis was performed stratifying the analysis per industry sponsorship (Appendix 5). The reasons supporting the GRADE appraisal are reported in Appendix 6. GRADE appraisal showed that non-industry-sponsored studies provided very low certainty of evidence, while industry-sponsored studies provided low certainty of evidence for pain and function improvements after asynchronous telerehabilitation, which do not impact the conclusions reported previously.

Discussion

Principal findings

To our knowledge, this is the first systematic review evaluating the effectiveness of telerehabilitation incorporating biofeedback to enable asynchronous care in individuals presenting MSK conditions.

The research gathered in this systematic review suggests that asynchronous telerehabilitation with biofeedback provided by inertial motion trackers may be effective in improving pain and function compared to other interventions based on low certainty of evidence. A large majority of the included digital interventions were supported by wearable motion sensors composed of accelerometers and gyroscopes. Very low certainty of evidence was obtained for camera-based telerehabilitation interventions. Importantly, none of the included studies reported superior results of in-person care when compared to telerehabilitation.

Comparison with literature

Compared to face-to-face rehabilitation, remote synchronous care has been touted to be more affordable, accessible,[48,49] and as effective as in-person rehabilitation in several MSK conditions.[16,18,19,50] While these interventions are useful to mitigate geographic barriers, they may be insufficient to address time availability and scheduling constraints and do not take into account the shortage of human resources.[7,8] New care delivery models based on biofeedback-based asynchronous telerehabilitation have emerged with the ambition of being an alternative scalable solution to solve access constraints. However, to date, no systematic reviews have critically examined the potential of such interventions. The present systematic review reports similar findings to the previously reported in synchronous care, suggesting the effectiveness for improving pain and function of an asynchronous model.

Diverse MSK conditions were addressed in this systematic review, with almost all focused on chronic pain, except for one single-arm study targeting acute MSK conditions. Different results were observed depending on the chronic pain condition studied. For chronic knee and low back pain in particular, the results suggest better outcomes for pain after asynchronous telerehabilitation than usual care. This is consistent with findings of previous systematic reviews focusing on remote synchronous care.[15] Of note, a significant proportion of trials (43%, $N = 6/14$) were dedicated to post-surgical rehabilitation,[35,37,38,45,47] with results also indicating comparable outcomes in pain and function compared to in-person rehabilitation,[35,37,47] usual care,[38,40] or no intervention.[45] This is in line with results reported in a previous systematic review and meta-analysis,[19] which found no difference between technology-assisted rehabilitation and in-person physical therapy following total hip/knee replacement, although including studies where intervention group combined telerehabilitation with in-person treatment. This finding is particularly auspicious considering the potential of this modality as an alternative avenue to provide scalable and equitable care. It may decrease waiting time between discharge and the initiation of

outpatient rehabilitation, circumventing obstacles to access in-person care.

Technology in telerehabilitation

The digitalization of healthcare has been seen as a natural evolution of care delivery, considering that more than 63.5% of the global population now has internet access (Worldwide Digital Population as of October 2022[51]). Initial developments involved telemedicine through synchronous telehealth appointments. Yet, despite being helpful, this may be insufficient for growing needs as it lacks scalability.[52] Asynchronous telerehabilitation may unlock the potential of democratizing access to care by reaching historically underserved populations. The asynchronous telerehabilitation interventions herein leveraged different technologies to provide real-time biofeedback to patients, resulting in effective and clinically supported care delivery. Most evidence supporting the effectiveness of such interventions in MSK care was gathered with programs whose biofeedback was supported by wearable motion sensors composed of accelerometers and gyroscopes. Historically, these were first applied in this context, and therefore most of the advanced programs are currently supported by this type of technology.[35,42,43,47] Only four studies provided camera-based telerehabilitation, and these did not provide sufficient evidence regarding pain and disability.[37,38,44,45] The potential of camera-based solutions has been showcased in other industries,[53] so a beneficial application to healthcare delivery might become more evident with improved technology and implementation and further research.

Patient-centered care

Digital interventions may offer highly scalable solutions to deliver evidence-based interdisciplinary interventions,[54] improving continuity of care in cases where trained health professionals may not be readily available[52] and promoting adherence to treatment.[55,56] In line with a paradigm shift toward a biopsychosocial model, clinical guidelines increasingly recommend conservative multimodal interventions consisting not just a "one-size-fits-all" stand-alone exercise but also a tailored exercise program combined with patient education and behavior changes. The lack of adoption of multimodal interventions has been previously highlighted a shortcoming in care delivery.[57] In the present systematic review, less than half of the trials included multimodal digital programs ($N = 6$).[35,36,42,43,46,47] Although these studies provided some evidence for pain management effectiveness, more research is needed to better understand the impact of each intervention component on outcomes. To foster the adoption of patient-centered approaches, interventions must be tailored and continuously adapted to patient's goals and needs. In the present study, although most studies reported some tailoring of exercise programs, not all reported how the exercise protocol progression was administered.[34,37,40–42]

Therapeutic alliance

For patient–therapist interactions, compelling evidence has found that the therapeutic alliance (defined as the interaction between participants during the therapeutic process) can influence patient's adherence and treatment outcomes, with communication being a key factor.[58–60] The perception of impersonal care with telehealth has been a concern reported in previous published qualitative research embedded within clinical trials.[61] However, previous studies have challenged this notion with reports of patients stating that relationship with the healthcare provider was not affected with videoconferencing[62] and that the comfort of being at home may provide a more relaxed and personal encounter.[63] Elliott et al.[64] reported that communication, particularly the establishment of rapport and the development of patient-centered relationships, was frequently mentioned by highly satisfied patients with telemedicine. Improvements in communication channels (including simple phone calls, text messaging, emails, or videoconferencing) may provide easy access to healthcare professionals, and more timely feedback. This is particularly critical in asynchronous care, where communication needs to be more dynamic and interactive than with scheduled appointments. In the present systematic review, the great majority of studies reported some type of communication during interventions, through diverse strategies. Some interventions used a more simplistic approach, using communication channels solely for exercise reminders,[34,42] or as a tool available only to healthcare professionals (who would reach out to the patient as needed).[37,41,44] Others diversified and optimized communication channels, allowing bidirectional communication with patients.[35,36,38,43,45,46] However, very few details on these parameters were disclosed in the included trials, which is a gap that should be narrowed in future research.

Adherence and satisfaction

One of the major concerns in rehabilitation is patient adherence.[65–67] The reasons behind low adherence to rehabilitation interventions are multifactorial, including challenges in access (both geographical and time barriers), costs (e.g., travel costs, work time off, and potentially childcare costs), or, more recently, the perceived risk of contracting communicable infections. In patients prescribed home-based exercises, non-adherence is reported to be as high as 50%.[68] Reasons for this non-adherence levels include low self-efficacy and locus of control, patient beliefs, doubts regarding exercise execution, lack of feedback, and lack of accountability.[68]

Telerehabilitation, allied with the development of motion sensing technology, can bring important advantages in this field. Although all studies acknowledge the ability of telerehabilitation systems to register participants' exercise usability, only 11 studies provided metrics of adherence.[35,36,38,39,41–47] A wide variety of adherence metrics were reported in these studies, highlighting the lack of standardization. Nevertheless, overall adherence was high, as indicated by the volume of exercise completed being similar to that initially prescribed.[35,36,38,39,42–47] Future research and guidelines should seek to address the lack of consensus on proper outcome measures in this domain.

Satisfaction was assessed less frequently but, similarly to adherence, was high to very high for telerehabilitation in the seven studies in which it was measured.[34–36,38,44,46,47] This is in accordance with literature that reports patients' perception of telerehabilitation as generally positive,[16,69,70] with the provision of feedback being one of the most desirable features.[71,72]

Strengths, limitations, and future directions

This review has important strengths. To our knowledge, this is the first systematic review specifically focused on the effectiveness of asynchronous telerehabilitation incorporating biofeedback technology in the management of MSK conditions. The search gathered evidence from several MSK conditions, including post-surgical telerehabilitation.[35,37,38,40,45,47] The included trials were thoroughly assessed using validated reference-standard tools (i.e., the Cochrane ROB tool and GRADE approach), both for ROB and certainty of evidence appraisal. Communication with corresponding authors of the included trials was also conducted in cases where further details/data were needed.

However, this review also contains several limitations. A small number of RCTs were deemed eligible and three of the included studies had a high ROB.[40,41,45] There was high heterogeneity among the included trials including for conditions studies, interventions, and outcome measures, precluding the conduct of a meta-analysis.

To attenuate this limitation, a narrative synthesis based on calculated SMD was conducted, which improved the standardization of outcomes and decreased bias. Outcomes were assessed using patient-reported outcome measures. Although these can be prone to be influenced by subjective factors, an important outcome to assess on MSK rehabilitation is the impact of the condition on a patient's activities of daily living. Therefore, the evaluation of patients' perspectives about their condition is paramount, which can be conducted through patient-reported outcome measures.

Comparison groups were very heterogeneous, with only three studies[35,37,47] comparing telerehabilitation with similar interventions provided in-person, limiting the conclusions regarding equivalence or non-inferiority of this innovative approach. Further studies investigating the clinical outcomes compared to in-person rehabilitation are needed.

Patient adherence and satisfaction were addressed, but diverse metrics were used, which hinders rigorous appraisal. Standardization of these outcomes is required.

It is noteworthy that the most studied MSK conditions involved the hip, low back, or proximal joints. No study included patients with distal joints conditions, which warrants caution regarding generalization of findings.

Further rigorous clinical trials are warranted to draw conclusions based on more solid certainty, besides including long-term outcomes to evaluate the consistency of results. It also remains unclear which patients may benefit most from this treatment delivery and if there are clusters of patients in which these are not recommended. Identifying treatment responders is a priority for pain medicine and can favorably alter the risk:benefit ratio. Finally, the cost-effectiveness of asynchronous telerehabilitation with biofeedback was not ascertained in this review and should be explored in future research.

Conclusions

In conclusion, low to very low certainty of evidence suggests that exercise-based asynchronous telerehabilitation which incorporates motion sensors biofeedback technology is effective in improving pain and function in patients with MSK conditions. There is still insufficient evidence to evaluate the utility of telerehabilitation involving camera-based motion tracking. Considering the scalability of interventions with asynchronous care and the potential to democratize care accessibility and promote adherence, further research and development is warranted. Future studies should also address long-term outcomes and cost-effectiveness.

Contributorship: F.D.C., V.Y., and F.C. conceived the idea. D.J., F.C., and B.W. carried out the study selection, data extraction, data analysis, and manuscript drafting. D.J., F.C., F.D.C., V.Y., and S.C. contributed for interpretation of data. A.A., M.M., J.K.S., J.L., V.B., S.C., F.D.C., and V.Y. contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript.

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Ethical Approval: Institutional review board approval was not required as this article was a systematic review of the literature and not original research.

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Guarantor: V.Y.

Informed Consent: Patient consent was obtained in the studies included in this systematic review. No further consent was requested since this systematic review of the literature only used publicly available data.

Availability of Data: All relevant data is included in the review or available as supplementary material. Further data may be provided upon reasonable request to the corresponding author.

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Appendix 1. PRISMA checklist.

Section and topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	p. 1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for abstracts checklist.	p. 2–3
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	p. 3–5
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	p. 5
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	p. 6 and 7 and Table 1
Information sources	6	Specify all databases, registers, websites, organizations, reference lists, and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	p. 6
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	p. 6 and Appendix 2
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	p. 8
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	p. 8 and 9
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g., for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	p. 8 and 9
	10b	List and define all other variables for which data were sought (e.g., participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	p. 8 and 9
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	p. 9

(continued)

Appendix 1. Continued.

Section and topic	Item #	Checklist item	Location where item is reported
Effect measures	12	Specify for each outcome the effect measure(s) (e.g., risk ratio and mean difference) used in the synthesis or presentation of results.	p. 10
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g., tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	p. 9
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	p. 9 and 10
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	p. 10
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	p. 9
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g., subgroup analysis and meta-regression).	-
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	p. 10
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	p. 9
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	p. 9
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	p. 10 and Fig. 1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	p. 6
Study characteristics	17	Cite each included study and present its characteristics.	p. 11 and 12 and Table 2 and Appendix 3 and Appendix 4
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	p. 20 and Figure 2
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g., confidence/credible interval), ideally using structured tables or plots.	p. 23–26 and Table 3 and Figure 3

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Appendix 1. Continued.

Section and topic	Item #	Checklist item	Location where item is reported
Results of syntheses	20a	For each synthesis, briefly summarize the characteristics and risk of bias among contributing studies.	p. 23–26
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g., confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	p. 23–26 and Table 3 and Figure 3
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	-
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	p. 26 and 27 and Appendix 5 and Appendix 6
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	-
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	p. 25 and 26 and Table 3
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	p. 27–32
	23b	Discuss any limitations of the evidence included in the review.	p. 32 and 33
	23c	Discuss any limitations of the review processes used.	p. 32 and 33
	23d	Discuss implications of the results for practice, policy, and future research.	p. 32 and 33
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	p. 5
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	p. 5
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	-
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	p. 34
Competing interests	26	Declare any competing interests of review authors.	p. 35
Availability of data, code, and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms, data extracted from included studies, data used for all analyses, analytic code, and any other materials used in the review.	p. 35

Appendix 2: The search used for each of the databases searched.

PubMed search (using filters: species, humans; language, English; publication date, 1 January 2016 until 2 May 2022) *N* = 1271	Scopus search (using filters: publication date, published from 2016 until present; limit to language, English; source type, journal; document type, article) *N* = 2000
#1: "Musculoskeletal Diseases" [Mesh] OR "Musculoskeletal Pain" [Mesh] OR "Chronic Pain" [Mesh] OR "Low Back Pain" [Mesh] OR "Neck Pain" [Mesh] OR "Neuralgia" [Mesh] OR "Shoulder Pain" [Mesh] OR "musculo*" [Title/Abstract] OR "orthop*" [Title/Abstract] OR "pain" [Title/Abstract] OR "chronic pain" [Title/Abstract] OR (chronic[Title/Abstract] AND pain*[Title/Abstract]) OR "arthritis" [Title/Abstract] OR "osteoarthritis" [Title/Abstract] OR "low back" [Title/Abstract] OR "hip" [Title/Abstract] OR "knee" [Title/Abstract] OR "ankle" [Title/Abstract] OR "shoulder" [Title/Abstract] OR "back" [Title/Abstract] OR "backache" [Title/Abstract] OR "neck" [Title/Abstract] or "cervical" [Title/Abstract] OR "spine" [Title/Abstract] OR "elbow" [Title/Abstract] OR "wrist" [Title/Abstract] OR "hand" [Title/Abstract] #2: "Telemedicine" [Mesh] OR "Telerehabilitation" [Mesh] OR "Mobile Applications" [Mesh] OR tele*[Title/Abstract] OR ehealth*[Title/Abstract] OR "e-health" [Title/Abstract] OR e-health[Title/Abstract] OR m-health*[Title/Abstract] OR "mhealth*" [Title/Abstract] OR remote[Title/Abstract] OR "web-based*" [Title/Abstract] OR "mobile health" [Title/Abstract] OR smartphone*[Title/Abstract] OR "mobile phone*" [Title/Abstract] OR "virtual reality" [Title/Abstract] OR "videoconferenc*" [Title/Abstract] OR "video conferenc*" [Title/Abstract] #3: "Rehabilitation" [Mesh] OR "Physical Therapy Modalities" [Mesh] OR "Exercise Movement Techniques" [Mesh] OR "Exercise Therapy" [Mesh] OR "Exercise" [Mesh] OR "physiotherap*" [Title/Abstract] OR "physical therap*" [Title/Abstract] OR "rehab*" [Title/Abstract] OR "exercise*" [Title/Abstract] OR "movement" [Title/Abstract] OR "physical activity" [Title/Abstract] OR "nonpharmacologic*" [Title/Abstract] OR "non-pharmacologic*" [Title/Abstract] OR "pain management" [Title/Abstract] OR "self-management" [Title/Abstract] #4: "Clinical Trial" [Publication Type] OR "Controlled Clinical Trial" [Publication Type] OR "Randomized Controlled Trial" [Publication Type] OR "Random Allocation" [Mesh] OR random*[Title/Abstract] OR "controlled trial*" [Title/Abstract] OR "clinical trial" [Title/Abstract] OR "controlled clinical trial" [Title/Abstract] OR RCT[Title/Abstract] OR RCTs[Title/Abstract] OR trial[Title/Abstract] OR "interventional" [Title/Abstract] #5: #1 AND #2 AND #3 AND #4	#1: TITLE-ABS-KEY("musculo*" OR "orthop*" OR "pain" OR "chronic pain" OR (chronic AND pain*) OR "arthritis" OR "osteoarthritis" OR "low back" OR "hip" OR "knee" OR "ankle" OR "shoulder" OR "back" OR "backache" OR "neck" or "cervical" OR "spine" OR "elbow" OR "wrist" OR "hand") #2: TITLE-ABS-KEY(tele* OR internet* OR ehealth* OR "e-health" OR m-health* OR mhealth* OR remote OR "web-based*" OR "mobile health" OR smartphone* OR "mobile phone*" OR "virtual reality" OR "videoconferenc*" OR "video conferenc*") #3: TITLE-ABS-KEY("physiotherap*" OR "physical therap*" OR "rehab*" OR "exercise*" OR "physical activity" OR "nonpharmacologic*" OR "non-pharmacologic*" OR "pain management" OR "self-management") #4: TITLE-ABS-KEY(random* OR "controlled trial*" OR "controlled clinical trial" OR "clinical trial" OR RCT OR RCTs OR trial OR "interventional") #5: #1 AND #2 AND #3 AND #4

PEDro database (*N* = 464):
The Abstract and Title field was searched for combinations for each of the following terms from two concepts, combining separately each keyword from the first concept group with those in the second concept group:
physiotherap* OR "physical therapy" OR exercise* OR self-management
AND
telerehab* OR remote* OR internet* OR digital* OR "virtual reality"
For example: physiotherap* telerehab*
Method: clinical trial
Published Since: 2016

Appendix 3. Description of the intervention of the included studies.

Author, year of publication	Intervention
Inertial motion sensor-based interventions	
Y. P. Chen et al., 2020	Shoulder exercises were provided by a mobile app (Patient App) with wearable inertial measurement units sensors and screen by an avatar. A set of exercises was prescribed daily, with tailored adjustments by a supervising physical therapist or physician. A mobile app (Doctor App) was also available for physical therapists and physicians, providing patient's information (range of motion measurements and exercise completion rates). Unidirectional communication by health professionals through text messages through the app.
Y. Choi et al., 2019	Assistive passive shoulder (flexion, cross-body adduction, and sleeper stretch) exercises using a smartphone application with built-in motion sensors, providing real-time visual and auditory feedback. The application included alarm reminders. Communication by a clinical assistant focusing on remembering exercise sessions.
Correia et al., 2019	Exercise, education, and Cognitive Behavioral Therapy through a mobile app with a digital biofeedback system with wearable inertial measurement units sensors, under asynchronous remote monitoring from a physical therapist. Exercises encompass mobility, strengthening, and balance. Tailored progressions were performed by the physical therapist, based on patient performance and self-reported pain and fatigue. Bidirectional scheduled communication was included to check on patient adaptation, review the program, and assess adverse events.
Correia et al., 2018	Exercise, education and CBT through a mobile app with a digital biofeedback system with wearable inertial measurement units sensors, under asynchronous remote monitoring from a physical therapist. Exercises encompass mobility, strengthening, and balance. Tailored progressions were performed by a physical therapist, based on patient performance and self-reported pain and fatigue. Bidirectional scheduled and on-demand communication was included.
Costa et al., 2022	Exercise, education, and CBT through a mobile app with a digital biofeedback system with wearable inertial measurement units sensors, under asynchronous remote monitoring from a physical therapist. Tailored progressions were performed by a physical therapist, according to patients' condition. Bidirectional scheduled and on-demand communication was included through a dedicated smartphone app or calls.
Janela et al., 2022	Exercise, education, and CBT through a mobile app with a digital biofeedback system with wearable inertial measurement units sensors, under asynchronous remote monitoring from a physical therapist. Tailored progressions were performed by the physical therapist, according to patients' condition. Bidirectional scheduled and on-demand communication was included through a dedicated smartphone app or calls.
Mecklenburg et al., 2018	Exercise, education, CBT, weight loss, and psychosocial support through a personal coach and team-based interactions, performed in a tablet app with wearable motion sensors. Access to treatment as usual was maintained. Exercise targeted stretching and strengthening, with tailored progression by a personal coach. Communication through text messages and reminders were sent to participants not engaging with the program. Participants were also able to communicate with the personal coach.
Sarig Bahat et al., 2017	Virtual reality-based exercise with an illustrated handout of the exercises and ways to progress provided to participants, including range of motion (ROM) and velocity and accuracy modules. Tailored progression of exercises was performed by a physical therapist. Scheduled communication by a physical therapist was included.

(continued)

Appendix 3. Continued.

Author, year of publication	Intervention
Shebib et al., 2019	Exercise therapy, education, CBT, and recommendation for aerobic activities, through a personal coach performed in a tablet app with wearable motion sensors. Access to treatment as usual was maintained. Included tailored progression by a personal coach. Bidirectional scheduled communication was included through text or call.
A. Wijnen et al., 2020	Exercises were performed through a tablet for instructions, provided by means of a web-based app with motion sensors. The program encompasses strengthening and walking exercises. Tailored progression on the exercises was performed by a physical therapist. Scheduled communication was included by weekly telephone support from a physical therapist.
Camera-based interventions	
Eichler et al., 2019	Exercises through a system including an application installed in a minicomputer with internet access paired with Kinect sensors (camera) and screened by an avatar. Exercises targeted strength and postural control. Tailored progression was performed by a supervising therapist. Bidirectional on-demand communication was included.
W. D. Marley et al., 2022	Exergames (exercises incorporated in games), targeting mobility, control, activation of the kinetic chain, arm velocity, and strength. Exercises were performed using the MIRA system with real-time biofeedback by Kinect sensors (camera) with visual display. Intervention tailoring was performed by a physical therapist, specifically in terms of duration and difficulty according to patients' ability. Remote monitoring was possible through an online portal, with weekly revisions on patient's performance and respective exercise adjustments. Unidirectional communication occurred only in the case of problems.
Prvu Bettger et al., 2020	Exercise through a virtual telehealth system with motion tracking technology (camera) with avatar display, under remote monitoring of a physical therapist. Exercises were tailored by a physical therapist. Patients were able to receive in-person physical therapy as clinically deemed necessary. Regular scheduled communication (weekly virtual video calls) and on-demand with an assigned physical therapist were included.
B. Steiner et al., 2020	Individually adapted home-based exercises delivered via the AGTRehaCare Web interface with depth camera-based biofeedback (marker-less tracking system). Exercises were tailored for each patient during the intervention. Unidirectional communication by the physical therapist (by telephone) was performed when needed.

Appendix 4. Adverse events and reasons for dropouts.

Author, year of publication	Description
Inertial motion sensor-based interventions	
Y. P. Chen et al., 2020	AE IG: 1 patient with progressive shoulder pain and weakness 1 month after rehabilitation (diagnosed with full-thickness rotator cuff tear) CG: no AE
	Dropout reasons: no dropouts
Y. Choi et al., 2019	AE: did not report
	Dropout reasons: no dropouts
Correia et al., 2019	AE IG: three patients developed pain during hip abduction (spontaneous recovery after 2 weeks); one patient with inflammatory signs in the surgical wound; one patient had a fall (not related to the intervention and no need of hospital assistance). CG: one patient had a surgical wound infection (with hospital readmission and procedure revision); one patient developed groin pain; two patients with inflammatory signs in the surgical wound; one patient had a thrombophlebitis; one patient with unilateral lower limb edema (spontaneous recovery); one patient had a fall (no need of hospital assistance) (no statistically significant differences between groups).
	Dropout reasons IG: three patients were excluded due to developing pain during hip abduction; two patients did not adapt to the intervention. CG: two patients were excluded due to hospital readmission for a surgical wound infection and due to developing groin pain.
Correia et al., 2018	AE IG: one patient had a thrombophlebitis CG: one patient had a thrombophlebitis; one patient had a surgical wound infection (with hospital readmission and procedure revision); one patient with alcohol abuse; three patients with inflammatory signs in the surgical wound (no differences between groups).
	Dropout reasons IG: seven patients withdrew consent; one patient was excluded due to attending additional physical therapy outside the study. CG: two patients were excluded due to hospital readmission for a surgical wound infection and due to alcohol abuse.
Costa et al., 2022	AE: did not report
	Dropout reasons: 29 patients with low compliance, 3 patients referred for conventional physical therapy, 9 patients with other reasons
Janela et al., 2022	AE: did not report
	Dropout reasons: 42 patients with low compliance, 8 patients with other reasons

(continued)

Appendix 4. Continued.

Author, year of publication	Description
Mecklenburg et al., 2018	AE: did not report
	Dropout reasons IG: 14 patients did not respond to invitation; 1 patient had an accident; 6 patients due to personal reasons (time constraints or stress at work). CG: 7 patients entered the IG due to an administrative error.
Sarig Bahat et al., 2017	AE IG: five patients with virtual reality-associated side effects (sickness) and headache.
	Dropout reasons IG: three patients with virtual-reality side effects; one patient due to pain; one patient due to time CG1 (laser training group): one patient due to sickness with hospital admission; one patient due to headache from exercises; two patients due to time CG2 (waiting list): one patient due to side effects; four patients due to time
Shebib et al., 2019	AE: did not report
	Dropout reasons IG: 4 patients were unresponsive; 1 patient had unrelated surgery before study start; 17 patients did not respond to invitation CG: one patient entered the IG due to an administrative error; one patient discontinued intervention due to back surgery
A. Wijnen et al., 2020	AE: did not report
	Dropout reasons: no dropouts
Camera-based interventions	
Eichler et al., 2019	AE: did not report
	Dropout reasons IG: seven patients due to personal reasons; one patient due to medical reasons CG: ten patients due to personal reasons; five patients due to medical reasons; one patient discontinued intervention
W. D. Marley et al. 2022	AE IG: one patient developed biceps pain following shoulder surgery (had an injection; not related to the study intervention). CG: one patient with post-operative pain and stiffness
	Dropout reasons IG: one patient was lost to follow-up CG: one patient withdrew from the study

(continued)

Appendix 4. Continued.

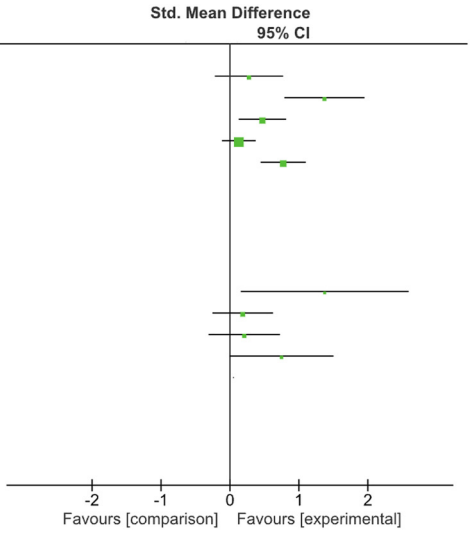
Author, year of publication	Description
Prvu Bettger et al., 2020	AE IG: 12 patients had rehospitalizations in 12 weeks; 27/139 patients had a fall. CG: 30 patients had rehospitalizations in 12 weeks; 20/137 patients had a fall. (the difference on the number of rehospitalizations between groups was statistically significant; the difference on falls was not significant).
	Dropout reasons IG: two patients withdrew from the study. CG: one patient withdrew from the study.
B. Steiner et al., 2020	AE: did not report
	Dropout reasons: two patients were excluded retrospectively as they underwent additional clinical exercise in parallel to the study.

Abbreviation: AE, adverse events.

Appendix 5. Sensitivity analysis: effect direction plots.

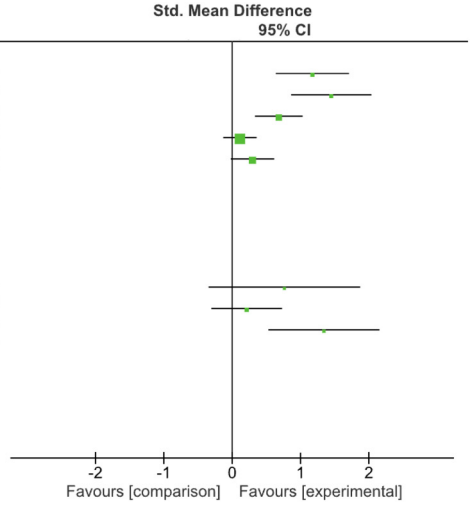
A. Telerehabilitation versus comparison groups with two sub-groups: industry-sponsored and non-industry-sponsored; outcome, pain.

Study or Subgroup	Telerehabilitation Mean	SD	Total	Comparison Mean	SD	Total	Std. Mean Difference 95% CI
2.8.1 Industry sponsorship							
Correia et al, 2019	100	5.2	35	98	8.89	31	0.28 [-0.21, 0.76]
Correia et al 2018	90.5	7.4	30	78	10.4	29	1.37 [0.80, 1.94]
Mecklenburg et al, 2018	69.7	17.1	101	61.6	17.2	54	0.47 [0.14, 0.81]
Prvu Bettger et al, 2020	97.3	2	140	97	2.6	140	0.13 [-0.11, 0.36]
Shebib et al, 2019	66.2	21.6	113	49.5	21.4	64	0.77 [0.46, 1.09]
Heterogeneity: Chi² = 21.65, df = 4 (P = 0.0002); I² = 82%							
Test for overall effect: Z = 5.77 (P < 0.00001)							
2.8.2 No industry sponsorship							
Chen et al, 2020	98	0.6	7	96.7	1.1	7	1.37 [0.17, 2.58]
Choi et al, 2019	98.2	2.5	42	97.8	1.7	42	0.19 [-0.24, 0.61]
Sarig Bahat et al, 2017	68.9	23.6	30	64	22.9	30	0.21 [-0.30, 0.72]
Wijnen et al, 2020	94	3.4	15	87.9	10.7	15	0.75 [0.00, 1.49]
Heterogeneity: Chi² = 4.73, df = 3 (P = 0.19); I² = 37%							
Test for overall effect: Z = 2.34 (P = 0.02)							



B. Telerehabilitation versus comparison groups with two sub-groups: industry-sponsored and non-industry-sponsored; outcome, function.

Study or Subgroup	Telerehabilitation Mean	SD	Total	Comparison Mean	SD	Total	Std. Mean Difference 95% CI
2.9.1 Industry sponsorship							
Correia et al, 2019	93	8.15	35	82	10.37	31	1.17 [0.65, 1.70]
Correia et al 2018	90.5	7.4	30	76	11.9	29	1.45 [0.87, 2.03]
Mecklenburg et al, 2018	62.6	16.1	101	51.6	15.9	54	0.68 [0.34, 1.02]
Prvu Bettger et al, 2020	82.7	13.6	140	80.9	17.7	140	0.11 [-0.12, 0.35]
Shebib et al, 2019	82.4	12	113	78.9	11.2	64	0.30 [-0.01, 0.61]
Heterogeneity: Chi² = 29.44, df = 4 (P < 0.00001); I² = 86%							
Test for overall effect: Z = 5.83 (P < 0.00001)							
2.9.2 No industry sponsorship							
Chen et al, 2020	90.2	12.4	7	80.2	12.1	7	0.76 [-0.34, 1.86]
Sarig Bahat et al, 2017	76.3	15.7	30	73.1	14	30	0.21 [-0.30, 0.72]
Wijnen et al, 2020	92.8	8.5	15	79	11.3	15	1.34 [0.54, 2.15]
Heterogeneity: Chi² = 5.58, df = 2 (P = 0.06); I² = 64%							
Test for overall effect: Z = 2.77 (P = 0.006)							



Appendix 6. Sensitivity analysis: GRADE appraisal.

Study		Sample size	Assessment time point	Comparison	Standardized mean difference (95% CI)	Risk of bias assessment	Overall certainty of evidence	Reasons for downgrade
Pain								
Industry sponsorship	Correia et al. 2019	66	8 weeks	In-person rehabilitation	0.28 (−0.21, 0.76)	Moderate	Low	Inconsistency due to high heterogeneity (one level); indirectness (half level); publication bias (half level)
	Correia et al. 2018	59	8 weeks	In-person rehabilitation	1.37 (0.80, 1.94)	Moderate		
	Mecklenburg et al. 2018	155	12 weeks	Education	0.47 (0.14, 0.81)	Some concerns		
	Prvu Bettger et al. 2017	280	12 weeks	Usual care	0.13 (−0.11, 0.36)	Some concerns		
	Shebib et al. 2019	177	12 weeks	Education	0.77 (0.46, 1.09)	Some concerns		
Non-industry sponsorship	Chen et al. 2020	14	12 weeks	Exercise instructions and education	1.37 (0.17, 2.58)	Serious	Very Low	Serious risk of bias in two studies (two levels); indirectness (half level); imprecision due to sample size (one level)
	Choi et al. 2019	84	12 weeks	Exercise instructions	0.19 (−0.24, 0.61)	Some concerns		
	Sarig Bahat et al. 2017	60	4 weeks	Laser-oriented exercises	0.21 (−0.30, 0.72)	Some concerns		
	Wijnen et al. 2020	27	12 weeks	Usual care	0.78 (−0.01, 1.58)	Serious		
Function								

(continued)

Appendix 6. Continued.

Study		Sample size	Assessment time point	Comparison	Standardized mean difference (95% CI)	Risk of bias assessment	Overall certainty of evidence	Reasons for downgrade
Industry sponsorship	Correia et al. 2019	66	8 weeks	In-person rehabilitation	1.17 (0.65, 1.70)	Moderate	Low	Inconsistency due to high heterogeneity (one level); indirectness (half level); publication bias (half level)
	Correia et al. 2018	69	8 weeks	In-person rehabilitation	1.45 (0.87, 2.03)	Moderate		
	Mecklenburg et al. 2018	155	12 weeks	Education	0.68 (0.34, 1.02)	Some concerns		
	Prvu Bettger et al. 2017	280	12 weeks	Usual care	0.11 (−0.12, 0.35)	Some concerns		
	Shebib et al. 2019	177	12 weeks	Education	0.30 (−0.01, 0.61)	Some concerns		
Non-industry sponsorship	Chen et al. 2020	14	12 weeks	Exercise instructions and education	0.76 (−0.34, 1.86)	Serious	Very Low	Serious risk of bias in two studies (two levels); inconsistency due to high heterogeneity (one level); indirectness (half level); imprecision due to sample size (one level)
	Sarig Bahat et al. 2017	60	4 weeks	Laser-oriented exercises	0.21 (−0.30, 0.72)	Some concerns		
	Wijnen et al. 2020	27	12 weeks	Usual care	1.36 (0.51, 2.22)	Serious		

GRADE working group grades of evidence:
High certainty: We are very confident that the true effect lies close to that of the estimate of the effect.
Moderate certainty: We are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
Low certainty: Our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect.
Very low certainty: We have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect.