

Technology-assisted rehabilitation after total hip arthroplasty: a systematic review of robot- and sensor-based interventions

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Abstract

Introduction. Robot- and sensor-based interventions are increasingly used in postoperative rehabilitation, but their clinical effects after total hip arthroplasty (THA) remain unclear.

Methods. Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidance, we searched PubMed, Embase, CINAHL, Scopus, and Web of Science databases for randomised controlled trials evaluating robot- or technology-assisted physiotherapy delivered in the postoperative phase after THA. Three reviewers independently screened records, extracted data, and assessed the risk of bias using the Cochrane tool.

Results. From 181 records, three trials met eligibility criteria. Interventions included an exoskeleton (Hybrid Assistive Limb), a visualized loading-control robot combined with conventional rehabilitation, and an electromyography-based (EMG-based) rehabilitation robot. Compared with conventional rehabilitation, robot- or technology-assisted interventions showed signals of short-term benefits in pain, hip range of motion (particularly hip extension), functional scores, and walking endurance in some studies, whereas walking speed and maximal strength outcomes were inconsistent. Quality of life improved in one trial despite no between-group difference in maximal strength.

Conclusions. Evidence for the efficacy of robot- or technology-assisted postoperative rehabilitation after THA is limited and heterogeneous. Current trials suggest potential early benefits for selected outcomes, but firm conclusions are precluded by a small number of studies, variability in devices and dosing, and short follow-up. Well-designed, adequately powered trials with standardised outcomes are needed.

Key words: arthroplasty, replacement, hip, rehabilitation, robotics, gait, pain, range of motion

Introduction

Total hip arthroplasty (THA) is a common and effective procedure for end-stage hip disease, yet a meaningful proportion of patients experience persistent functional limitations and altered gait patterns during recovery [1].

Robotic technologies have expanded across the THA care pathway, particularly in robotic arm-assisted surgical techniques. Systematic reviews and comparative studies suggest that robot-assisted THA can improve surgical accuracy and may influence patient-reported outcomes compared with manual techniques, although findings are mixed [2–7]. Clinical outcomes across short- to long-term follow-up – including minimal clinically important improvement and joint awareness – have also been reported [8–12].

While robotic technologies have primarily been studied in the context of surgical precision and implant positioning, postoperative recovery remains strongly influenced by the quality and timing of rehabilitation. Even when surgical accuracy is optimised, patients may continue to experience functional limitations, altered gait patterns, and reduced muscle performance during the recovery process [13, 14]. Therefore, increasing attention has been directed toward technological innovations that support postoperative rehabilitation, including robotic and sensor-based physiotherapy systems designed to assist movement training, monitor loading patterns, and provide real-time feedback during recovery.

Postoperative rehabilitation aims to restore mobility, strength, and safe load progression. Although several reviews

have examined general rehabilitation strategies after THA, most have focused on conventional exercise programs, tele-rehabilitation, or perioperative care pathways. The specific role of robot- or technology-assisted rehabilitation devices in the postoperative phase have received limited attention [15, 16]. Furthermore, existing reviews often combine hip and knee arthroplasty populations or evaluate heterogeneous rehabilitation approaches without isolating the effects of robot- or sensor-based systems. Consequently, the evidence regarding technology-assisted rehabilitation, specifically after THA, remains fragmented and difficult to interpret. Recent advances have expanded the use of tele- and technology-enabled approaches to support standardised training and monitoring outside of traditional face-to-face sessions [17, 18].

Robot- and sensor-based systems may further enhance rehabilitation by delivering high-dose, repeatable practice with real-time feedback (e.g., weight-bearing control, biofeedback, or mechanical assistance). However, device types and protocols vary widely, and the magnitude and consistency of clinical benefits after THA are uncertain [19–24].

To clarify the clinical role of emerging rehabilitation technologies after THA, the research question of this review was formulated according to the PICO framework: Population (P): adults undergoing primary total hip arthroplasty; Intervention (I): robot- or technology-assisted postoperative physiotherapy; Comparator (C): usual care or conventional rehabilitation; and Outcomes (O): pain, hip range of motion, functional outcomes, gait performance, muscle strength, and quality of life. Accordingly, the guiding research question was: “Do robot-

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or technology-assisted rehabilitation interventions improve postoperative recovery outcomes compared with conventional rehabilitation after total hip arthroplasty?”.

The primary aim of this systematic review was to synthesise randomised evidence on robot- or technology-assisted physiotherapy applied in the postoperative rehabilitation phase after THA and to describe effects on pain, hip range of motion (ROM), function, gait, muscle strength, and quality of life (QoL). Previous systematic reviews have primarily evaluated robotic assistance in surgical procedures or combined hip and knee arthroplasty populations. In contrast, the present review specifically focuses on randomised controlled trials investigating robot- or technology-assisted physiotherapy interventions delivered during postoperative rehabilitation after THA. By isolating postoperative rehabilitation technologies and synthesising randomised evidence, this review aims to clarify the current evidence base and identify key gaps for future research.

Subjects and methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A completed PRISMA checklist is provided as Table S1 in Supplementary materials. The review protocol was prospectively registered on the Open Science Framework (OSF; <https://doi.org/10.17605/OSF.IO/6VZ9U>) [25].

Eligibility criteria

We included randomised controlled trials published within the last 10 years (January 2015–December 2025) involving adults undergoing primary THA. Eligible studies evaluated postoperative robot- or technology-assisted physiotherapy (e.g., exoskeletons, robot systems providing visualised loading control, or EMG-based robotic training) compared with usual care or conventional rehabilitation. Trials focusing exclusively on preoperative rehabilitation, robot-assisted surgical techniques without a postoperative rehabilitation device, non-randomised designs, animal studies, and grey literature were excluded.

In this review, technology-assisted rehabilitation was defined as physiotherapy interventions incorporating robotic systems, wearable exoskeleton devices, EMG-driven rehabilitation robots, or sensor-based systems providing real-time biomechanical or load feedback during therapeutic exercise or gait training. The search was limited to studies published within the last 10 years (2015–2025) to reflect contemporary rehabilitation technologies, as many robot- and sensor-based systems have been introduced or substantially updated during the past decade.

Data sources and search strategy

We searched PubMed, Embase, CINAHL, Scopus, and Web of Science databases. Search terms combined concepts for THA (e.g., “total hip arthroplasty”, “hip replacement”) and robot- or technology-assisted rehabilitation (e.g., “robot”, “exoskeleton”, “biofeedback”, “assistive device”). No language restrictions were applied.

Study selection and data extraction

Three reviewers independently screened titles/abstracts, assessed full texts, and extracted data using a standardised form. Disagreements were resolved by consensus. Inter-rater

reliability across reviewers showed substantial agreement (Fleiss’ kappa = 0.798).

Risk of bias assessment

Risk of bias was assessed using the Cochrane risk of bias tool (random sequence generation, allocation concealment, blinding of participants/personnel, blinding of outcome assessment, incomplete outcome data, and selective reporting) [26]. Any disagreements between reviewers regarding risk of bias assessments were resolved through discussion and consensus. If consensus could not be reached, a third reviewer adjudicated the decision.

Data synthesis

Because of substantial heterogeneity across studies, a quantitative meta-analysis was not performed. The included trials differed markedly in several aspects, including the type of technological intervention (exoskeleton systems, load-control robotic devices, and EMG-based rehabilitation robots), the timing of rehabilitation initiation, the intensity and duration of intervention protocols, and the length of follow-up periods. In addition, outcome measures and reporting formats varied across studies. For these reasons, findings were synthesised narratively.

Results

The database search identified 181 records. After screening and full-text review, three randomised controlled trials met the eligibility criteria (Figure 1).

Study characteristics

Interventions and comparators varied substantially (Table 1). Setoguchi *et al.* [27] evaluated a wearable exoskeleton (Hybrid Assistive Limb) during early rehabilitation over 3 weeks. Liu *et al.* [28] investigated a visualised loading-control robot

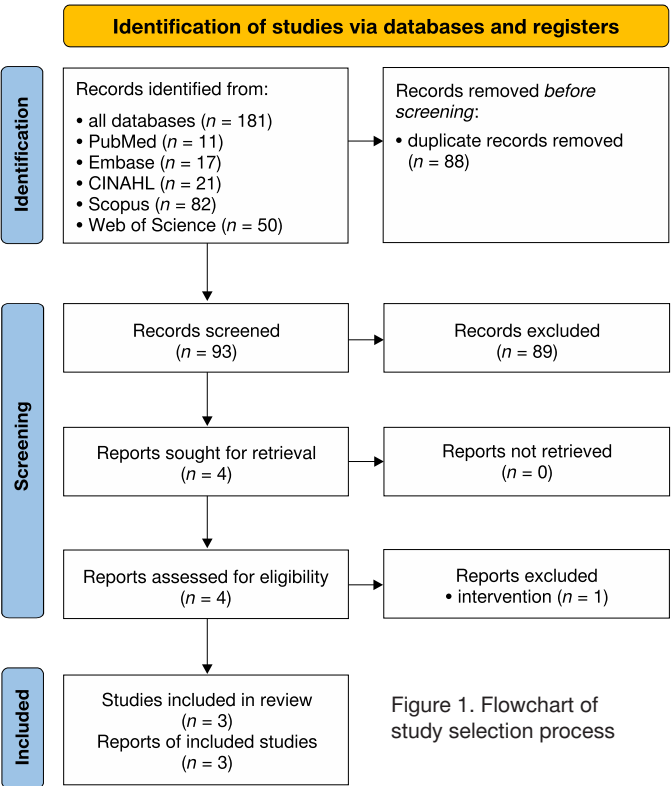


Figure 1. Flowchart of study selection process

combined with conventional rehabilitation, reporting outcomes at 1 month. In turn, Milewska *et al.* [29] examined an EMG-based rehabilitation robot (Luna-EMG) delivered as an inpatient program over 3 weeks in participants enrolled on average 7.2 months post-surgery [27–29] (Table 2).

Risk of bias

Across studies, the reporting of allocation concealment and blinding was limited, resulting in several domains rated

as unclear risk of bias. Outcome assessor blinding was inconsistently described, and selective reporting could not be ruled out in some trials (Figure 2).

Effects by outcome domain (Table 3)

Across the included trials, technology-assisted rehabilitation demonstrated potential benefits for pain, hip ROM, and selected functional outcomes, whereas gait speed and maximal strength findings remained inconsistent.

Table 1. Characteristics of selected studies and participants (n = 3)

Author (year)	Country / setting	Sample size (total n; robot / control)	Participants (indication)	Age (mean ± SD)	Sex (M/F)	Postop timepoint for enrollment	Operation approach
Setoguchi <i>et al.</i> (2022) [27]	Japan / hospital	n = 16 (R:8 / C:8)	coxarthrosis (THA)	R: 74.0 ± 4.47 C: 63.88 ± 7.75	R: 2/6 C: 2/6	1 week postop	posterior approach
Liu <i>et al.</i> (2025) [28]	China / hospital and home	n = 126 (R:63 / C:63)	femoral neck fracture (THA)	R: 75.4 ± 6.2 C: 76.4 ± 5.0	R: 28/35 C: 32/31	postop day 1–2	posterior approach
Milewska <i>et al.</i> (2025) [29]	Poland / hospital	n = 66 (R:34 / C:32)	advanced osteoarthritis (THR)	R: 71.3 ± 8.2 C: 71.3 ± 9.0	R: 9/25 C: 15/17	R: 6.9 ± 12 months postop C: 7.5 ± 11.1 months postop total mean 7.2 ± 11.5 months postop	not specified

F – female, M – male, C – control group, R – robot (intervention) group
postop – post operation, THA – total hip arthroplasty, THR – total hip replacement

Table 2. Intervention details (n = 3)

Author (year)	Experimental intervention	Robot/device type	Comparator	Dose (length / freq. / duration)	Co-interventions	Rehab phase
Setoguchi <i>et al.</i> (2022) [27]	Hybrid Assistive Limb (HAL)	exoskeleton (bioelectrical signals)	typical PT	40 min / 3 times/ week / 2 weeks (total 6)	ROM, strength training	early postop (weeks 1–3)
Liu <i>et al.</i> (2025) [28]	visualised load-bearing based robot (screen feedback)	load-bearing based robot	standard walker	20–30 min / 3 times/day / 5–7 days + home	preop prehab, ankle pump, isometric quads	acute inpatient and early postop
Milewska <i>et al.</i> (2025) [29]	Luna-EMG robot	EMG-driven diagnostic robot	standard rehab	30 min (15 min/limb) / daily / 3 weeks	gluteal muscles and lower limb rotor exercises	inpatient rehab (3-week stay; mean 7.2 mo postop)

EMG – electromyography, mo – months, postop – post operation, preop prehab – pre operative pre habilitation, PT – physical therapy, rehab – rehabilitation, ROM – range of motion

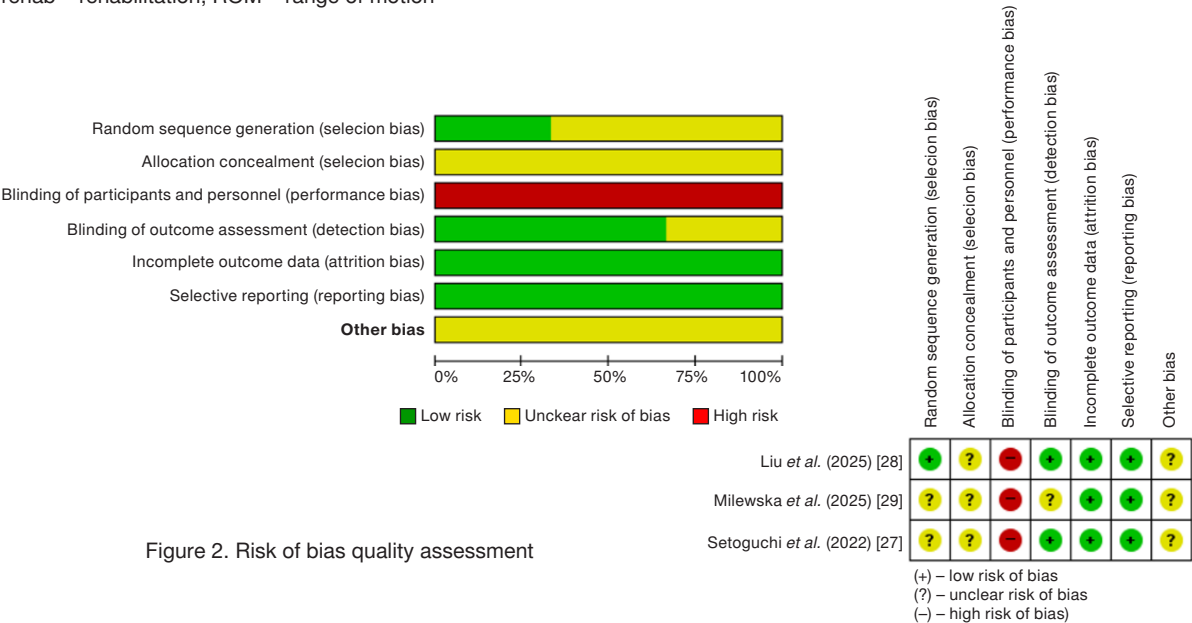


Table 3. Outcomes and between-group effects (n = 3)

Author (year)	Outcome domain	Outcome measure	Time-points	Group results (follow-up) exp vs. ctrl	Between-group comparison (p / stats)	Direction of effect
Setoguchi <i>et al.</i> (2022) [27]	ROM	hip extension	3 wk	−3.2 (mean) vs. −7.5 (mean)	p < 0.05	favours robot
		full range of motion	3 wk	29.1 (mean) vs. 24.2 (mean)	p < 0.05	favours robot
	function	HHS	3 mo	88.3 ± 9.24 vs. 93.9 ± 4.64	p = 0.188	no difference
	gait	single support time (%)	3 wk	7.1 (mean) vs. 1.2 (mean)	no significant difference	no difference
		double support time (%)	3 wk	8.7 (mean) vs. 2.9 (mean)	no significant difference	no difference
		cadence (steps/min)	3 wk	7.6 (mean) vs. 6.5 (mean)	no significant difference	no difference
		velocity (cm/s)	3 wk	0.8 (mean) vs. 0.5 (mean)	no significant difference	no difference
		stride length (cm)	3 wk	19.5 (mean) vs. 8.8 (mean)	no significant difference	no difference
		anterior/posterior variability	3 wk	6.4 (mean) vs. 2.8 (mean)	no significant difference	no difference
		lateral variability	3 wk	7.8 (mean) vs. 4.8 (mean)	no significant difference	no difference
Liu <i>et al.</i> (2025) [27]	pain	VAS score	1 mo	2.2 ± 1.0 vs. 2.5 ± 0.9	p = 0.049	favours robot
	ROM	hip ext-flex ROM	1 mo	80.6 ± 9.0 vs. 73.9 ± 7.2	p = 0.000	favours robot
	function	Harris score	1 mo	80.5 ± 12.9 vs. 75.4 ± 15.2	p = 0.012	favours robot
	gait	3-min walk dist	1 mo	51.0 ± 9.6 vs. 45.2 ± 7.7	p = 0.003	favours robot
Milewska <i>et al.</i> (2025) [29]	strength	max strength	3 wk	27.37 ± 12.45 vs. 27.81 ± 14.63	p = 0.9969	no difference
	QoL	DCFC scale	3 wk	14.71 ± 4.16 vs. 23.81 ± 5.62	p < 0.0001	favours robot

ctrl – control group, DCFC – demographic and clinical features questionnaire, dist – distance, exp – experimental (robot) group, ext-flex – extension-flexion, HHS – Harris Hip Score, mo – month(s), QoL – quality of life, ROM – range of motion, VAS – visual analogue scale, wk – week(s)
Values are presented as mean ± SD unless otherwise indicated. Statistical significance was set at p < 0.05.

Pain/symptoms: Liu *et al.* [28] reported significantly lower pain scores at 1 month in the robot-assisted rehabilitation group compared with usual care. However, the number of trials reporting on this outcome was small, and the rehabilitation protocols were heterogeneous [22, 23, 28].

Hip ROM (with emphasis on hip extension): Liu *et al.* [28] reported improved hip flexion-extension ROM at 1 month, and Setoguchi *et al.* [28] found better hip extension after exoskeleton-assisted training. Overall, selected ROM measures and functional outcomes showed improvement, though the data were derived from a limited number of trials with protocol heterogeneity [21, 27, 28].

Function (Harris Hip Score/HHS): Functional outcomes were mixed. Liu *et al.* [27] reported better HHS at 1 month in the robot-assisted group, whereas Setoguchi *et al.* [28] found no between-group difference at 3 months. The included trials demonstrated variability in assessment timing, co-interventions, and weight-bearing progression [24, 27, 28].

Gait: Gait-related findings were mixed; walking endurance improved in one study [27], whereas gait velocity did not differ between groups in another [28]. Within the assessed trials, technology-assisted interventions demonstrated selective, time-dependent outcomes on specific gait domains, with differences observed between isolated spatiotemporal parameters and summary gait indices [27, 28, 30, 31].

Muscle strength and quality of life: Milewska *et al.* [29] found no between-group difference in maximal muscle strength, but quality of life outcomes favoured the robot-assisted intervention. Across the short-duration interventions evaluated, no significant between-group differences were observed in absolute muscle strength, whereas measures of perceived function and quality of life showed improvement [29, 32, 33].

Discussion

This systematic review found limited randomised evidence on robot- or technology-assisted postoperative rehabilitation after THA. Across three trials, signals of benefit were most apparent for early pain reduction, hip ROM (notably hip extension), selected functional scores, and walking endurance, while effects on gait speed and maximal strength were inconsistent. The heterogeneity of devices (exoskeleton, load-control robot, EMG-based robot), differences in rehabilitation phase (acute vs subacute/chronic), and variation in dosing and co-interventions likely explain the mixed pattern of results [27, 28, 29]. Furthermore, integrating patients at markedly different stages of recovery – ranging from the early acute postoperative phase to several months post-surgery – limits the generalisability of the current findings and warrants cautious interpretation.

These findings are broadly consistent with previous reviews evaluating robotic rehabilitation after joint arthroplasty, which reported potential benefits in functional outcomes but emphasised the limited number of high-quality trials and considerable heterogeneity in intervention protocols. However, unlike previous syntheses that combined hip and knee arthroplasty populations, the present review specifically focuses on THA, highlighting the scarcity of randomised evidence targeting postoperative rehabilitation technologies in this population.

Mechanistically, visual feedback and loading control may facilitate safer and more symmetrical weight-bearing during early gait retraining, potentially reducing symptom provocation and enabling higher training volumes. Exoskeleton assistance may target hip extension deficits by providing mechanical support for terminal stance, while EMG-driven systems may enhance motor learning through biofeedback. Resto-

ration of hip extension and dynamic hip motion is clinically relevant, as the latter has been associated with passive hip range of motion and muscle strength before and after THA [34]. Additionally, feasibility and safety of targeted hip motion assistance using a single-joint Hybrid Assistive Limb robot have been demonstrated in healthy adults, supporting the plausibility of wearable robotic assistance for hip-focused training [35]. Despite these plausible mechanisms, current evidence is insufficient to determine which patient subgroups benefit most or whether early gains persist to mid- and long-term outcomes [23, 27–29].

Future trials should use harmonised outcome sets (pain, hip ROM including extension, functional performance tests, gait measures, patient-reported outcomes, and adverse events) and report device dosing parameters explicitly. Comparative effectiveness studies that isolate the add-on value of robotic systems over well-defined standard rehabilitation, along with longer follow-up, are essential to inform clinical decision-making [22, 23].

From a clinical perspective, the current evidence does not yet support routine implementation of robotic rehabilitation systems after THA. While early improvements in selected outcomes were observed, the limited number of trials and methodological heterogeneity suggest that such technologies should currently be considered experimental or adjunctive rather than standard components of postoperative rehabilitation.

Limitations

Several limitations should be considered. First, only a small number of trials were available, and sample sizes were modest. Second, outcomes and follow-up times were not standardised, precluding quantitative synthesis. Third, reporting of methodological safeguards (allocation concealment, blinding) was often incomplete, which may bias estimates [26]. Fourth, cost-effectiveness and feasibility outcomes were rarely reported, despite their importance for implementation. Fifth, the small sample sizes of the included trials increase the possibility of type II error, meaning that potentially meaningful clinical effects may not have been detected due to insufficient statistical power. Sixth, the reporting of adverse events or safety outcomes in the included trials was limited. Although no major complications were reported, the absence of systematic safety reporting prevents firm conclusions regarding the safety profile of these interventions.

Conclusions

Preliminary evidence suggests that robot- or technology-assisted postoperative rehabilitation after THA may offer potential benefits for selected short-term outcomes, particularly hip extension and walking endurance, but the evidence base remains small and heterogeneous. Robust, adequately powered randomized trials are needed before routine clinical adoption can be recommended.

Data availability

Data extracted and analysed in this review are available from the corresponding author upon reasonable request.

Ethical approval

The conducted research is not related to either human or animal use.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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AI-assisted tools

AI-assisted tools were used for language editing and figure drafting under author supervision. All outputs were verified against the source data, and the authors take full responsibility for the content.

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Supplementary materials

Table S1. PRISMA 2020 Checklist

Section	Item	PRISMA Checklist Item	Location in Manuscript
Title	1	identify the report as a systematic review	title
Abstract	2	provide a structured summary of the review	abstract
Introduction	3	describe the rationale for the review in the context of existing knowledge	introduction
Introduction	4	provide an explicit statement of the objectives or research questions (PICO)	introduction (PICO paragraph)
Methods	5	specify the inclusion and exclusion criteria for the review	eligibility criteria
Methods	6	specify all databases and information sources searched	data sources and search strategy
Methods	7	present the full search strategy for at least one database	data sources and search strategy
Methods	8	describe the process for selecting studies	study selection and data extraction
Methods	9	describe the process for collecting data	study selection and data extraction
Methods	10	list and define all outcomes for which data were sought	eligibility criteria / results
Methods	11	specify methods used to assess risk of bias	risk of bias assessment
Methods	12	specify effect measures used	results
Methods	13	describe methods of synthesis	data synthesis
Methods	14	describe methods used to assess risk of bias due to missing results	risk of bias assessment
Methods	15	describe methods used to assess certainty of evidence	discussion / limitations
Results	16	describe results of search and study selection	results / Figure 1
Results	17	present characteristics of included studies	Table 1 / Table 2
Results	18	present risk of bias for each study	Figure 2
Results	19	present results of individual studies	results / Table 3
Results	20	present results of syntheses	effects by outcome domain
Results	21	present assessments of reporting bias	risk of bias section
Results	22	present certainty of evidence	discussion / limitations
Discussion	23	provide interpretation of results and implications	discussion
Discussion	24	discuss limitations of the evidence	limitations section
Other information	25	provide registration information	methods (OSF registration)
Other information	26	declare competing interests	conflict of interest
Other information	27	describe data availability	data availability

OSF – open science framework, PICO – PICO framework: population (P): adults undergoing primary total hip arthroplasty, intervention (I): robot- or technology-assisted postoperative physiotherapy, comparator (C): usual care or conventional rehabilitation, outcomes (O): pain, hip range of motion, functional outcomes, gait performance, muscle strength, and quality of life