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# AI-Driven Digital Rehabilitation Versus Supervised Physiotherapy Following Total Knee Arthroplasty: Evidence from Randomized Controlled Trials

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## ABSTRACT

**Background:** Supervised physiotherapy after total knee arthroplasty (TKA) is limited by access, cost and adherence. Artificial intelligence (AI)-driven digital rehabilitation systems, which analyze movement and give real-time feedback at home, may extend structured rehabilitation beyond the clinic. This review compared AI-driven digital rehabilitation with supervised physiotherapy after TKA.

**Methods:** PubMed/MEDLINE, Embase, Scopus, Web of Science, CENTRAL, CINAHL, PEDro, IEEE Xplore, ClinicalTrials.gov and the WHO ICTRP were searched from inception to August 2026. Randomized controlled trials (RCTs) in adults after primary TKA comparing AI-driven rehabilitation (automated movement analysis with feedback, algorithm-driven progression or a virtual coach) with supervised physiotherapy or unsupervised home exercise were eligible. Two reviewers independently screened records, extracted data and assessed risk of bias with RoB 2. Narrative synthesis followed SWiM; certainty was rated with GRADE.

**Results:** Seven RCTs (2020–2025; 726 participants) were included: four compared AI-driven rehabilitation with supervised physiotherapy and three with unsupervised home exercise. Against supervised physiotherapy, knee function and range of motion did not differ in any trial, and pain was similar in three trials, while one small pilot reported higher pain with the sensor system. Both non-inferiority trials met their margins, and the largest trial (n = 306) reported lower 12-week healthcare costs (median $1,050 vs $2,805) and fewer rehospitalizations. Against unsupervised exercise, one trial found no difference and two favored the intervention. No trial was at low risk of bias; three had some concerns, three were at high risk and one could not be assessed. Certainty was low versus supervised physiotherapy and very low versus unsupervised exercise.

**Conclusion:** AI-driven digital rehabilitation may produce similar short-term recovery to supervised physiotherapy after TKA at lower cost, but its benefit over unsupervised home exercise is very uncertain. Larger, rigorously designed trials with longer follow-up and full economic evaluation are needed.

**Keywords:** *Arthroplasty; Artificial Intelligence; Knee; Physical Therapy; Telerehabilitation*

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## INTRODUCTION

Total knee arthroplasty (TKA) is the definitive surgical treatment for end-stage knee osteoarthritis and one of the most frequently performed orthopedic procedures worldwide. Demand continues to grow, and in the United States the annual number of primary TKAs among Medicare patients is projected to more than double by 2040[1]. TKA reliably reduces pain and corrects deformity, but surgical success does not guarantee a good functional result. About one in eight patients still report unfavorable pain one to two years after surgery[2], and around one in ten remain dissatisfied with the outcome[3]. Postoperative rehabilitation is therefore a central part of recovery, and clinical practice guidelines recommend structured, progressive exercise to restore knee range of motion, quadriceps strength and functional mobility[4].

Despite its importance, conventional supervised physiotherapy after TKA has well-recognized limitations. Access to outpatient services is constrained by travel distance, cost, therapist availability and shorter hospital stays.

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Rehabilitation content, dosage and progression also vary widely between settings and are often poorly reported[5]. Many patients are discharged to unsupervised home exercise programs, where exercise quality cannot be monitored or corrected and adherence is difficult to sustain beyond the short term, even with digital support[6]. These gaps have encouraged interest in technology-enabled models that can extend structured rehabilitation beyond the clinic.

Recent advances in digital health have produced a new generation of artificial intelligence (AI)-driven rehabilitation systems. These platforms combine wearable inertial sensors, camera-based motion tracking or augmented-reality interfaces with algorithms that analyze movement in real time. They give the patient immediate corrective feedback and adapt the program to their progress, while clinicians monitor recovery remotely[7]. Several randomized controlled trials (RCTs) have tested such systems after TKA. A large multicenter trial found that a virtual exercise system with three-dimensional motion tracking was non-inferior to traditional physiotherapy and reduced healthcare costs[8], and an AI-powered biofeedback system with inertial sensors produced favorable short- and medium-term outcomes compared with face-to-face home rehabilitation in a non-randomized study[9]. Other trials have shown that augmented-reality and smartphone-based systems with real-time feedback achieve outcomes comparable to conventional programs[10,11].

Several systematic reviews have examined this field, but they have pooled technologies that differ substantially in their mechanism of action. Earlier reviews assessed telerehabilitation broadly, including videoconference-based therapy[12], or focused only on mobile applications[13]. A recent meta-analysis of smart device-assisted telerehabilitation pooled 22 RCTs involving 2,181 participants and found no significant overall difference from conventional rehabilitation in pain or WOMAC scores, although augmented- and virtual-reality subgroups showed benefits in specific domains[14]. A separate meta-analysis of eight app-based trials (694 patients) reported better pain, mobility performance and early range of motion, but rated the certainty of evidence as low to moderate[15], and the most recent review of 23 trials of interactive remote rehabilitation found no consistent superiority over conventional care[16]. These reviews grouped AI-driven systems together with simple video-guided apps, virtual-reality games and telephone or video consultations, and combined supervised and unsupervised control groups. This heterogeneity may have obscured the specific contribution of intelligent, real-time feedback. In addition, adherence, patient satisfaction, safety and cost have received limited attention.

We therefore conducted this systematic review to synthesize the evidence from RCTs that evaluated AI-driven digital rehabilitation specifically. Our question was: in adults after primary TKA, is AI-driven digital rehabilitation as effective as supervised physiotherapy? We aimed to (i) compare the effectiveness of AI-driven digital rehabilitation with supervised physiotherapy on pain, knee function, range of motion and physical performance; (ii) evaluate adherence, patient satisfaction, safety and healthcare resource use; and (iii) appraise the methodological quality and certainty of the available evidence. The review is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement[17].

## METHODOLOGY

### *Protocol and Reporting*

The review was conducted in accordance with the Cochrane Handbook for Systematic Reviews of Interventions[18] and reported according to the PRISMA 2020 statement[17]. The narrative synthesis was reported following the Synthesis Without Meta-analysis (SWiM) guideline[19]. The review question, eligibility criteria, outcomes, risk-of-bias approach and synthesis plan were agreed before the search began. The protocol was not registered in PROSPERO or any other registry. Ethical approval was not required because only published data were used.

### *Review Question and Eligibility Criteria*

The review question was framed with the PICOS (Population, Intervention, Comparator, Outcomes, Study design) framework: *in adults after primary TKA, is AI-driven digital rehabilitation as effective as supervised physiotherapy for pain, function and range of motion?* Eligibility criteria are summarized in (Table 1).

**Table 1. Eligibility criteria (PICOS)**

| Element | Inclusion | Exclusion |
|---|---|---|
| **Population** | Adults (≥ 18 years) who underwent primary unilateral or bilateral TKA for knee osteoarthritis, regardless of sex, ethnicity, comorbidity or surgical approach. | Revision TKA, unicompartmental knee arthroplasty, arthroplasty for fracture or tumor; mixed hip and knee samples unless TKA data were reported separately. |
| **Intervention** | AI-driven digital rehabilitation containing at least one of: (a) automated capture of movement (inertial sensors, depth or RGB cameras, computer vision) with algorithmic analysis generating real-time corrective feedback; (b) algorithm-driven adaptation of exercise dose or progression; (c) a machine-learning-based or rule-based virtual coach. Home- or clinic-based, with or without remote clinician oversight. | Videoconference-only telerehabilitation; apps delivering only exercise videos, written instructions or reminders without movement analysis; robotic devices, continuous passive motion, neuromuscular electrical stimulation and exoskeletons; virtual-reality gaming without automated performance feedback. |
| **Comparator** | Primary: supervised physiotherapy delivered in person by a physiotherapist (inpatient, outpatient or home visits). Secondary: unsupervised usual-care home exercise (e.g., brochure-based), synthesized as a separate comparison. | No control group; both groups receiving an AI-driven intervention; no rehabilitation in the control group. |
| **Outcomes** | Primary: pain (VAS, NRS); patient-reported knee function (WOMAC, KOOS/KOOS-JR, Oxford Knee Score); knee range of motion (goniometer or validated sensor). Secondary: physical performance (TUG, gait speed, 6MWT, 30-s chair stand); muscle strength; health-related quality of life (EQ-5D, SF-36/12); adherence; satisfaction; adverse events; healthcare resource use and costs. Time points: short-term (≤ 6 weeks), medium-term (> 6 weeks to 3 months), long-term (> 3 months). | Usability or technical accuracy only, with no clinical outcome. |
| **Study design** | Randomized controlled trials, including pilot, feasibility and non-inferiority RCTs. | Quasi-experimental, non-randomized, observational and crossover designs; protocols, reviews, case reports and conference abstracts without a full-text report. |
| **Other** | Full-text articles in any language, published from database inception to the search date. | Duplicate publications of the same trial (the most complete report was retained). |

### *Information sources and search strategy*

PubMed/MEDLINE, Embase (Ovid), Scopus, Web of Science Core Collection, the Cochrane Central Register of Controlled Trials (CENTRAL), CINAHL, PEDro and IEEE Xplore were searched from inception to August 2026. IEEE Xplore was included to capture trials published in engineering and technology journals. ClinicalTrials.gov and the WHO International Clinical Trials Registry Platform (ICTRP) were searched to identify completed trials and to check for selective outcome reporting. The reference lists of included trials and of previous systematic reviews of digital rehabilitation after TKA[12–16] were hand-searched. No language restrictions were applied.

The search strategy was developed by the lead author (HA). It combined three concept blocks (knee arthroplasty, AI-driven or digital rehabilitation technology and randomized trial design) using Medical Subject Headings (MeSH), Emtree terms and free-text terms joined with OR within blocks and AND between blocks. The technology block was kept broad to maximize sensitivity, and the AI-driven criterion was applied at screening. The PubMed strategy is shown in (Table 2) and was adapted for each database.

**Table 2. PubMed/MEDLINE search strategy**

| Block | Search terms |
|---|---|
| **#1 Knee arthroplasty** | "Arthroplasty, Replacement, Knee"[Mesh] OR "total knee arthroplast*"[tiab] OR "total knee replacement*"[tiab] OR "knee arthroplast*"[tiab] OR "knee replacement*"[tiab] OR TKA[tiab] OR TKR[tiab] |
| **#2 AI-driven / digital rehabilitation** | "Artificial Intelligence"[Mesh] OR "Machine Learning"[Mesh] OR "Wearable Electronic Devices"[Mesh] OR "Augmented Reality"[Mesh] OR "Telerehabilitation"[Mesh] OR "Mobile Applications"[Mesh] OR "artificial intelligence"[tiab] OR "machine learning"[tiab] OR "deep learning"[tiab] OR "computer vision"[tiab] OR "motion track*"[tiab] OR "motion capture"[tiab] OR "inertial sensor*"[tiab] OR "inertial measurement unit*"[tiab] OR wearable*[tiab] OR biofeedback[tiab] OR "real-time feedback"[tiab] OR "digital rehabilitation"[tiab] OR "digital physiotherap*"[tiab] OR "virtual coach"[tiab] OR "augmented reality"[tiab] OR telerehabilitation[tiab] OR "tele-rehabilitation"[tiab] OR "app-based"[tiab] OR smartphone*[tiab] |
| **#3 Randomized trial** | "Randomized Controlled Trial"[pt] OR randomized[tiab] OR randomised[tiab] OR randomly[tiab] OR "controlled trial"[tiab] OR trial[ti] |
| **#4 Combined** | #1 AND #2 AND #3 |

### Study Selection

Records from all sources were imported into the Rayyan software application[20], and duplicates were removed. Two reviewers (WJ and IS) independently screened titles and abstracts against the eligibility criteria and then read the full texts of records that appeared relevant. Before formal screening, they piloted the criteria on a sample of 50 records. Because applying the AI-driven criterion requires judgment, the reviewers kept a decision log recording which intervention component (a, b or c in Table 1) was or was not met for each borderline study. Reasons for excluding full-text articles were recorded. Disagreements at either stage were resolved by discussion and, when consensus could not be reached, by a third reviewer (HA). The selection process is presented in a PRISMA 2020 flow diagram (Figure 1)[17].

### Data Extraction

Two reviewers (WJ and IS) extracted data independently using a standardized Microsoft Excel form, piloted on two included trials and refined before full use. Extracted data were cross-checked, and discrepancies were resolved by re-reading the full text and by discussion with a third reviewer (HA). The following items were extracted:

- **Study identifiers:** first author, year, journal, country and setting, trial registration and funding.
- **Design and participants:** design (superiority or non-inferiority, pilot), number randomized and analyzed per group, age, sex, body-mass index, and unilateral or bilateral TKA.
- **Intervention:** described with the Template for Intervention Description and Replication (TIDieR) checklist[21], including technology type, the AI or algorithmic component, type and timing of feedback, exercise content and dose, start time after surgery, duration and level of remote clinician involvement.
- **Comparator:** who delivered it, setting, number and duration of sessions and exercise content.
- **Outcomes:** instrument, time point, group means (SD) or change scores, between-group differences with 95% confidence intervals and p-values, adverse events, adherence, satisfaction and cost data.
- **Authors' conclusions** and limitations stated by the authors.

Results were recorded as intervention versus control. Values presented only in figures were read from the figure and labeled as approximate, and data not reported in the trial publications were recorded as "not reported".

### Risk-of-Bias Assessment

Risk of bias was assessed for the primary outcomes of each trial (pain, patient-reported knee function and knee range of motion) using the revised Cochrane risk-of-bias tool for randomized trials (RoB 2)[22]. Two reviewers (WJ and IS) assessed each trial independently and resolved disagreements by discussion with a third reviewer (HA). The tool covers five domains: (1) the randomization process, (2) deviations from intended interventions, (3) missing outcome data, (4) measurement of the outcome and (5) selection of the reported result. Each domain was judged as low risk, some concerns or high risk of bias, and the overall judgment corresponded to the most severe domain-level judgment.

Because participants and therapists cannot be blinded to digital or supervised rehabilitation, particular attention was paid to whether outcome assessors were blinded for performance-based measures and to the self-reported nature of pain and function scores. Use of intention-to-treat analysis was checked, and selective reporting was assessed by comparing published outcomes with trial registry entries and published protocols. Judgments were tabulated using the conventions of the robvis tool[23].

### Data Synthesis

The trials differed substantially in the technology tested, the intensity of the comparator, the outcome instruments and the follow-up time points, so a meta-analysis was not appropriate. A structured narrative synthesis was undertaken and reported according to SWiM[19]. Trials were grouped by comparator (supervised physiotherapy or unsupervised home exercise) and then by outcome and time point, and effects were described using the between-group differences reported by each trial.

Heterogeneity was explored descriptively across pre-specified characteristics: technology type (wearable inertial sensor, camera-based motion tracking or augmented reality), level of remote clinician oversight, intervention duration and follow-up time point. Robustness was examined by restricting the synthesis to trials with some concerns (excluding those at high risk of bias) and by excluding pilot trials.

### Certainty of Evidence

The certainty of the evidence for each primary outcome and for healthcare costs was assessed with the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach[24], adapted for synthesis without meta-analysis[25]. Evidence from RCTs started at high certainty and was

rated down for risk of bias, inconsistency, indirectness, imprecision and publication bias. Formal assessment of publication bias was not possible because fewer than ten trials contributed to each comparison.

## RESULTS

### Study Selection

The database searches identified 486 records, and a further 24 records were identified through trial registers and citation searching. After removal of 110 duplicates, 400 titles and abstracts were screened, of which 355 were excluded. The full texts of 45 reports were assessed for eligibility, and 38 were excluded, most commonly because the intervention did not meet the AI-driven criterion (videoconference-only telerehabilitation or apps delivering exercise videos without movement analysis; n = 20) or because the study was not randomized (n = 12). Other reasons were an ineligible study population (n = 4) and the absence of relevant outcome data (n = 2). The study by Correia et al.[9] was excluded at this stage despite its AI-powered biofeedback intervention, because participants were allocated by place of residence rather than at random. Seven RCTs met the eligibility criteria and were included[8,10,11,26–29]: four compared AI-driven rehabilitation with supervised physiotherapy and three with unsupervised home exercise. No trial was suitable for meta-analysis. The selection process is shown in (Figure 1).

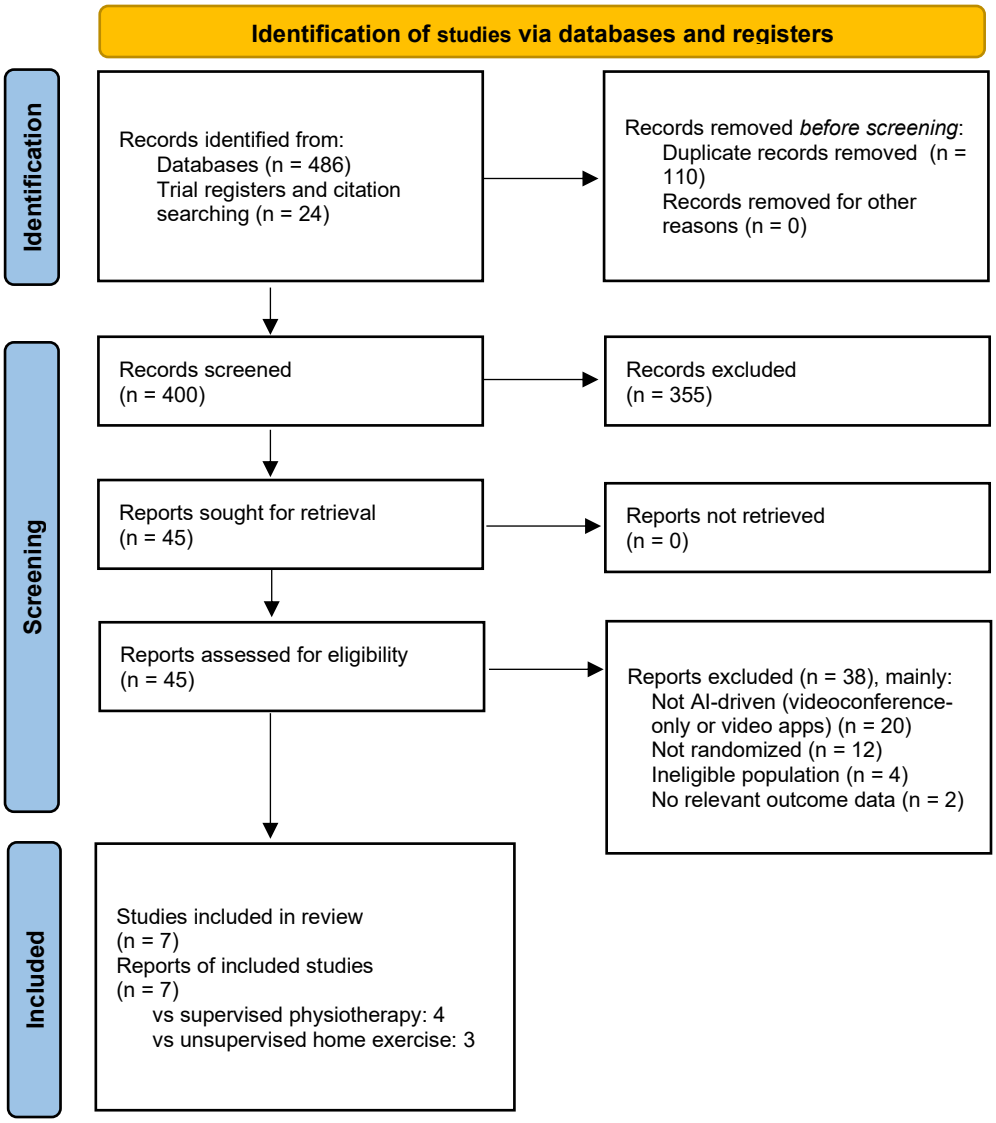



***Figure 1. PRISMA 2020 flow diagram of study***

### Characteristics of The Included Studies

The seven trials were published between 2020 and 2025 and randomized 726 adults after primary TKA: 510 in four trials with a supervised physiotherapy comparator and 216 in three trials with an unsupervised home-exercise comparator (Table 3). Sample sizes ranged from 38 to 306, and the multi-center VERITAS trial[8] alone contributed 42% of participants. Two trials were designed as non-inferiority trials[8,28],

and one was a pilot that stopped early[26]. Three trials were conducted in East Asia, two in the USA and one each in Singapore and Spain.

All systems were used at home for 4 to 12 weeks, and most let a physiotherapist monitor progress remotely. Five tracked movement with wearable inertial sensors or a depth camera and gave real-time feedback during exercise[8,10,26,27,29]. Pua et al.[28] used a tablet linked to a digital goniometer, a portable force platform and a time-of-flight sensor that measured knee range of motion, sit-to-stand symmetry and gait speed automatically and gave instant feedback on these measures, but not on exercise performance. Zhao et al.[11] described a smartphone application-based system whose movement-analysis component could not be confirmed from the available report. Comparators ranged from full clinic-based physiotherapy to a printed exercise brochure, and two trials tested the technology as an add-on or hybrid model rather than as a replacement for supervised care[26,27]. Authors of two trials reported research support from, or a financial interest in, the technology tested[8,26].

**Table 3. Characteristics of the included studies (n = 7), ordered by comparator and year**

| Study | Country; design | Randomized / analyzed (I/C) | Age (y); female | AI-driven intervention | Comparator | Duration / follow-up | Outcomes | Main findings |
|---|---|---|---|---|---|---|---|---|
| **Comparator: supervised physiotherapy** | | | | | | | | |
| **Prvu Bettger et al., 2020[8]** | USA (4 sites); multicenter RCT, non-inferiority | 306 / 287 (143/144) | 65; 62.5% | VERA: in-home 3-D biometric motion tracking, avatar coach with audio-visual feedback; weekly telehealth visits with a remote physiotherapist | Traditional home and/or outpatient clinic physiotherapy | 12 wk / 6 and 12 wk | Costs (primary); KOOS; knee flexion/extension; gait speed; pain; falls; rehospitalization | Median cost $1,050 vs $2,805 (p < 0.001); rehospitalizations 12 vs 30 (p = 0.007); non-inferior for KOOS, ROM and gait speed; falls 19.4% vs 14.6% |
| **Bell et al., 2020[26]** | USA; pilot RCT, stopped early | 38 / 20 (10/10) | 64.4; 48% | interACTION: IMUs on thigh and shank, app with color-coded real-time feedback, clinician portal; 2 wk clinic familiarization, then visits tapered | Clinic physiotherapy 2–3×/wk for up to 10 wk plus home program | 10 wk / 5 and 10 wk | Value: ΔADLS/cost (primary); NPRS; active ROM; VR-12; 6MWT, stairs, TUG, balance | No difference in value (0.013 vs 0.018; p = 0.32), ADLS change or cost; pain at 10 wk higher with interACTION (NPRS 3.7 vs 2.2; p = 0.043) |
| **Pua et al., 2024[28]** | Singapore; RCT, non-inferiority | 114 (56/58) / 114 (mITT) | 66.8 vs 66.1; 64% vs 71% | Tablet with digital goniometer, portable force platform and time-of-flight sensor measuring knee ROM, sit-to-stand symmetry and gait speed, with instant feedback; asynchronous remote monitoring after a | Hospital-based outpatient physiotherapy, ≥ 5 sessions over 10 wk | 10 wk / 12 and 24 wk | Fast gait speed (primary); KOOS function; weight-bearing pain; quadriceps strength; ROM; QALY; costs | Non-inferior for fast gait speed (0.02 m/s at 12 wk; 95% CrI −0.05 to 0.10), KOOS, pain and ROM; quadriceps strength lower at 12 wk but not 24 wk; adherence and satisfaction favored HBR; intervention |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | therapist home visit | | | | cost S$227 lower |
| **Nuevo et al., 2024**[27] | Spain; RCT | 52 (26/26) / 45 (23/22) | 68.3 vs 68.8; 39% vs 64% | ReHub®: wearable inertial sensor, algorithm-generated real-time biofeedback and virtual coach; remote monitoring and messaging | Same fast-track home exercise plan with up to 10 physiotherapist home visits, without ReHub (add-on design) | 4 wk / 2 and 4 wk | Knee ROM (primary); TUG; quadriceps and hamstring strength; VAS; WOMAC; EQ-5D-5L; adherence; usability; adverse events | Higher adherence and quadriceps strength with ReHub; no difference in other outcomes; one ReHub-related adverse event; SUS 83/100 |
| **Comparator: unsupervised home exercise** | | | | | | | | |
| **Shim et al., 2023**[10] | Korea; multicenter RCT | 56 (28/28) / 54 (ITT) | 68.3 vs 73.0; 82% vs 75% | Kinect depth camera tracking 25 joints; exercises shown by an avatar with real-time feedback on screen; performance reviewed by a physician | Brochure-based home exercise | 12 wk / 3, 12 and 24 wk | 4-m gait speed (primary); WOMAC; EQ-5D-5L; NRS; BBS; ROM; muscle strength | No group × time interaction for any outcome; gait-speed change 0.37 vs 0.42 m/s (p = 0.438); dropout 10 vs 4; no adverse events |
| **Zhao et al., 2024**[11] | China; RCT | 100 (50/50) | NR | Smartphone application-based remote rehabilitation system | Home-based rehabilitation with outpatient guidance | 12 wk / 2, 6 and 12 wk | Knee ROM at 12 wk (primary); VAS; WOMAC; KSS; SF-36; SLST; 5xSST; satisfaction; costs; 90-day readmission | Greater knee ROM at 12 wk (124° vs 119°; p = 0.01); better SF-36 physical function, SLST and 5xSST; no difference in WOMAC, KSS, costs or 90-day readmission |
| **Jung et al., 2025**[29] | Korea; single-center RCT | 60 (30/30) / 49 (24/25) | 66–67; 100% | eCEN Care: two wearable sensors (thigh and calf), smartphone app with real-time feedback, clinician web dashboard | Self-directed home rehabilitation with intermittent outpatient supervision | 12 wk from day 7 / 3, 6 and 12 wk | WOMAC (primary: total); KOOS; EQ-5D-5L; knee ROM; gait speed; gait ROM | Better WOMAC function (group effect −3.8; p = 0.001) and KOOS pain (5.28; p < 0.001); gait ROM at 12 wk 55.3° vs 47.9° (p = 0.037); gait speed similar |

Results are presented as intervention vs control. NR, not reported in the available report; CrI, credible interval; HBR, hospital-based rehabilitation; ITT, intention to treat; mITT, modified intention to treat. 5xSST, Five Times Sit-to-Stand Test; 6MWT, 6-Minute Walk Test; ADLS, Activities of Daily Living Scale; BBS, Berg Balance Scale; C, control; EQ-5D-5L, EuroQol 5-Dimension 5-Level; I, intervention; IMU, inertial measurement unit; KOOS, Knee Injury and Osteoarthritis Outcome Score; KSS, Knee Society Score; NPRS/NRS, Numeric (Pain) Rating Scale; QALY, quality-adjusted life year; ROM, range of motion; SF-36, Short Form-36; SLST, Single-Leg Stance Test; SUS, System Usability Scale; TUG, Timed Up and Go; VAS, Visual Analogue Scale; VERA, Virtual Exercise Rehabilitation Assistant; VR-12, Veterans RAND 12-Item Health Survey; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; wk, weeks.

### Risk of bias in the included studies

No trial was at low overall risk of bias (Table 4). Three trials had some concerns[8,27,28], three were at high risk[10,26,29] and one could not be assessed because information on randomization, attrition and registration was not available[11]. Participants and therapists could not be blinded, so deviations from intended interventions and outcome measurement raised some concerns in every trial: pain and function were self-reported, and assessors were not blinded in two trials[8,26]. The high-risk judgments arose from missing outcome data in Bell et al.[26], where 20 of 38 randomized participants were analyzed, and in Shim et al.[10], where 10 of 28 participants in the intervention group and 4 of 28 controls withdrew, and from retrospective registration with incomplete reporting of the stated primary outcome in Jung et al.[29] Groups in Shim et al. also differed at baseline in age and body-mass index.

**Table 4. Risk of bias of the included studies (RoB 2)**

| Study | D1 | D2 | D3 | D4 | D5 | Overall |
|---|---|---|---|---|---|---|
| **Prvu Bettger et al., 2020[8]** | ? | ? | ✓ | ? | ? | ? |
| **Bell et al., 2020[26]** | ✓ | ? | ✗ | ? | ? | ✗ |
| **Pua et al., 2024[28]** | ✓ | ? | ✓ | ? | ✓ | ? |
| **Nuevo et al., 2024[27]** | ✓ | ? | ✓ | ? | ✓ | ? |
| **Shim et al., 2023[10]** | ? | ? | ✗ | ? | ✓ | ✗ |
| **Zhao et al., 2024[11]** | NI | ? | NI | ? | NI | NI |
| **Jung et al., 2025[29]** | ? | ? | ? | ? | ✗ | ✗ |

✓, low risk; ?, some concerns; ✗, high risk; NI, no information. D1, randomization process; D2, deviations from intended interventions; D3, missing outcome data; D4, measurement of the outcome; D5, selection of the reported result. Judgments refer to the primary outcomes of this review (pain, patient-reported knee function and knee range of motion).

### Primary Outcomes

Results are presented separately for the two comparators.

### Pain

All seven trials reported pain. Against supervised physiotherapy, three of four trials found no difference between groups. In VERITAS[8], virtual physiotherapy was non-inferior to traditional care for pain; Pua et al.[28] found tele-monitored rehabilitation non-inferior for knee pain during weight-bearing; and Nuevo et al.[27] found no difference in VAS pain at 2 or 4 weeks. In the pilot trial by Bell et al.[26], pain at 10 weeks was higher in the sensor group than in the clinic group (NPRS 3.7 vs 2.2, p = 0.043), although no other outcome differed and the authors attributed this finding to the small sample. Against unsupervised home exercise, Shim et al.[10] found no group × time interaction for NRS pain over 24 weeks, whereas Jung et al.[29] reported less pain with the wearable-sensor system (KOOS pain group effect 5.28, p < 0.001). Zhao et al.[11] measured VAS pain, but the result was not available.

### Patient-Reported Knee Function

All seven trials reported patient-reported knee function. Against supervised physiotherapy, none found a difference: VERITAS[8] and Pua et al.[28] showed non-inferiority on the KOOS, Nuevo et al.[27] found no difference in WOMAC, and in Bell et al.[26] the change in the Activities of Daily Living Scale was similar (30.5 vs 33.6 points, p = 0.555). Against unsupervised home exercise, two of three trials found no difference in WOMAC: Shim et al.[10] over 24 weeks and Zhao et al.[11], who also found no difference in the Knee Society Score, although SF-36 physical function was better with the app (61.5 vs 45.5, p < 0.001). Only Jung et al.[29] reported better WOMAC function (group effect −3.8, p = 0.001), less stiffness and better KOOS activities of daily living with the sensor system.

### Knee Range of Motion

Range of motion was the primary outcome in two trials[11,27]. Against supervised physiotherapy, VERITAS[8] and Pua et al.[28] found AI-driven rehabilitation non-inferior for knee range of motion, and neither Nuevo et al.[27] nor Bell et al.[26] found a difference between groups. Against unsupervised home exercise, Zhao et al.[11] found greater knee range of motion at 12 weeks with the app (124° ± 8.7° vs 119° ± 5.5°, p = 0.01), Shim et al.[10] found no difference, and Jung et al.[29] reported greater knee motion during gait at 12 weeks (55.3° ± 10.8° vs 47.9° ± 10.4°, p = 0.037).

### Sensitivity and Heterogeneity

When the synthesis was restricted to the three trials with some concerns[8,27,28], which together randomized 472 participants, none showed a difference between groups for pain, knee function or range of motion, so the conclusion of no clear difference was unchanged. The one result favoring the comparator (pain in Bell et al.[26]) and the results favoring the intervention in Jung et al.[29] came from trials at high risk of bias, and excluding the pilot trial[26] did not change the conclusions. Results did not differ by type of technology: the camera-based[8,10], inertial-sensor[26,27] and device-measurement[28] systems all produced results similar to those of their comparators. Benefits were seen only against unsupervised home exercise[11,29], in trials that were at high risk of bias or could not be assessed.

### Secondary Outcomes

#### Physical Performance and Muscle Strength

Performance-based outcomes did not differ between groups in five trials. Gait speed was non-inferior in VERITAS[8] and Pua et al.[28] (fast gait speed, the trial's primary outcome) and similar between groups in Shim et al.[10] and Jung et al.[29] The TUG did not differ in Nuevo et al.[27], nor did a combined functional battery in Bell et al.[26] Zhao et al.[11] was the only trial to report better performance with the intervention, on the Single-Leg Stance Test and Five Times Sit-to-Stand Test. Quadriceps strength was greater with ReHub in Nuevo et al.[27], did not differ in Shim et al.[10], and in Pua et al.[28] favored hospital-based rehabilitation at 12 weeks (0.09 Nm/kg, 95% CrI 0.001 to 0.18) but not at 24 weeks.

### Health-Related Quality of Life

EQ-5D-5L scores did not differ in Nuevo et al.[27] or Shim et al.[10], and VR-12 scores did not differ in Bell et al.[26] Pua et al.[28] reported non-inferiority for quality-adjusted life years. Jung et al.[29] reported a group effect on EQ-5D-5L ($p = 0.017$), and Zhao et al.[11] better scores on some SF-36 domains with the intervention.

### Adherence and Satisfaction

Adherence was measured in different ways and could not be compared directly. Nuevo et al.[27] reported higher exercise adherence with ReHub than with paper-based home exercise ($p = 0.002$). In contrast, adherence and satisfaction both favored hospital-based rehabilitation in Pua et al.[28] (adjusted odds ratios 0.49, 95% CrI 0.20 to 0.92, and 0.84, 95% CrI 0.43 to 1.44). In Bell et al.[26], participants used the sensor system for 37% of prescribed sessions between weeks 3 and 10, compared with 50% adherence to the paper exercise log in the control group. Usability ratings were high where measured: the System Usability Scale score for ReHub was 83 of 100[27], and all participants and physiotherapists surveyed in Bell et al.[26] said they would use the system again, although they reported problems with sensor calibration, repetition counting and app failures.

### Adverse Events

Five trials reported adverse events. In VERITAS[8], falls were reported by 19.4% of participants in the virtual physiotherapy group and 14.6% in the usual-care group, while rehospitalizations were fewer with virtual physiotherapy (12 vs 30, $p = 0.007$). In Pua et al.[28], adverse events were similar between groups, with non-serious events, including non-injurious falls and near misses, in 8 and 9 participants. Nuevo et al.[27] reported one adverse event related to ReHub, Shim et al.[10] observed none, and Zhao et al.[11] found no difference between groups. Bell et al.[26] and Jung et al.[29] did not report adverse events.

### Healthcare Costs

Four trials reported costs. Against supervised physiotherapy, median 12-week healthcare costs in VERITAS[8] were $1,050 with virtual physiotherapy and $2,805 with traditional care ($p < 0.001$), a mean saving of $2,745 per patient, and in Pua et al.[28] mean intervention costs over 24 weeks were S$227 lower with tele-monitored rehabilitation. In the pilot trial by Bell et al.[26], total costs did not differ ($2,452 vs $2,231, $p = 0.67$). Against home-based rehabilitation, Zhao et al.[11] found no difference in rehabilitation costs or 90-day readmissions.

### Certainty of Evidence

Compared with supervised physiotherapy, certainty was low for pain, knee function, range of motion and healthcare costs; compared with unsupervised home exercise, it was very low for all primary outcomes (Table 5).

**Table 5. GRADE summary of the certainty of evidence**

| Outcome | Studies (participants) | Risk of bias | Inconsistency | Indirectness | Imprecision | Other | Certainty | Summary of findings |
|---|---|---|---|---|---|---|---|---|
| AI-driven rehabilitation vs supervised physiotherapy | | | | | | | | |
| **Pain** | 4 (510) | Serious (−1): no | Not serious: 3 of 4 no | Serious (−1): different AI | Not serious: two non- | — | ⨁⨁◯◯ Low | May result in little or no |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | trial at low risk; one at high risk | difference; one small high-risk trial favored control | components; add-on and hybrid designs | inferiority trials | | | difference in pain |
| **Knee function** | 4 (510) | Serious (−1): self-reported by unblinded participants | Not serious: all 4 no difference or non-inferior | Serious (−1): as above | Not serious | — | ⊕⊕◯◯ Low | May result in little or no difference in knee function |
| **Knee range of motion** | 4 (510) | Serious (−1): no trial at low risk | Not serious: all 4 no difference or non-inferior | Serious (−1): as above | Not serious | — | ⊕⊕◯◯ Low | May result in little or no difference in range of motion |
| **Healthcare costs** | 3 (458) | Serious (−1): assessors not blinded in two trials | Not serious: 2 lower, 1 no difference (pilot) | Serious (−1): two health systems; different cost items | Not serious | — | ⊕⊕◯◯ Low | May reduce short-term healthcare costs |
| AI-driven rehabilitation vs unsupervised home exercise | | | | | | | | |
| **Pain, function and range of motion** | 3 (216) | Very serious (−2): two at high risk, one not assessable | Serious (−1): one trial no difference, two favored the intervention | Not serious | Serious (−1): small trials; effect sizes partly unavailable | — | ⊕◯◯◯ Very low | The evidence is very uncertain |

Certainty started at high for randomized controlled trials and was rated down for each serious concern. Participants are the numbers randomized. Supervised comparator: Prvu Bettger et al., Bell et al., Pua et al. and Nuevo et al.; costs from Prvu Bettger et al., Bell et al. and Pua et al. Unsupervised comparator: Shim et al., Zhao et al. and Jung et al. ⊕⊕◯◯, low; ⊕◯◯◯, very low.

# DISCUSSION

## *Summary of Main Findings*

This systematic review synthesized seven RCTs, involving 726 adults after primary TKA, that compared AI-driven digital rehabilitation with supervised physiotherapy or with unsupervised home exercise. Three main findings emerged. First, compared with supervised physiotherapy, AI-driven rehabilitation produced similar knee function and range of motion in all four trials, and pain was similar in three of the four; the exception was a small pilot trial at high risk of bias[26]. The two trials designed and powered as non-inferiority trials both met their margins[8,28]. Second, the two trials that measured healthcare costs at scale found that AI-driven rehabilitation lowered them[8,28], and the largest trial also reported fewer rehospitalizations[8]. Third, compared with unsupervised home exercise, the results were inconsistent: one trial found no difference[10], while the two trials that favored the intervention were at high risk of bias or could not be assessed[11,29]. Taken together, these findings suggest that AI-driven systems can deliver short-term recovery similar to supervised physiotherapy with fewer clinic visits, but they do not yet show that the technology improves outcomes beyond what a structured, supervised program already achieves.

## *Comparison with Previous Reviews*

Our findings are broadly consistent with earlier syntheses of digital and remote rehabilitation after TKA, while sharpening their interpretation. Zhai et al.[14] pooled 22 trials of smart device-assisted telerehabilitation and found no overall difference from conventional rehabilitation in pain or WOMAC scores, with small benefits limited to augmented- and virtual-reality subgroups and to knee extension. Peng et al.[16] pooled 23 trials of interactive remote rehabilitation and likewise found no consistent superiority over conventional care, with only a very small short-term benefit in active knee extension and a quadriceps-strength effect that was not robust. By contrast, the meta-analysis of eight app-based trials by Ma et al.[15] reported better pain, mobility and early range of motion with mobile applications, and an earlier review of mobile application-based rehabilitation reached a similar conclusion[13].

The present review differs from these syntheses in restricting inclusion to

interventions with an automated movement-analysis, adaptive or virtual-coaching component, and in analyzing supervised and unsupervised comparators separately. This distinction appears to matter. Earlier reviews combined videoconference therapy, video-only apps and AI-driven systems, and mixed supervised and unsupervised controls in the same comparison[12,14,15]. In our synthesis, apparent benefits arose only when AI-driven systems were compared with minimal care, whereas comparisons with supervised physiotherapy consistently showed no difference. The positive pooled effects reported by some earlier reviews may therefore reflect, at least partly, the low intensity of the control condition rather than a specific effect of the technology.

### Interpretation of Findings

Several explanations may account for the finding that AI-driven rehabilitation matched, but did not exceed, supervised physiotherapy. Recovery after primary TKA follows a strong natural trajectory, and both groups improved substantially in every trial[10], which leaves limited room for between-group differences in the short term. Supervised physiotherapy is also an active comparator: a physiotherapist observing and correcting exercise in person provides the same kind of feedback that AI systems aim to automate. Equivalence between the two is therefore a plausible and clinically useful result, because it implies that automated feedback can substitute for part of the therapist's supervisory role.

The design of individual trials also shaped what could be detected. In Nuevo et al.[27], both groups received the same physiotherapist home visits, so the trial tested whether AI-driven feedback added value to supervised care; the only benefits were greater adherence and quadriceps strength. In Bell et al.[26], the intervention arm received tapered clinic visits rather than none, so the comparison was between a hybrid model and full clinic care. These designs reflect how such technologies are likely to be used in practice, as a complement to, rather than a full replacement for, the physiotherapist.

The comparison with unsupervised home exercise is clinically important, because many patients rely on a home program after discharge, and sustaining adherence to it is difficult[6]. In this setting, real-time feedback and remote monitoring could plausibly improve exercise quality and adherence, and two trials reported benefits in range of motion, physical performance, pain and function[11,29]. These findings, however, came from trials at high or uncertain risk of bias, and the third trial found no difference over 24 weeks despite its own high and unequal dropout[10]. Whether AI-driven feedback improves outcomes over unsupervised exercise therefore remains uncertain.

### Adherence, Usability and Safety

Adherence is the mechanism through which AI-driven rehabilitation is expected to work, yet it was measured inconsistently and could rarely be compared between groups. Nuevo et al.[27] found higher adherence with the AI-driven system, whereas in Bell et al.[26] participants used the sensor system for only 37% of prescribed sessions. Usability and satisfaction ratings were high where measured[26,27], but technical problems with sensor calibration, repetition counting and app failures were common[26]. These findings are relevant because TKA recipients are predominantly older adults, and digital literacy, eyesight, dexterity and caregiver support may limit uptake. In the non-randomized study by Correia et al.[9], which was excluded from this review, about one in five patients withdrew in the first week because they could not use the system, and most of those remaining needed a caregiver's help.

Safety reporting was inconsistent and adverse events were rarely defined in advance. In VERITAS[8], falls were somewhat more frequent with virtual physiotherapy than with usual care (19.4% vs 14.6%), although rehospitalizations were fewer, whereas in Pua et al.[28] falls and near misses were similar between groups. The VERITAS signal was not tested statistically and may reflect chance or differences in reporting, but falls should still be monitored when patients exercise at home without a therapist present.

### Implications for Health Services

Lower healthcare costs were the most consistent advantage of AI-driven rehabilitation. In the largest trial, median 12-week costs fell from $2,805 to $1,050 per patient, largely because fewer post-acute and outpatient visits and rehospitalizations were needed[8], and Pua et al.[28] also reported lower intervention costs. These savings, combined with similar clinical outcomes, suggest that AI-driven systems could help health services meet the rising demand for TKA rehabilitation[1] and extend structured rehabilitation to patients who live far from outpatient services. This may be particularly relevant in low- and middle-income countries such as Pakistan, where physiotherapists are concentrated in cities and

travel costs are a major barrier to attendance. However, all cost data came from high-income health systems, and none of the trials included device purchase, maintenance or data costs in a full economic evaluation, so these findings cannot be transferred directly to other settings.

### *Implications for Practice and Research*

For clinicians, the current evidence supports AI-driven rehabilitation as a reasonable alternative or adjunct to supervised physiotherapy for selected patients after uncomplicated primary TKA, particularly those who are comfortable with technology, have support at home and face barriers to attending clinic. Remote monitoring by a physiotherapist, which was part of nearly all included interventions, should be retained, and patients' ability to use the system should be checked before discharge.

For researchers, adequately powered, multicenter non-inferiority trials with blinded outcome assessment, intention-to-treat analysis and prospective registration are needed. Trials should describe the AI or algorithmic component in enough detail to allow replication, for example using the TIDieR checklist[21], and should report adherence objectively, adverse events with standard definitions and outcomes beyond six months. Full economic evaluations that include technology costs, and trials in low- and middle-income settings and among older adults with limited digital literacy, are also needed.

### *Strengths and Limitations*

This review has several strengths. It used an explicit, component-based definition of AI-driven rehabilitation, which addresses a key weakness of previous reviews that grouped technologies with different mechanisms of action. It searched eight databases, including an engineering database, and two trial registers without language restrictions, and it analyzed supervised and unsupervised comparators separately. It assessed risk of bias with RoB 2 and the certainty of evidence with GRADE, and it followed the SWiM guideline for narrative synthesis.

The review also has limitations. At the review level, the protocol was not registered, which increases the risk that methodological decisions were influenced by knowledge of the evidence, although the eligibility criteria and outcomes were defined before the search. Applying the AI-driven criterion required judgment: the movement-analysis component of one system could not be confirmed from the available report[11], and the system in Pua et al.[28] measured movement automatically but did not analyze exercise performance, so its inclusion rests on a broad reading of the criterion. Trial-level data were incomplete for one trial, which prevented a full risk-of-bias assessment[11]. Because the number of trials was small, publication bias could not be assessed formally. At the evidence level, only seven trials were eligible, one trial contributed 42% of participants[8], and the three trials with an unsupervised comparator were small. No trial was at low risk of bias, mainly because participants and therapists could not be blinded and pain and function were self-reported. Interventions, comparators and outcome instruments varied widely, which precluded meta-analysis. Follow-up did not exceed 24 weeks, so the long-term effects of AI-driven rehabilitation remain unknown. Finally, all trials were conducted in North America, Europe, East Asia and Southeast Asia, which limits applicability to other health systems.

## CONCLUSION

Low-certainty evidence from four RCTs suggests that AI-driven digital rehabilitation after primary TKA results in little or no difference in pain, knee function and range of motion compared with supervised physiotherapy, while reducing short-term healthcare costs. Whether it improves outcomes compared with unsupervised home exercise is very uncertain. AI-driven rehabilitation may therefore be considered as an alternative or adjunct to supervised physiotherapy for selected patients, but larger, well-designed trials with longer follow-up and full economic evaluation are needed before it can be recommended as a replacement for supervised care.

**Author Contributions**

**HA:** Conception and design, search strategy, data interpretation, and manuscript writing
**WJ:** Study selection, data extraction, and risk-of-bias assessment
**IS:** Study selection, data extraction, and risk-of-bias assessment
**GF:** Literature review, manuscript editing, and critical review
**UW:** Data interpretation, critical review, and final approval

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