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Applications of Exoskeleton Robots for Rehabilitation in Patients with Knee Osteoarthritis: A Scoping Review

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Abstract: ***Background:*** ***Exoskeleton robots have emerged as a promising rehabilitation technology for patients with knee osteoarthritis (KOA). However, existing studies vary in their clinical applications and outcome assessments, and the available evidence has not yet been systematically mapped. This scoping review aimed to systematically map the current applications of exoskeleton robots in KOA rehabilitation, characterize the existing literature, and identify gaps in the current evidence base.*** ***Methods:*** ***This review followed the PRISMA-ScR guidelines to conduct a scoping review of the literature on the effectiveness of exoskeleton devices in the rehabilitation of patients with knee osteoarthritis. We searched PubMed, Scopus, the Cochrane Library, Embase, Web of Science, the Chinese Biomedical Literature Database (CBM), China National Knowledge Infrastructure (CNKI), the Wanfang Data Knowledge Service Platform, and the Chinese Science and Technology Journal Database (VIP) for studies published from database inception to September 1, 2026. Data were extracted using a standardized template and synthesized through content analysis.*** ***Results:*** ***Of the 1,709 records retrieved from the nine databases, 13 studies were ultimately included. Of these, 11 investigated exoskeleton-assisted rehabilitation during the early postoperative period following total knee arthroplasty (TKA), while two involved patients with KOA receiving conservative treatment. The devices evaluated included HAL, HWA, Keeogo, lightweight pneumatic exoskeletons, and other hybrid or modified knee exoskeletons. The outcomes assessed primarily covered pain, knee function and range of motion, gait and walking ability, lower-limb muscle strength and joint kinetics, quality of life, and device safety. Although some studies reported favorable effects of exoskeleton-assisted rehabilitation on relevant outcomes, considerable heterogeneity existed across studies, and the available evidence remains limited. Further research is therefore needed to establish the overall clinical effectiveness of exoskeleton-assisted rehabilitation in patients with KOA.*** ***Conclusion:*** ***Exoskeleton robots show potential for rehabilitation in patients with KOA and may help alleviate pain and improve knee function and walking ability, with a generally favorable safety profile. However, the current evidence remains limited. Further high-quality clinical studies are needed to clarify their clinical efficacy, identify appropriate target populations, and evaluate their long-term effects.***

Keywords: Knee osteoarthritis, Exoskeleton robots, Rehabilitation, Total knee arthroplasty, Scoping review.

1. Background

With the rapid ageing of China's population, the burden of knee osteoarthritis (KOA) is increasing, making it a major public health concern affecting the health and quality of life of middle-aged and older adults [1,2]. KOA is a chronic degenerative joint disease characterized primarily by pain, stiffness, and restricted mobility, which can substantially impair activities of daily living in severe cases [2]. Conservative treatments, including pharmacological management and exercise therapy, are the main treatment options for patients with early- to moderate-stage KOA [3], whereas total knee arthroplasty (TKA) is generally considered the principal surgical treatment for patients with advanced disease who do not respond adequately to conservative management [4]. Exercise-based rehabilitation plays a crucial role in improving pain and physical function in both patients receiving conservative treatment for KOA and those undergoing TKA [5–7]. However, KOA-related pain and functional limitations may reduce patients' willingness to participate in rehabilitation exercises. Although TKA can effectively alleviate symptoms in patients with advanced KOA, full recovery of lower-limb function often requires a prolonged period. During the early postoperative period, some patients may experience increased pain, reduced lower-limb muscle strength, and impaired walking ability [8–10], potentially compromising their motivation to engage in rehabilitation and maintain exercise adherence. Furthermore, one study reported that approximately 55.8% of patients experienced high levels of kinesiophobia at hospital discharge, which may further hinder early functional recovery [2]. Therefore, providing safe and effective support for exercise-based rehabilitation while minimizing the physical burden and discomfort associated with exercise remains an important consideration in KOA rehabilitation management.

In recent years, advances in rehabilitation robotics have facilitated the growing application of lower-limb exoskeleton robots in the rehabilitation of patients with motor impairments, offering new technological support for conventional rehabilitation approaches [11]. As wearable assistive devices, exoskeleton robots can provide support and assistance during knee joint movements [12]. The application of exoskeletons in patients with KOA has primarily focused on early rehabilitation following TKA, with these devices assisting patients during exercise training to facilitate the early resumption of ambulation and recovery of lower-limb function [13]. However, the outcome measures used in existing studies vary considerably, and the findings are not entirely consistent. Therefore, this scoping review aims to systematically identify and synthesize the evidence on the use of exoskeletons in KOA rehabilitation, with a particular focus on the patient populations receiving these interventions, clinical application settings, outcome measures, and key findings. It also seeks to identify gaps in the current evidence, thereby informing the design of future clinical studies and

providing guidance for the clinical application of exoskeletons in KOA rehabilitation.

2. Materials and Methods

The methodological steps of this study follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) checklist and the 2020 updated guidelines, and are strictly carried out in accordance with the relevant guidelines of the Joanna Briggs Institute (JBI) [14,15].

2.1 Identifying the Research Question

Through reviewing the literature, we aim to address the following issues: 1) What types of exoskeleton robots have been studied in patients with knee osteoarthritis? 2) What are the characteristics of the study populations, clinical settings, and exoskeleton-assisted rehabilitation interventions? 3) What assessment indicators are used in symptom management, and what is the effectiveness of its application?

2.2 Literature Search Strategy

A comprehensive literature search was conducted in the following electronic databases: PubMed, Scopus, Cochrane Library, Embase, Web of Science, the Chinese Biomedical Literature Database (CBM), China National Knowledge Infrastructure (CNKI), Wanfang Data Knowledge Service Platform, and the Chinese Science and Technology Journal Database (VIP). The search strategy combined controlled vocabulary (e.g., MeSH terms), free-text terms, and Boolean operators. The databases were searched from inception to September 1, 2026.

The following search terms were used: “Osteoarthritis, Knee,” “Knee Osteoarthritides,” “Knee Osteoarthritis,” “Osteoarthritis of Knee,” “Osteoarthritis of the Knee,” “Exoskeleton Device,” “Device, Exoskeleton,” “Devices, Exoskeleton,” “Exoskeleton Devices,” “Robotic Exoskeleton,” “Exoskeleton, Robotic,” “Exoskeletons, Robotic,” and “Robotic Exoskeletons.” The search strategy for PubMed was as follows: ((“Osteoarthritis, Knee”[Mesh]) OR (((((Osteoarthritis, Knee) OR (Knee Osteoarthritides)) OR (Knee Osteoarthritis)) OR (Osteoarthritis of Knee)) OR (Osteoarthritis of the Knee)) OR (Knee Joint))) AND ((“Exoskeleton Device”[Mesh]) OR (((((((Exoskeleton Device) OR (Device, Exoskeleton)) OR (Devices, Exoskeleton)) OR (Exoskeleton Devices)) OR (Robotic Exoskeleton)) OR (Exoskeleton, Robotic)) OR (Exoskeletons, Robotic)) OR (Robotic Exoskeletons))).

2.3 Study Selection

Import the retrieved literature into EndNote 21.0 software and remove duplicate references. Two researchers (XG, MTC) will first screen the literature by independently reading the titles, abstracts, and full texts. If the first two authors fail to reach a consensus, the decision will be made in consultation with a third researcher (ZHW). The inclusion and exclusion criteria for the literature are shown in Table 1.

Table 1: Inclusion and exclusion criteria for this study.

Inclusion criteria	Exclusion criteria
● The study subjects are patients with knee osteoarthritis (KOA); ● The research focus is on the application of exoskeleton robots in patients with KOA, with empirical findings reported in relation to their use, feasibility, safety, or functional outcomes; ● The types of literature include randomized controlled trials, quasi-experimental studies, cohort studies, cross-sectional studies, case series, and feasibility studies; ● The publication language is either Chinese or English.	● Specific details of the interventions are missing, making it impossible to extract useful information; ● The full text is unavailable; ● Conference abstracts and other non-original publications.

2.4 Charting the Data

Thirteen studies were ultimately included (Fig.1). Data were extracted from these studies and the extraction results were organized in tabular form. The extracted information was collected and summarized in a structured manner, primarily including the first author and year of publication, country, study design, sample size, clinical context, type of exoskeleton, intervention protocol, outcome measures, main findings, biomechanical changes, and other relevant information such as safety.

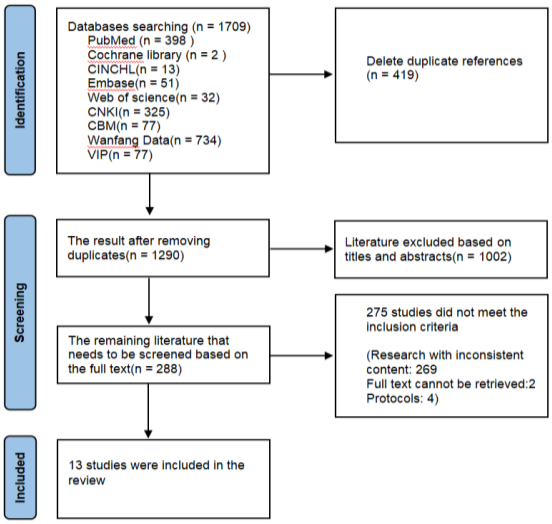


Figure 1: Flow chart of the literature search strategy

2.5 Collation, Summarizing, and Reporting Results

Grounded in the methodological principles of scoping reviews, this scoping review presents its findings through a narrative synthesis, with the objectives of integrating diverse evidence, providing more detailed information, and serving as a reference for researchers and healthcare professionals.

3. Results

A total of 1,709 articles were retrieved in this study, with the search time frame spanning from the inception of each database to September 1, 2026. After removing 419 duplicate articles, 1002 articles unrelated to the topic of this study were excluded following an initial screening of titles and abstracts. The remaining articles were subjected to full-text reading and evaluation, resulting in 13 studies being ultimately included, with their key information extracted as shown in Table 2.

Table 2: Characteristics and main result from the 16 studies.

No	Author, Country, Year	Study design	Sample	Clinical context	type of exoskeleton	intervention protocol	Outcome Indicators	main findings	other relevant information
1	R. Ezzibdeh USA 2019	Pilot study	n=3, mean age 59 ± 3 years; primary TKA due to KOA	Early postoperative rehabilitation after TKA	Lightweight pneumatic knee exoskeleton (Roam Robotics)	Patients independently donned the device with staff guidance and performed simple mobility tasks, including a 15-ft walk and three stair ascent/descent cycles	Questionnaire assessing wound interference, stability, pain, safety, manageability and stair-climbing	No wound interference or increased knee pain; all patients felt more stable. Two-thirds found the device manageable and safe and reported stair-climbing assistance; one-third found it cumbersome and unsafe for stair use	Preliminary feasibility and safety were demonstrated, with favorable wound compatibility. Device fit, force control, and customization require further improvement; formal adherence was not assessed
2	Kenichi YoshikawaJapan 2018	Non-randomized controlled pilot study	n=19, HAL: 9 patients; control: 10 patients; severe OA and RA	Early postoperative rehabilitation after TKA	HAL-SJ	HAL training for 4 weeks, approximately 1–5 weeks after TKA; 11.6 ± 0.8 sessions; 14.4 ± 5.9 min/session; knee flexion/extension exercise and level-ground gait training; conventional PT provided concurrently	SWS, MWS, step length, cadence; knee ROM; knee flexion/extension torque; WOMAC-P and WOMAC-F	HAL group showed significantly greater SWS and MWS at weeks 4 and 8; greater step length at selected time points; better passive/active knee extension ROM during early postoperative period; greater knee extension torque at week 8; early improvement in WOMAC pain	No adverse events were reported among the 9 patients who completed HAL training. Preliminary feasibility was demonstrated; patients completed HAL-assisted knee exercise and gait training under therapist supervision
3	Zhihao Zhou China 2026	pre-post Pilot study	n=5, acute-phase post-TKA patients with severe KOA; 4 healthy subjects for device-interference evaluation	Acute postoperative gait rehabilitation after primary unilateral TKA	portable rigid-soft hybrid knee exoskeleton(Hybrid-KEX II)	10-m pre-walk → personalized trajectory/modeling → 3-min overground exoskeleton-assisted walking → 10-m post-walk at self-selected speed; ≤30-s rests allowed	Maximum Knee Flexion Angle；Range of Knee Joint Angles；Patient Subjective Feedback	Maximum knee angle increased from 16.45° ± 4.61° to 26.43° ± 2.52° (P<0.05); knee angle range increased from 12.64° ± 2.44° to 24.46° ± 3.54° (P<0.05)	Knee kinematics improved (maximum angle ↑9.98°, ROM ↑11.82°); no falls/emergency stops; preliminary feasibility and safety demonstrated.
4	K. Koseki Japan 2020	Case Report	n=1, 76-year-old female; unilateral TKA	Early postoperative rehabilitation after TKA	Honda Walking Assist (HWA); lightweight hip-wearable exoskeleton	4–5 sessions/week, 20 min/session, 18 sessions over 1–5 weeks; hospital-based; integrated with conventional rehabilitation including ROM, stretching, strengthening, balance, ADL, gait and stair training	Knee ROM；Knee Joint Extension Torque；Self-Selected Walking Speed (SWS)；Maximum Walking Speed；Gait Patterns	Knee extension ROM, knee extension torque, SWS, and MWS improved; passive knee extension reached 0° at week 8, while SWS and MWS increased to 1.25 and 1.46 m/s, respectively	Knee ROM and kinematics improved at week 5, including knee flexion during loading response/swing, hip extension, and ankle plantarflexion. All 18 sessions were completed with no AEs or pain exacerbation, supporting safety and feasibility
5	N. Kotani 2020 Japan	RCT	n=22, HAL-SJ:12 patients; CPT:10 patients; TKA patients with KOA	Early inpatient rehabilitation after TKA	Single-Joint Hybrid Assistive Limb (HAL-SJ)	From postoperative day 5: HAL-SJ-assisted active knee flexion every other day (5 × 10 reps/session; 5–10 min/session); CPT: conventional PT without robotic assistance	Active knee ROM; passive knee ROM; knee flexion muscle strength; VAS pain; active ROM at 6 months; long-term follow-up	Both groups improved in knee ROM, muscle strength, and pain; the HAL-SJ group showed greater improvements than the CPT group (P<0.01), with sustained functional benefits at 6 months	HAL-SJ-assisted knee flexion exercise was feasible in the early postoperative period; patients performed the prescribed active-assisted exercise, supporting its use in inpatient rehabilitation
6	Chris McGibbon 2022 Canada	RCT	n=24, Keeogo: 11 patients; control: 13 patients; unilateral KOA	Clinic- and home-based rehabilitation	bilateral powered knee assistance (Keeogo™)	6-week crossover study assessing immediate and cumulative effects; clinic-based testing and home use with/without Keeogo; activity monitored by actigraphy	TUG, 6MWT, timed stair test (TST), WOMAC, Fatigue Severity Scale (FSS), Activities-specific Balance Confidence Scale (ABC), Numeric Pain Rating Scale (NPRS), SF-36, actigraphy, usability, adverse events	No significant immediate effects on physical performance or activity; cumulative use improved stair performance, WOMAC pain, and function. TUG improved, whereas 6MWT did not. Better physical function correlated with reduced WOMAC pain ($r = -0.677$, $p < 0.001$) and stiffness ($r = 0.537$, $p = 0.007$)	No major adverse events; feasible for clinic- and home-based use, with device weight and battery life identified as key usability concerns
7	K Yoshikawa 2026 Japan	Non-randomized controlled pilot study	n=40 patients, 52 knees; HGT: 13 patients/13 knees; control: 29 patients/39 knees	Early inpatient rehabilitation after TKA for OA/RA	Honda Walking Assist (HWA-01); lightweight hip-wearable exoskeleton	HGT + standard rehabilitation, weeks 1–3; 4–5 sessions/week, ≤20 min/session, 8–10 sessions. Control: standard rehabilitation	SWS, MWS, step length, cadence; knee ROM/torque; WOMAC pain/function; SWS PASS; walking distance/time; BRPE	HGT attenuated the decline in SWS and MWS at 2 weeks and increased SWS PASS achievement at 4 weeks; no significant differences in knee ROM, torque, or WOMAC	Step length at MWS showed a significant time × group interaction at 2 weeks ($p = 0.036$). HGT was well tolerated: walking distance increased from 405 ± 297 to 810 ± 306 m, BRPE remained stable or slightly reduced (~11), ≥8/10 sessions were completed, and no major adverse events occurred
8	Kazunori Koseki 2021 Japan	Non-randomized controlled trial	n=21 patients, 22 knees; HWA: 10 patients/11 knees; control: 11 patients/11 knees	Early postoperative rehabilitation after TKA for OA/RA	Honda Walking Assist (HWA); lightweight hip-wearable exoskeleton	HWA + conventional rehabilitation, weeks 1–5 post-TKA; 4–5×/week, ~20 min/session, 17–20 sessions. Control: conventional rehabilitation	SWS, MWS, step length, cadence; active/passive knee ROM; knee extension/flexion torque; WOMAC pain/function	Reduced SWS/MWS decline at week 2; improved SWS/MWS and step length; higher WOMAC-f at week 8; no difference in knee torque	No severe AEs/skin problems; mild cuff pressure pain in 1 patient resolved after adjustment; pain decreased in 6/10 cases; safe, feasible, lightweight/easy to wear; all patients completed the intervention
9	Takaya Maeda 2024 Japan	RCT	n=76, HAL-SJ: 40 patients; CPT: 36 patients; end-stage KOA undergoing primary TKA	Acute postoperative rehabilitation after TKA	HAL-SJ	Seated knee extension exercises (50 reps/day; 5 sessions/week; 10 sessions) plus conventional rehabilitation	VAS; active and passive knee extension angles; isometric knee extension strength (MicroFET2); 10-m maximal walking test; TUG; KOOS	HAL-SJ vs CPT: greater active knee extension on days 1–3 and passive extension on day 3; immediate gains in active extension on days 1–5 and passive extension on days 3, 6, and 9. Post-training pain decreased on days 3 and 7, but between-group differences were nonsignificant, as were functional tests and KOOS	Improved active and passive knee extension;Adverse-event rates, formal feasibility outcomes, and adherence measures NR
10	Nikhil V. Divekar 2025 USA	Pilot study	n=4, 3 females, 1 male; aged 53–81 years; predominantly patellofemoral OA	Conservative management of KOA; ADL assistance	Powered bilateral knee exoskeleton based on the M-BLUE modular lower-limb exoskeleton system	After 2–3 h acclimation, participants performed level walking, ramp/stair ascent/descent, and sit-to-stand/stand-to-sit with and without active exoskeleton assistance, repeating each task until ≥10 valid gait/task cycles were obtained	Pain and task difficulty (modified WOMAC, 0–4); surface EMG of the vastus medialis oblique, vastus lateralis, and rectus femoris; mean and peak quadriceps activation; task completion time and knee extension velocity	Exoskeleton use reduced pain by 0.82 points and task difficulty by 0.57 points; the greatest pain reduction occurred during ramp descent (−1.75 points), with effects varying across participants and tasks	Quadriceps activation varied by participant and task, with a maximum 6.8% reduction during sit-to-stand ascent; no adverse events were reported, and acute use was feasible across daily-life activities
11	Takashi Fukaya 2017 Japan	Case Report	n=1, 76-year-old male; grade 4 knee OA	Early postoperative rehabilitation after TKA for severe KOA	HAL-SJ	12 HAL sessions over 4 weeks from 1 week post-TKA; active knee flexion/extension and gait training (~10 min each) over ~45 m with a U-shaped walker; assistance adjusted to walking status, with pain monitoring, intensity adjustment, and EMG feedback	Knee ROM; walking speed; walking rate; 10-m walking steps/step length; Timed Up and Go (TUG); knee extensor muscle strength; gait kinematics and kinetics; knee joint moments; pain/ADL status	Knee ROM, walking speed, walking rate, and TUG performance improved within 5 weeks; the patient regained ADL and could walk without pain; quadriceps strength did not sufficiently improve	Improved mid-stance knee extension, eliminated varus thrust, reduced knee abductor moment, and generated a knee extensor moment despite limited quadriceps strength gains.Safe and pain-free; continuous pain monitoring and intensity adjustment; no adverse events; single-patient feasibility demonstrated

12	Takaya Watabe 2025 Japan	RCT	n=76 enrolled; 72 analyzed; HAL-SJ: 35 patients; control: 37 patients; KOA undergoing primary TKA	Early inpatient rehabilitation after TKA	HAL-SJ	From postoperative day 7 to discharge: seated HAL-SJ-assisted knee flexion/extension (5 × 10 reps, 3 times/week); both groups received conventional rehabilitation	Passive knee ROM, extension lag, quadriceps and hamstring isometric strength (HHD), NRS pain, 10-m walking speed, KOOS	Improved knee extension ROM and higher KOOS-ADL scores at 3 months, shorter extension-lag duration, and greater hamstring strength at 2 weeks; no significant differences in knee flexion ROM, quadriceps strength, pain, walking speed, or hospital/rehabilitation stay duration	Improved knee extension ROM, reduced extension lag, and increased hamstring strength during inpatient rehabilitation. Detailed gait biomechanics, adverse-event rates, and formal adherence were NR; 4 participants were excluded for missing data or postoperative delirium
13	Takaya Watabe 2024 Japan	RCT	n=33 enrolled; 30 analyzed; early: 14 patients; control: 16 patients; KOA undergoing primary TKA	Early inpatient rehabilitation after TKA	HAL-SJ	HAL-SJ began within 4 h postoperatively vs on day 7 (5 × 10 reps; flexion progressed from 90° to 120°), alongside conventional rehabilitation	Knee circumference, passive knee ROM, quadriceps/hamstring strength, extension lag, NRS pain, length of stay, complications	Shorter extension-lag duration and greater knee flexion ROM at week 1, with no significant differences in strength, pain, swelling, or length of stay	Improved early knee flexion ROM and reduced extension lag, with no gait biomechanical assessment or HAL-SJ-related complications; 3 participants were excluded, feasibility was preliminarily supported, and adherence was NR

TKA: Total knee arthroplasty; **KOA:** Knee osteoarthritis; **HAL:** Hybrid Assistive Limb; **RA:** rheumatoid arthritis; **EMG:** Electromyography; **SWS:** self-selected walking speed; **MWS:** maximum walking speed; **ROM:** range of motion; **WOMAC-P:** Western Ontario and McMaster Universities Osteoarthritis Index subscales of pain; **WOMAC-f:** Western Ontario and McMaster Universities Osteoarthritis Index subscales of physical function; **ADL:** Activities of daily living; **RCT:** Randomized Controlled Trial; **CPT:** conventional physical therapy; **TUG:** timed up-and-go; **TST:** timed stair test; **SF-36:** Short Form-36 Health Survey; **HGT:** HWA-01 gait training plus standard rehabilitation; **BRPE:** Borg Rating Scale of Perceived Exertion.

3.1 Types and Characteristics of Exoskeleton Robots

Currently, exoskeleton devices available for the rehabilitation of patients with KOA remain relatively limited [11]. This review included 12 studies investigating six types of wearable exoskeletons. Six studies evaluated the use of the Hybrid Assistive Limb (HAL) in rehabilitation. [16–18]. HAL is available in single-leg and bilateral configurations [16,19]; however, all six studies used the single-leg version. Unlike exoskeletons that rely primarily on predefined movement patterns, HAL detects signals such as muscle activity to provide movement assistance, thereby promoting active patient participation in training [16]. Three additional studies investigated the use of the Honda Walking Assist (HWA) [6,20,21]. HWA is a lightweight wearable device that uses hip-mounted actuators to assist hip flexion and extension, while integrated angle and torque sensors monitor hip movement in real time [20]. A predefined gait-control algorithm regulates the timing and magnitude of assistive torque to promote bilateral lower-limb symmetry during walking [6]. One study evaluated a lightweight pneumatic knee exoskeleton [22]. The device uses pneumatic actuation to provide mechanical assistance and is characterized by its lightweight design and ease of use [22]. Another study introduced the portable hybrid exoskeleton KEX II, a rigid–soft hybrid system designed to assist overground gait training during the acute postoperative phase following TKA. The system incorporates a lightweight, joint-free linear actuator and a portable actuation unit [23]. Reference [11] investigated Keeogo, a bilateral lower-limb exoskeleton with a low-profile, orthosis-like design. The device provides adjustable knee assistance or resistance to support daily activities, including walking, stair climbing, and sit-to-stand transfers, and is intended for use in both clinical and home settings [11]. In addition, a study developed a bilateral knee exoskeleton adapted from a commercially available postoperative knee brace [24]. The device features a highly backdrivable design and does not require prior identification of specific movement tasks. Instead, it accommodates various daily activities by adjusting virtual springs and dampers and applying gravity and inertia compensation. This approach may help address limitations of conventional exoskeletons, including rigid actuation, device bulk, and delays in task recognition, and may offer a potential approach to the non-invasive conservative management of KOA.

3.2 Characteristics of Study Populations, Clinical Settings, and Rehabilitation Interventions

Among the 13 included studies, participants were classified into two groups according to the stage of KOA management: two studies [11,24] investigated patients receiving conservative treatment, whereas the remaining 11 studies [6,16–18,20–23,25–27] focused on early rehabilitation following TKA. Both studies involving conservatively managed patients included individuals with KOA who had not undergone joint replacement. Study [11] included 24 patients with unilateral KOA, of whom 11 received Keeogo-assisted intervention and 13 served as controls. The study evaluated the immediate effects of exoskeleton assistance in a clinical setting and its cumulative effects during home use, while also monitoring patients' physical activity levels. Study [24] included four patients with KOA (three women and one man), aged 53-81 years. The researchers assessed the device's assistance during activities of daily living by comparing participants' performance with and without active assistance during level walking, ramp ascent and descent, stair negotiation, and sit-to-stand transfers. Both studies used task-oriented assessments in which exoskeleton assistance was integrated into functional activities. Comparisons between assisted and unassisted conditions were used to explore the potential of these devices to address KOA-related pain and functional limitations.

The 11 studies involving patients in the early postoperative period primarily recruited individuals with advanced KOA undergoing primary TKA. Sample sizes varied substantially, ranging from single-patient studies to a study involving 76 patients. The initiation of exoskeleton-assisted rehabilitation also varied, beginning within 4 hours after surgery [27], at 24 hours postoperatively [22], on postoperative day 5 [17], or 1-5 weeks after surgery [6,16,18,20,21,25,26]. These studies were conducted mainly in inpatient wards or hospital-based rehabilitation settings. Exoskeleton-assisted training was generally added to conventional physical therapy and included range-of-motion exercises, muscle-strengthening exercises, balance training, gait training, and step training.

Overall, the included studies varied considerably in sample size, clinical setting, and the timing of exoskeleton-assisted intervention. Studies of conservatively managed patients primarily used small-sample, exploratory, task-oriented assessments to examine the potential assistance provided by exoskeletons during functional activities. In contrast, studies involving patients after TKA focused predominantly on early inpatient rehabilitation, with exoskeleton-assisted training generally incorporated into conventional rehabilitation programmes. These differences highlight the distinct contexts

in which exoskeletons have been investigated across stages of KOA management and underscore the need to consider differences in patient populations and intervention protocols when interpreting the findings.

3.3 Outcome Domains and Intervention Effects

Across the 13 included studies, outcome measures covered multiple domains, including pain, knee function and range of motion (ROM), lower-limb muscle strength, joint kinetics and balance, walking ability and quality of life, and device safety.

Pain was one of the most commonly assessed outcomes for evaluating the effects of exoskeleton-assisted rehabilitation. Regarding pain outcomes, study [23] did not report changes in pain following exoskeleton-assisted training. In contrast, study [22] reported, based on participants' subjective feedback, that no pain or discomfort occurred during training. The remaining 11 studies employed standardized pain assessment instruments, including the Visual Analogue Scale (VAS), Numeric Rating Scale (NRS), Numeric Pain Rating Scale (NPRS), and the pain subscale of the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC).

Among the studies reporting pain outcomes, the effects of exoskeleton-assisted training varied across studies. Studies [16,17] both reported greater improvements in pain scores in the exoskeleton-assisted training groups. Study [18], a single-case report, documented pain relief during HAL-assisted rehabilitation following TKA. However, the absence of a control group precluded attribution of the observed improvement specifically to the exoskeleton intervention. Study [21] found that pain decreased in 6 of the 10 participants in the intervention group, suggesting interindividual variability in pain responses. Study [11] reported a reduction in pain with cumulative use of the Keeogo device, although its immediate effect on pain was not statistically significant. In study [25], pain scores decreased from pre-training levels following HAL-SJ training on postoperative days 3 and 7; however, the between-group differences in pain outcomes were not statistically significant compared with conventional rehabilitation. Furthermore, study [24] found that the developed exoskeleton device provided some degree of acute pain relief during various functional activities of daily living, with the greatest reduction observed during downhill walking. In contrast, studies [6,20,26,27] found no significant effects of exoskeleton-assisted training on pain reduction.

Regarding knee function and range of motion (ROM), the included studies evaluated the effects of exoskeleton-assisted training primarily in terms of functional performance, knee joint ROM, and related functional outcomes. Studies [11,22,24] reported improvements in patients' ability to ascend and descend stairs with exoskeleton assistance. Studies [11,18,25] used the Timed Up and Go (TUG) test to assess functional mobility and reported varying degrees of improvement in test performance. In addition, 10 studies [6,16–18,20,21,23,25–27] reported outcomes related to knee joint ROM, suggesting that exoskeleton-assisted training may facilitate the recovery of knee mobility. Notably, study [21] followed patients for 8 weeks and found that, by week 8, knee joint ROM had largely returned to preoperative levels following TKA.

Regarding muscle strength, five studies [17,18,25–27] evaluated the effects of exoskeleton-assisted training on lower-limb muscle strength in patients with KOA. Studies [17,26] reported improvements in knee flexor and hamstring strength, respectively, suggesting that exoskeleton-assisted training may facilitate strength recovery in specific muscle groups. However, studies [25,27] found no significant superiority of exoskeleton-assisted training over conventional rehabilitation in improving muscle strength. Study [18] further reported that knee extensor strength had not fully recovered within 5 weeks postoperatively, although knee extension torque improved and extension lag decreased.

Regarding joint kinetics, three studies [18,20,21] assessed knee extension and/or flexion torque. Study [20] reported greater improvements in knee extension torque in the exoskeleton-assisted training group than in the conventional rehabilitation group at postoperative weeks 4 and 8. In contrast, study [21] found that knee extension and flexion torque initially decreased and subsequently recovered in both the HWA and conventional rehabilitation groups, with no statistically significant between-group differences. Study [18], a single-case report, described changes in postoperative knee extension torque but did not provide quantitative measurements. Overall, the evidence regarding the effects of exoskeleton-assisted training on knee joint kinetics remains limited and inconsistent.

Regarding balance, objective assessments were limited. Only study [22] reported, based on subjective patient feedback, that participants perceived greater stability while walking when wearing the exoskeleton device. The remaining included studies did not explicitly report assessments of balance following exoskeleton-assisted training.

Regarding gait and walking ability, eight studies reported outcomes associated with exoskeleton-assisted training. Studies [6,12,16,18,20] assessed walking performance using measures such as self-selected walking speed (SWS) and maximum walking speed (MWS). Their findings suggested that exoskeleton-assisted training may improve walking speed. In addition, studies [11,18,26] reported potential benefits of exoskeleton devices, including HAL and Keeogo, in improving walking ability. Studies [11,17] also reported improvements in quality of life following the use of these devices.

Regarding device safety, the included studies generally reported favorable safety profiles. Studies [6,16,20,21,23,27] explicitly reported no serious adverse events during the study period. Nevertheless, several studies documented minor adverse events or device-related issues. Study [21] reported mild cuff-related pressure pain in one of 21 patients, which resolved after the relevant attachment was replaced. Study [11] documented one case of moderate thigh muscle pain and one battery malfunction that triggered an automatic safety shutdown; the latter did not result in a fall. Furthermore, study [22] reported that one participant considered the pneumatic exoskeleton bulky and expressed safety concerns, consequently declining stair training. These findings suggest that device weight, wearing comfort, and patients' perceptions of safety may influence the clinical acceptability of

exoskeletons and adherence to training.

4. Discussion

Exoskeleton robots have been widely used in the rehabilitation of neurological conditions, including stroke, cerebral palsy, and spinal cord injury, whereas research on their application in patients with KOA remains relatively limited [28]. Of the 13 studies included in this review, 11 focused on early rehabilitation following TKA in patients with KOA, while the remaining two investigated patients receiving conservative treatment. These findings indicate that exoskeleton-assisted rehabilitation has primarily been studied in two settings: early inpatient rehabilitation following TKA and home-based rehabilitation for patients receiving conservative treatment. Regarding device types, HAL and HWA were the most frequently investigated exoskeleton systems among the included studies. Other devices included a lightweight pneumatic exoskeleton, the portable hybrid exoskeleton KEX II, Keeogo, and a bilateral knee exoskeleton modified from commercially available postoperative knee braces. These devices differ in structural design, actuation mechanisms, and approaches to movement assistance, reflecting the diversity of exoskeleton technologies developed to address patients' functional needs and rehabilitation tasks. In patients recovering from TKA, exoskeletons are primarily used to support knee joint movement and functional training, including walking. In patients with KOA receiving conservative treatment, these devices may instead provide assistance during daily walking and other functional activities. However, direct comparisons between different exoskeleton systems are lacking, and the available evidence is insufficient to establish the superiority of any particular device for a specific patient population. Future research should therefore investigate the relationship between device characteristics and patients' functional needs to inform device selection and individualized clinical application.

Existing studies have evaluated the effects of exoskeleton-assisted rehabilitation primarily in terms of pain, knee function and ROM, gait and walking ability, lower-limb muscle strength, and balance. Overall, the included studies reported improvements in at least some outcome measures; however, the findings were not entirely consistent, and substantial variation existed in the outcome measures used across studies. These differences suggest that the effects of exoskeleton-assisted rehabilitation may be influenced by patient characteristics, rehabilitation stage, device-assisted mechanisms, and intervention protocols. Furthermore, objective assessments of balance remain limited, and evidence regarding the effects of exoskeletons on quality of life and long-term functional recovery is insufficient. Regarding device safety, several studies reported no serious adverse events, although a small number documented device- related discomfort, technical malfunctions, and concerns about wearing comfort and training safety. These findings suggest that device weight, wearing comfort, and patients' perceptions of safety may influence the clinical acceptability of exoskeletons and adherence to rehabilitation training. Accordingly, future device development and clinical implementation should place greater emphasis on human-device fit, wearing comfort, and patients' real-world experiences to improve device acceptability and practical feasibility in clinical settings.

Although existing studies have provided preliminary evidence of the potential value of exoskeletons in KOA rehabilitation, important gaps remain in the current evidence base. First, in terms of study populations, the available evidence is concentrated primarily on early rehabilitation following TKA, whereas studies involving patients with KOA receiving conservative treatment remain scarce. This imbalance limits the extent to which current findings can be generalized across different stages of disease management. As KOA is a chronic condition requiring long-term management, rehabilitation needs extend beyond the early postoperative period. Further research is therefore warranted to investigate the role of exoskeletons in assisting walking and supporting long-term functional management in patients who do not undergo surgery. In addition, a previous study [29] reported an association between preoperative quadriceps strength and postoperative functional recovery and patient satisfaction following TKA. This finding provides a rationale for investigating exoskeleton-assisted training as a potential prehabilitation strategy to improve quadriceps strength and support postoperative recovery. However, its effectiveness in this context requires further clinical evaluation.

Second, the included studies differed substantially in device types, intervention content, training frequency and duration, and concomitant conventional rehabilitation measures. Sample sizes were generally small, ranging from 1 to 76 participants. This heterogeneity in study design and intervention implementation complicates comparisons across studies and limits the assessment of intervention reproducibility and applicability in different clinical settings. Future studies should provide more standardized descriptions of device characteristics, intervention protocols, training dosage, and concomitant rehabilitation to facilitate comparisons and improve the reproducibility of findings.

Third, no standardized framework for outcome assessment has yet been established, with considerable variation in outcome selection and assessment time points. Long-term effects, training adherence, and patients' subjective experiences have also received insufficient attention. In addition to the outcome measures currently used, future studies should consider incorporating balance, quality of life, device acceptability, and adverse events into a more comprehensive assessment framework. Assessment time points should also be selected according to the rehabilitation trajectory to distinguish immediate assistive effects during device use, short-term functional improvements following the intervention, and the maintenance of functional gains over the longer term. High-quality clinical studies with rigorous designs, standardized reporting, and adequate follow-up are needed to clarify the value of exoskeletons across different rehabilitation settings for patients with KOA and to establish a more reliable evidence base for their clinical application.

5. Conclusion

This scoping review systematically mapped the current evidence on the application of exoskeleton robots in the rehabilitation of patients with KOA, covering device types, patient populations, clinical settings, intervention

characteristics, outcome measures, and reported effects. The findings suggest that exoskeleton-assisted rehabilitation may have potential benefits in alleviating activity-related pain and improving knee function and range of motion, gait and walking ability, lower-limb muscle strength, and joint kinetics, with a generally favorable safety profile. However, the limited number of studies and the heterogeneity in study designs, intervention protocols, and outcome assessments preclude definitive conclusions regarding the clinical efficacy and appropriate applications of exoskeletons in patients with KOA. Future research should include clinical studies involving diverse KOA populations and rehabilitation stages, standardize the reporting of intervention protocols and outcome measures, and further evaluate device safety, acceptability, and long-term effects to strengthen the evidence base for the clinical application of exoskeleton robots in KOA rehabilitation.

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