

REVIEW

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# Upper limb robotic rehabilitation following stroke: a systematic review and meta-analysis investigating efficacy and the influence of device features and program parameters

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## Abstract

**Background** Following stroke, upper limb impairment is common and frequently limits ability to perform everyday activities. Due to limited resources, current therapy levels are insufficient to optimise functional improvement. Robotic devices have potential to augment upper limb stroke rehabilitation, but knowledge regarding the optimal device features and intervention parameters is limited. This systematic review and meta-analysis aimed to determine the efficacy of upper limb robotic rehabilitation compared with conventional rehabilitation, and to critically explore the device features and programme parameters that influence rehabilitation outcomes.

**Methods** Six electronic databases were searched for RCTs that compared dose-matched robotic versus conventional rehabilitation following stroke, and measured activity level changes in upper limb outcomes. The efficacy of robotic compared with conventional rehabilitation was evaluated using random-effects ( $I^2 \geq 50\%$ ) or fixed-effect ( $I^2 < 50\%$ ) models. A systematic categorization of robotic device features and intervention parameters was conducted to facilitate subgroup analyses and meta-regression, enabling exploration of how these factors influence rehabilitation outcomes.

**Results** The review included 54 studies, involving 2744 participants. Meta-analysis demonstrated that robotic rehabilitation had a small, statistically significant positive effect on upper limb capacity compared with conventional rehabilitation (SMD 0.14, 95% CI [0.02, 0.26]), however these gains were not maintained at follow-up (SMD 0.05, 95% CI [-0.13, 0.24]). No significant differences were found between robotic and conventional rehabilitation for ADL outcomes either post-treatment (SMD 0.04, 95% CI [-0.05, 0.13]) or at follow-up (SMD 0.05, 95% CI [-0.13, 0.24]). Subgroup analyses provided crucial insights into the factors influencing robotic rehabilitation efficacy, revealing significant effects of device assistance ( $p = 0.0046$ ), joints mobilized ( $p = 0.0133$ ), degrees of freedom ( $p = 0.012$ ), device laterality ( $p = 0.0048$ ), and the number of devices used ( $p = 0.0001$ ).

**Conclusions** The results suggest that robotic rehabilitation does not result in clinically meaningful improvement in either upper limb capacity or ADL performance. However, this study's novel subgroup analyses highlight specific

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device features and intervention parameters that significantly influence efficacy. These findings provide critical guidance for the design, implementation, and future research of robotic rehabilitation.

**Keywords** Stroke, Rehabilitation, Robotics, Upper limb, Activities of daily living, Systematic review, Meta-analysis

## Introduction

Stroke is the third leading cause of adult disability worldwide, with 101 million people living with long-term effects [1]. Amongst people who have had a stroke, around 80% experience upper limb impairment, with 65% still experiencing deficits six months post stroke [2, 3]. This impairment significantly affects individuals' well-being and quality of life by limiting their ability to engage in daily activities [4]. Following a stroke some spontaneous motor recovery occurs, but further improvements usually rely on engagement in rehabilitation delivered by a specialised multidisciplinary team [5, 6]. Effective rehabilitation programmes emphasise high doses of therapy incorporating repetition, challenge, and task-specific practice to promote upper limb recovery [7–9]. However, the amount of rehabilitation currently being delivered is often insufficient to elicit optimal functional change, due to limited resourcing of rehabilitation services, shortages of clinicians and high caseloads [10]. Delivering optimum doses of rehabilitation therefore continues to be challenging for stroke services, necessitating a need for enhancing rehabilitation approaches.

The implementation of robotic devices offers a potential solution to address this shortfall by facilitating upper limb movements akin to conventional rehabilitation [11]. Robotic rehabilitation could improve functional outcomes for people recovering from stroke by enabling greater repetitions of upper limb movement, task specific practice and grading of the challenge level [12–14]. Rehabilitation robotics are classified according to their placement and the application of force to the upper limb, where exoskeleton devices have an external structural mechanism with the robot axes aligned with the anatomical axes of the wearer [15], whereas end-effector devices are attached to the wearer's distal upper limb and generate forces at the interface [16].

In this dynamically evolving field, upper limb stroke rehabilitation robotics have been evaluated through randomised control trials (RCTs) to gauge efficacy compared to conventional rehabilitation. Previous systematic reviews have investigated the overall effectiveness of rehabilitation robotics for upper limb rehabilitation following stroke [17–19], primarily focusing on 'body functions and structures' and 'activity' level outcomes according to the International Classification

of Functioning, Disability, and Health (ICF) [20]. 'Body functions and structures' are defined as the anatomical parts and physiological functions of body systems [20] and include measures of muscle strength and motor control. Systematic reviews evaluating 'body functions and structures' level outcomes have shown robotic rehabilitation may lead to significant improvement in hemiparetic upper limb muscle strength [17, 19] and motor control [17] compared with conventional rehabilitation in dose-matched [17] and non-dose matched trials [19]. Whereas Norouzi-Gheidari et al. [18] found comparable improvements in motor control and strength outcomes when robotic and conventional rehabilitation was dose-matched. However, additional sessions of robotic rehabilitation yielded better motor control outcomes compared with conventional rehabilitation alone [18], suggesting increased rehabilitation dosage may enhance 'body function and structures' outcomes.

Though there is some evidence to suggest that robotic rehabilitation may improve upper limb outcomes at the 'body function and structures' level, these improvements do not necessarily transfer to improved performance at the 'activities' level [21]. 'Activities' are defined by the ICF as the execution of a task or action by an individual [20]. Measures in this domain evaluates upper limb capacity of performing tasks such as unscrewing a lid or picking up an object [22], or evaluates performance during activities of daily living (ADLs) such as toileting or dressing. While some systematic reviews show improvements in upper limb capacity and ADL performance among people with stroke receiving robotic rehabilitation compared to conventional rehabilitation [19], dose matching remains inconsistent across trials. In dose-matched trials, Veerbeek [17] found no significant differences in upper limb capacity and ADL outcomes, and Norouzi-Gheidari [18] found no significant differences in ADL outcomes comparing robotic therapy with conventional rehabilitation. Consequently, the evidence for robotic rehabilitation's efficacy at the 'activity' level remains uncertain. Favourable outcomes in non-dose matched trials with increased sessions raise questions about whether improvements stem from the robotic treatment itself or simply from the additional volume of rehabilitation delivered.

Beyond dose-matching inconsistencies there are also considerable variations in how robotic rehabilitation

interventions are implemented. Studies have employed a range of robotic devices, each with distinct design features, and have implemented them within variable rehabilitation programmes and clinical environments. This has resulted in uncertainty about the best parameters for delivery [23]. To maximise robotic rehabilitation, there is a need to report on, and investigate, the specific features of robotic devices themselves, and the ways the robotic rehabilitation is delivered, which may lead to improved rehabilitation outcomes [24]. Researchers have begun to respond to this need by carrying out RCTs exploring whether features such as gamification of robotic devices [25], level of assistance provided by the device [26], provision of feedback from the device [27], or age of the user [28] has an impact on the effectiveness of robotic rehabilitation. A recent systematic review suggested that device type may be an important feature, with Moggio and colleagues [29] demonstrating that exoskeleton devices were more effective than end-effector devices for improving finger-hand muscle strength [29]. In contrast, Veerbeek's [17] systematic review reported that end-effector devices were more effective compared to exoskeleton devices for improving motor control outcomes for all upper limb joints [17]. Veerbeek [17] also explored subgroups based on the joint targeted by the device, reporting significantly larger improvements in upper limb muscle strength following robotic rehabilitation targeting the shoulder and elbow joints together compared with devices targeting the elbow, shoulder, wrist, hand, the whole arm, or combinations of these. Mehrholz et al. [30] conducted a network meta-analysis categorising robotic devices by key features and found no significant impact on outcomes based on laterality, device type, device placement, or glove-finger-based design [30]. This small body of emerging evidence suggests some device features may be more important in driving intervention efficacy.

This literature shows that there is uncertainty regarding the effectiveness of upper limb robotic rehabilitation on 'activity' level outcomes following stroke, and

limited evidence about the robotic device features and programme parameters that impact these outcomes, where many variables remain unexplored. Clarifying best delivery could enhance device design and implementation [23]. Therefore, this systematic review and meta-analysis aimed to 1) determine the efficacy of upper limb robotic rehabilitation on 'activity' level outcomes of upper limb capacity and ADL, in comparison with conventional rehabilitation in dose-matched trials, and 2) analyse the robotic device features and programme parameters which may contribute to improved robotic rehabilitation outcomes.

## Methods

This systematic review was registered in the PROSPERO database (CRD42022285794) and carried out according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [31].

## Search strategy

A systematic search was carried out in databases including Web of Science, OVID, CINAHL, Medline, Scopus, and PubMed Central (PMC). Table 1 shows the applied search strategy for identifying relevant literature. No start date limit was set on the search criteria of the databases, and the final search was completed on 31 March 2023. In addition to the database searches, reference lists of included RCTs, and relevant systematic and narrative reviews were screened for relevant publications.

## Study screening and eligibility assessment

All studies identified by the search strategy were uploaded to the Covidence online systematic review management tool, and duplicates were removed. Titles and abstracts, as well as relevant full-text articles were screened by one reviewer (KB) in accordance with the eligibility criteria in Table 2. A second reviewer (NS) was consulted if eligibility was unclear, and a consensus was reached.

**Table 1** Database search strategy

Rehabilitat\* OR exercise OR therapy OR train\*

AND

Cerebrovascular accident OR cerebral vascular accident OR Cardiovascular accident OR CVA OR stroke OR acute stroke OR chronic stroke

AND

Robotic\* OR robot OR robot assisted OR exoskeleton OR end-effector OR electromechanical

AND

Upper extremity OR upper limb OR arm OR hand OR wrist OR shoulder OR elbow OR finger

AND

Random\* control\* trial OR RCT OR control\* trial OR CT OR clinical trial

\* Truncation used to capture word variants

**Table 2** Eligibility criteria

	Inclusion	Exclusion
Participants	Adults over the age of 18 who had suffered a stroke resulting in loss of upper limb function	Adults who have suffered a cerebellar or brainstem stroke
Experimental intervention	Robotic exoskeleton or end-effector rehabilitation targeting the upper limb, for one or more sessions Robotic and conventional rehabilitation were dose-matched in terms of total training time	Robotic rehabilitation combined with another exploratory intervention such as transcranial direct current stimulation (tDCS) or brain-computer interfaces (BCI)
Comparison intervention	Conventional occupational therapy or physiotherapy interventions to rehabilitate upper limb, such as task-specific training, strength training, repetitive practice, constraint-induced movement therapy (CIMT)	Comparison interventions that also use robotics unless the robotic component was very brief (< 10 min) Comparison treatment combined with another exploratory intervention such as tDCS or BCI
Outcomes	Evaluation of 'activity' level outcomes including (a) upper limb capacity or (b) ADL as classified by the International Classification of Functioning Disability and Health model (ICF)	
Study design	Randomised control trials (RCTs) with a parallel-group trial design Where there was more than one experimental group, provided that the study followed a parallel-group design and fit other criteria, data from both experimental groups was included	Randomised crossover trials or other study designs
Publication	Full-text peer-reviewed journal articles published in English	Conference abstracts

### Category development, piloting and training process

An initial literature review was conducted to identify a classification framework for upper limb robotic rehabilitation which would support data extraction. However, no existing system was identified which comprehensively captured both robotic device features [24, 32, 33] and intervention parameters [34, 35] relevant to the research question. To address this gap, a structured framework for categorization of key device features and program parameters was developed based on literature findings and expert input from the research team, including engineers (WB, UR), a designer (ERR), an occupational therapist (KB), and physiotherapists (NS, GA). Experts provided insights on whether features or parameters were considered clinically relevant, definable, and generally reported either in research or associated materials. Proposed categories were discussed by the research team and either refined or excluded through consensus.

A custom-designed extraction form was developed in Excel to ensure consistency and accuracy in data collection. Data extraction was piloted by KB, NS, and GA; each independently extracted data from 13 selected articles, then convened to clarify and refine definitions for each category. Consensus was achieved before proceeding with full data extraction. The final categorization framework is presented in Table 3.

Where multiple devices were used in the intervention, data was extracted and categorised to reflect the overall effect of all devices. For example, if two different devices were implemented, where the first device produced wrist

movement in a single plane (flexion/extension) and the second device produced shoulder movement in three planes (abduction/adduction, flexion/extension, rotation), the 'joints mobilised' category would be 'whole arm', and the 'degrees of freedom' category answer would be '4'.

### Data extraction and categorisation

Following completion of the data extraction piloting phase, KB completed the remainder of the extractions independently. A second reviewer (NS) was consulted if extraction was unclear, and a consensus was reached. Extracted data included the general study information (study authors, year of publication, number of experimental groups, sample size) and participant characteristics (age & SD, time since stroke & SD). and robotic device including description (device type, degrees of freedom, joints mobilised, assistance, gravity, portability, laterality, gamification, feedback), robotic intervention delivery parameters (setting, training time, number of devices, real word interaction, bimanual training, supervision amount, supervisor qualification), and comparison treatment description.

Outcome measures were extracted and categorised as: a) upper limb capacity, and b) ADL. Upper limb capacity was defined according to the ICF domains: 'fine hand use' [d440] and 'hand and arm use' [d445]. This construct included measures such as the Action Research Arm Test (ARAT), Wolf Motor Function Test (WMFT), and Box and Blocks Test (BBT). ADL was defined as a

**Table 3** Device feature and programme parameter categories

Subgroup analysis category	Category descriptor	Category levels
Device features		
Device type	The type of device determined by how the device was applied to the upper limb Where 'exoskeletons' (Fig. 1) were defined as having an external structural mechanism where the robot axes are aligned with the anatomical axes of the wearer; and 'end-effectors' (Fig. 2) were defined as devices which provide support and forces to the wearer's limb only at its most distal part which is attached to the wearer's extremity	Exoskeleton OR End-effector
Degrees of freedom (DOF)	The number of DOF or axes of motion of the participant's upper limb controlled or moved by the robot (Fig. 3). Main movements (degrees of freedom) of the upper extremity included: 1. Shoulder adduction/abduction 2. Shoulder flexion/extension 3. Shoulder internal(medial)/external(lateral) rotation 4. Elbow flexion/extension 5. Forearm pronation/supination 6. Wrist adduction (ulnar deviation)/abduction (radial deviation) 7. Wrist flexion/extension 8. Flexion/extension of all fingers = 1 DOF (not 4) 9. Flexion/extension of thumb = 1 DOF (Flexion/extension of all fingers and thumb = 2 DOF (hand grasp/release)) 10. Thumb adduction/abduction	Continuous moderator (Between 1–10)
Joints mobilised	The joints of the upper limb that were moving as a result of the action of the robotic device (not the fixation points of the device on the upper limb) Where 'proximal' encompassed devices which moved the upper limb from the shoulder to the elbow joint, 'distal' devices moved the upper limb anywhere past the elbow joint including the forearm, wrist, hand, or fingers, and 'whole arm' included devices which moved the upper limb at both proximal and distal components	Proximal OR Distal OR Whole arm
Assistance	The amount of assistance provided by the device to the wearer to perform upper limb movements Where 'full' assistance required no active movement from the wearer and device completed the entirety of the movement (the upper limb was moved passively). Devices were categorised as providing 'partial' assistance when the wearer actively contributed to the movement and the device supplemented the movement. Devices which provided both full and partial assistance were classified 'both' No attempt was made to quantify the amount of assistance provided by the device in the 'partial' category due to a lack of consistency and clarity in the reporting of what constituted differing amount of assistance	Full OR partial OR both
Gravity	The planes of movement in space which the device moved the upper limb Where 'against gravity' encompassed devices which moved the upper limb in the vertical plane, and 'planar' included devices which moved the upper limb in the horizontal plane. Some devices generated movements in both planes	Against gravity OR planar OR both
Portability	The portability of the device while it is in use by the wearer Where 'portable' devices allowed the wearer to mobilise on foot while the device was in use, and 'stationary' devices required that the wearer stay fixed at the device (sitting, lying, or standing while in use)	Portable OR stationary
Laterality	The attachment of the device to either one or both upper limb(s) Where 'unilateral' devices were only worn on the affected upper limb, and 'bilateral' devices were attached to both the impaired and unimpaired upper limb. Some devices were able to be used both bilaterally and unilaterally in the intervention	Unilateral OR bilateral OR both

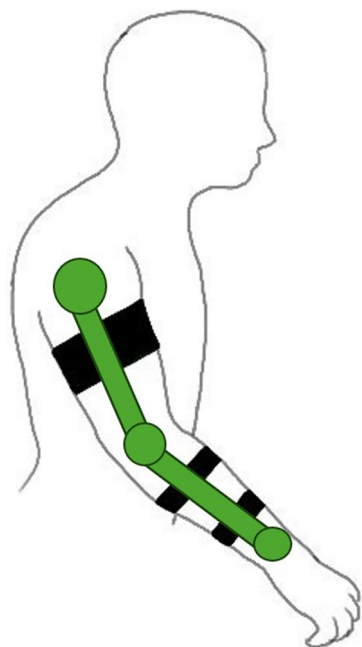
**Table 3** (continued)

Subgroup analysis category	Category descriptor	Category levels
Gamification	The inclusion of gamification or virtual reality paired with the device Where 'gamification' included devices where a game component was present, and 'no gamification' included devices where there was no game component as part of the intervention delivery	Gamification OR No gamification
Feedback	The ability for the device to provide objective feedback on the wearer's performance or knowledge of results Where 'feedback' included devices which provided feedback, and 'no feedback' included devices which did not provide feedback. Feedback provided from the device (not the clinician) included modalities such as a game score, a beep/noise, or a repetition count No attempt was made to differentiate different types of feedback due to a lack of consistency and clarity in the reporting of feedback provided by the device	Feedback OR No feedback
Technology advancement	Exploring improvement of effectiveness of devices as the development of technology advances Where the year of publication was taken to measure by proxy whether devices developed in more recent years were more effective than 'older' devices	Continuous moderator (Year of publication)
Programme features		
Setting	The location where the device was implemented with the participant for the trial Where 'inpatient' included interventions delivered to stroke patients in an inpatient hospital setting, 'outpatient' included settings where the participants travelled to attend sessions, such as outpatient hospital clinics, rehabilitation research centres, and medical centres, and 'home' included interventions delivered in the participants' home environment	Inpatient OR Outpatient OR Home
Participant age	The mean age of the participants in the experimental and conventional trial groups	Continuous moderator (Mean age)
Time since stroke	The mean amount of time in weeks post-stroke which the participants in the experimental and conventional groups commenced the trial protocol	Continuous moderator (Mean time in weeks)
Total training amount	The amount of intervention time participants spent training with the robotic device as the experimental treatment and the dose matched time with the conventional treatment Additional 'usual care' intervention time for both groups was not included in the dose amount. The total hours spent training with the intervention was calculated by multiplying session duration (hours) x frequency of weekly trainings (sessions per week) x number of weeks in training (weeks of training) Where a range value for time was given, the average time was taken. For example, 90–105 min, 97.5 was taken	Continuous moderator (Time spent training with intervention in hours)
Delivery mode	The number of participants receiving the treatment at the same time during the intervention Where 'solo' interventions were delivered with one participant at a time, and 'group' interventions were delivered with two or more participants present during the session	Solo OR Group
Number of devices	The number of devices which were utilised as part of the experimental intervention protocol Interventions were either delivered with a 'single' device, or utilised 'multiple' devices	Single OR multiple
Real-world (object) interaction	Whether the device enables interaction with real world objects (such as blocks, mugs, other objects used in ADLs or rehabilitation interventions) and if this was a part of how the intervention was delivered Interventions were either delivered facilitating 'object interaction' or were delivered with 'no object interaction.'	Object interaction OR No object interaction

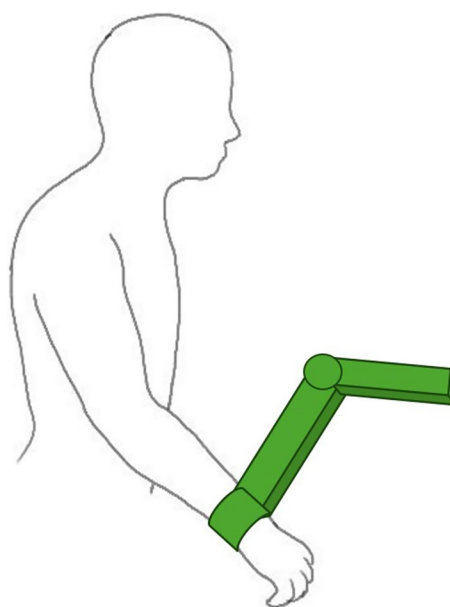
**Table 3** (continued)

Subgroup analysis category	Category descriptor	Category levels
Bimanual training	The utilisation of bimanual training in the intervention delivery. If the impaired upper limb with the device attached and the non-affected upper limb not wearing the device were both engaged in a bimanual task, such as folding clothes at the same time. This was also applicable to devices which were attached to both upper limbs Devices were either implemented in a 'bimanual training' intervention programme, or there was 'no bimanual training.'	Bimanual training OR No bimanual training
Supervision	The level of supervision provided to the user during training sessions The participant either completed 'self-training' with distant, limited, or no supervision, or was fully 'supervised' during training sessions No attempt was made to quantify the proportion of training sessions completed under supervision due to lack of consistency and clarity in the reporting of supervision provided during intervention delivery	Self-training OR Supervised
Supervisor qualification	The qualification level of the supervisor overseeing the robotic intervention programme implementation Where a 'professional' comprised an Occupational Therapist or Physiotherapist supervising the device implementation, and an 'assistant' comprised a therapy assistant, rehabilitation assistant, or research assistant providing supervision	Professional OR Assistant

combination of the following ICF domains: 'washing oneself' [d510], 'caring for body parts' [d520], 'toileting' [d530], 'dressing' [d540], 'eating' [d550], and 'drinking' [d560]), and included measures such as the Barthel Index

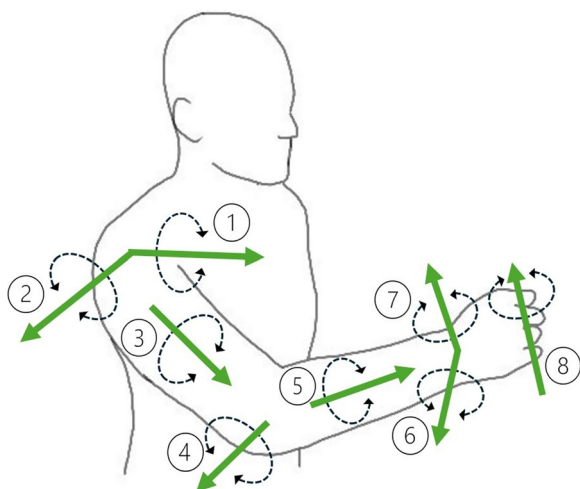


**Fig. 1** Exoskeleton type device



**Fig. 2** End-effector type device

(BI) and the Functional Independence Measure (FIM). The number of outcomes was limited to one upper limb capacity and one ADL per study. Where more than one measure of upper limb capacity or ADL were reported, the outcome was selected based on a hierarchy determined by the following factors: (a) reliability and validity of the measures, (b) how much/how well the measure addressed the construct, (c) how many items in the measure addressed the construct, and (d) how commonly



**Fig. 3** Upper limb DOF for robotic rehabilitation

used the tool was in practice. For example [36], Functional Independence Measure (FIM) score was taken over the Motor Activity Log (MAL) score for ADL construct, as while both had good reliability and validity, the FIM addresses more ADL items than the MAL (MAL addresses some upper limb capacity constructs).

Outcome measure data were extracted according to the above (measures used, unit of measurement, ICF construct addressed, measurement timepoints), and results from all studies were also extracted (mean & SD for experimental and conventional groups at baseline, post-treatment, and follow up timepoints).

Where studies had multiple experimental groups, data was extracted for each study arm that met the inclusion criteria and were treated as a separate comparison. Where a publication did not describe device feature or intervention parameter characteristics in enough detail, the researchers investigated device user manuals, manufacturer websites, other published material to gather full detailed information for data extraction. When further clarification was required regarding experimental device and intervention descriptions or missing outcome data, the study authors were contacted to request this information.

### Methodological quality

To obtain valid conclusions from the systematic review and meta-analysis, two reviewers (KB and SO) independently assessed included studies utilising the Cochrane Risk of Bias 2 tool (RoB2) [37]. Any disagreements were discussed until consensus was reached. The RoB2 covers five domains of bias, including bias arising from randomisation; bias due to deviations from intended interventions; bias due to missing outcome data; bias in

measurement of the outcome; and bias in selection of the reported result. The overall risk of bias for each study was categorised as low, some concerns, or high risk. RoB2 evaluations were completed for each outcome if a study reported measures for both upper limb capacity and ADL.

### Meta-analyses

To address the first aim of the review, the summary Excel sheet was exported to R and analyses were conducted using the *metafor* package [38, 39]. Meta-analyses were conducted for both pre- to post- intervention scores as well as pre- to follow-up- intervention scores to explore whether any gains were maintained at follow-up. Pre- to post- intervention and pre- to follow-up- intervention mean differences were used for analysis. If not available, these were computed from the individual pre- and post-intervention means and standard deviations. These means and standard deviations were then used to obtain standardised mean differences between the intervention and conventional treatment groups. When standard errors (SEs), but not SDs, were available, the missing SDs were computed with the following formula:  $SD = SE \times \sqrt{n}$  [40]. A random-effects model was used for a meta-analysis if the heterogeneity statistic ( $I^2$ ) was greater than 50%, otherwise the meta-analysis was conducted with a fixed-effects model [17]. Where studies had more than one experimental group, data which had been extracted for each study arm were analysed as separate comparisons (e.g., robotics 1 vs conventional, robotics 2 vs conventional). Pooled effect sizes were reported along with their 95% confidence intervals (CIs). An effect size was considered significant if its CI did not overlap zero. Between-study heterogeneity was reported with both  $\text{Tau}^2$  and  $I^2$  statistics and their statistical significance was reported with a chi-squared test. In the presence of any potential outlying studies, sensitivity analyses were conducted by excluding these studies and reanalysing the data to validate the evidence from the meta-analysis [41].

To address the second aim of the review to determine the effect of various device features and programme features, subgroup analyses were conducted for upper limb capacity and ADL if the overall meta-analysis showed significant pooled effect size and greater than 10% between-study heterogeneity. Separate fixed effects or random effects meta-analyses were performed for each construct. When evaluating features that had categorical variables (such as exoskeleton versus end-effector for type of device), studies were divided into subgroups accordingly. When evaluating features that had continuous variables (such as total training time or participant age), a meta-regression model was employed. Pooled sub-group mean differences were reported with their 95% CIs and the

statistical significance was based on the non-overlap with zero. For continuous moderators, model coefficient signifying the change in pooled mean difference between interventions for each unit change in the moderator is reported with its 95% CI. Statistical significance of the sub-group differences is reported with Cochran's Q statistic, degrees of freedom and p-value. For the continuous moderator, F-statistic along with numerator, denominator degrees of freedom and p-value are reported. Statistical significance threshold was set at 0.05. This analysis plan is in line with the earlier meta-analysis work in post-stroke rehabilitation literature [17].

### Meta-analyses result validation

Result validation checks were completed following the quantitative analysis to ensure validity of the raw data entered into the statistical model. KB examined the direction of effect (positive or negative), and the statistical significance of the effect (indicated by  $p < 0.05$ ) of the results computed by the meta-analyses and compared these to what was reported in the original articles to ensure the results were matched. Any mismatches noted were discussed with UR. If required, UR checked outcome data extractions to ensure accuracy.

## Results

### Study selection

Figure 4 depicts the results of the literature search. Following screening, 54 RCT studies were included in the review.

### Study and participant characteristics

Table 4 depicts the main study and participant characteristics of the RCTs included in the review. The 54 included studies reported data for 2744 participants.

There were 7 multiple-armed studies [42–48] where there was more than one experimental group compared with the conventional group, which were analysed as separate comparisons (e.g., robotics 1 versus conventional, robotics 2 versus conventional). For the purposes of reporting results, these are labelled as separate comparisons; for example, [42] represents unilateral robotic treatment versus conventional treatment and [42] represents bilateral robotic treatment versus conventional treatment.

### Device feature and programme parameters

The full description of device features and programme parameters can be found in the Supplementary File. The graphics below depict the distribution of studies using different device features and intervention parameters across subgroup categories for discrete (Fig. 5) and continuous (Fig. 6) variables.

### Methodological quality

The risk of bias assessment was completed for each outcome for each study and is presented in Fig. 7. Twenty studies measured both upper limb capacity and ADL, where the majority of these ( $n = 13$ ) had the same risk of bias rating across the two outcomes. In seven studies [43, 48, 56, 77, 79, 87, 89], the rating for domain 4 (bias in measurement of the outcome) was 'Low' for upper limb capacity outcomes, and 'Some concerns' for ADL outcomes. For simplicity, these domain 4 ratings have been presented as 'Some concerns' in Fig. 7 and identified with a #. This variability in domain 4 ratings did not affect the overall risk of bias for that outcome within each study. The majority of studies raised concerns regarding bias in Domain 5 due to the absence of reporting a pre-defined data analysis plan. Only one study was identified with a low overall risk of bias, therefore the certainty of the evidence was deemed low to moderate.

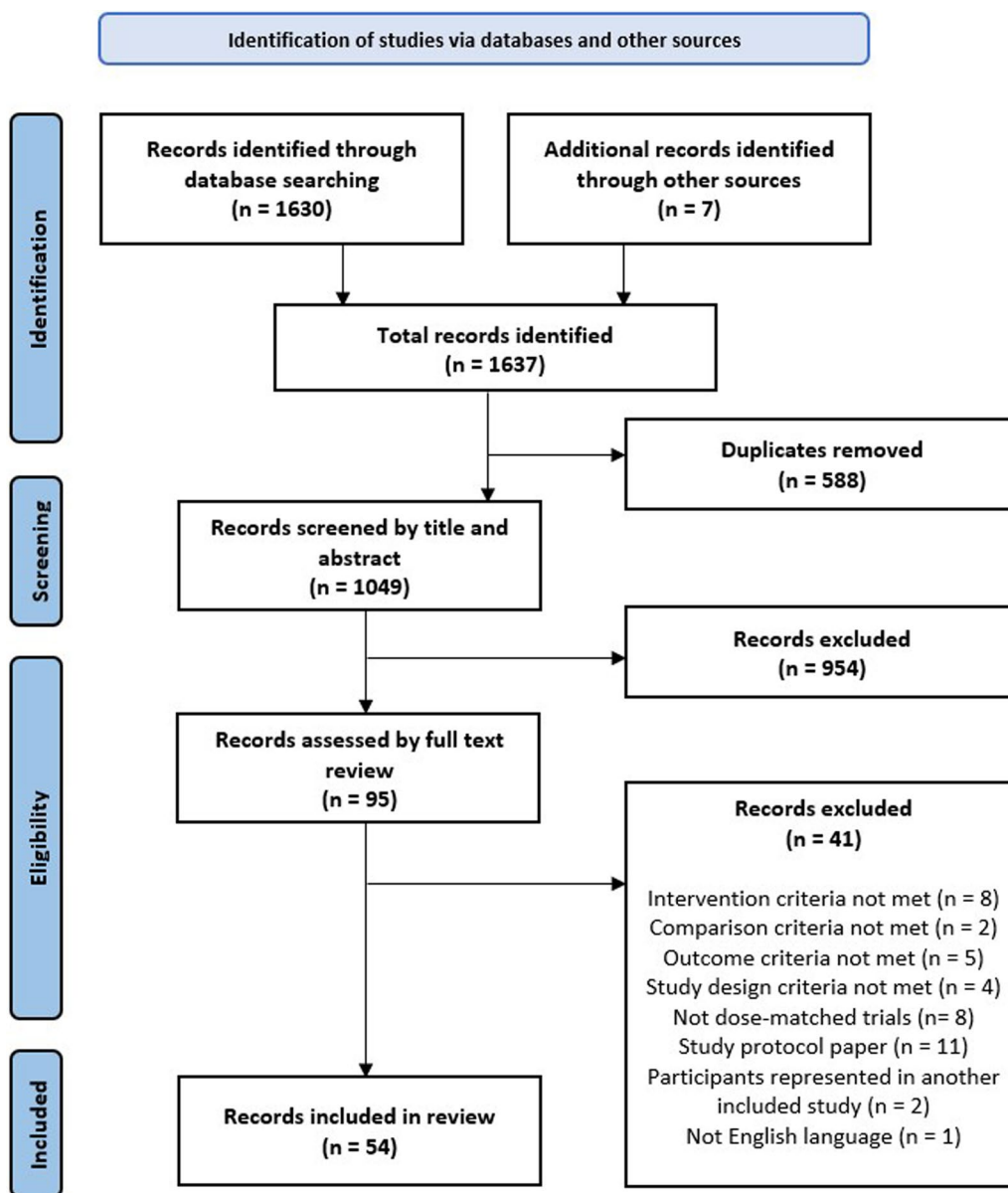
### Quantitative analysis

All included studies were suitable for inclusion in the quantitative analysis.

### Efficacy of robotic rehabilitation on upper limb activity

**Upper limb capacity outcomes** Pre to post-intervention changes in upper limb capacity were assessed in 40 RCTs ( $N = 1995$ ), with 3 studies [42, 43, 48] analysing multiple experimental groups. Post-intervention, the effect of robotic rehabilitation compared to conventional rehabilitation was statistically significant (SMD 0.14, 95% CI [0.02, 0.26]) (Fig. 8A). Changes in upper limb capacity were assessed at follow-up time points in 19 RCTs ( $N = 1118$ ), with one study [43] analysing multiple experimental groups. The significant effect of robotic rehabilitation compared with conventional rehabilitation was not maintained at follow-up (SMD 0.05, 95% CI [− 0.13, 0.24]) (Fig. 8B).

**ADL outcomes** Pre to post-intervention changes in ADL outcomes were assessed in 34 RCTs ( $N = 1894$ ), with 6 studies [43, 44] analysing multiple experimental groups. Post-intervention, the overall effect of robotic rehabilitation was non-significant when compared to conventional rehabilitation (SMD 0.04, 95% CI [− 0.05, 0.13]) (Fig. 9A). Changes in ADL outcomes were assessed at follow-up in 13 RCTs ( $N = 941$ ), with 2 studies [43, 47] analysing multiple experimental groups. There were no significant effects of robotic rehabilitation compared with conventional rehabilitation at follow up (SMD 0.00, 95% CI [− 0.13, 0.13]) (Fig. 9B).



**Fig. 4** Study selection results

**Efficacy of various device and programme features of robotic rehabilitation**

ADL outcomes did not exhibit a significant between-intervention pooled effect size and between-study heterogeneity. Therefore, sub-group analyses were not performed for these outcomes. Whereas the upper limb capacity outcomes showed a significant pooled effect size and greater than 10% between-study heterogeneity at the post-intervention time point. Sub-group analyses and meta-regression were performed for this data.

*Subgroup analyses (discrete variables)* The results from the subgroup analysis of discrete variables are summarised in Table 5 and full analysis details can be found in the Supplementary File. There were statistically significant subgroup differences for the joints mobilised, assistance, laterality, number of participants, and number of devices. These are described further below.

*Device features Joints mobilised by the device (distal, proximal, or whole-arm)*

There was a significant effect of the subgroup “joints mobilised” ( $p = 0.0133$ ), where larger and statistically

**Table 4** Study and participant characteristics

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Aprile et al. [49]	n = 111	6.9w (5.9)	69.5y (10.9)	Motore, Amadeo Tyromotion, Diego Tyromotion	n = 113	6.5w (5.8)	68.5y (11.5)	Soft tissue and joint mobilisation, repetitive practice, movement facilitation, mental imagery, splinting, strengthening, functional tasks	45 min, 5x pw, 6w 22.5 h total	Baseline, 6w, 3 m	ULC: ARAT ADL: MBI
Budhota et al. [50]	n = 22	65.4w (64.5)	56.3y (10.4)	H-man	n = 22	55.7w (46.8)	54.6y (10.9)	Passive mobilisation, active-assisted approaches, neurodevelopmental techniques, repetitive tasks, functional reach training, upper limb inclined board, motorised arm bike	60 min, 3x pw, 6w 18 h total	Baseline, 3w, 6w, 12w, 24w	ULC: ARAT
Burgar et al. [51]	n = 19	2.5w (1.7)	62.5y (8.7)	MIME	n = 18	1.5w (0.7)	68.1y (14.0)	Soft tissue and joint mobilisation, progressive resistive exercises, progression to functional tasks, exposure to MIME device	60 min, 5x pw, 3w 15 h total	Baseline, 3w, 6 m	ULC: WMFT (FAS score) ADL: FIM (UL score)

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Byl et al. [42]	n = 5	530.4w (260.0)	54.2y (20.5)	UL-EXO7	n = 5	332.8w (228.8)	59.3y (6.8)	Task oriented training, repetitive training, postural alignment, reaching, grasping, object manipulation, self-care activities	90 min, 2 x pw, 6w 18 h total	Baseline, 6w	ULC: "Motor performance skill"
Byl et al. [42]	n = 5	436.8w (218.4)	65.2y (5.4)	UL-EXO7	n = 5	332.8w (228.8)	59.3y (6.8)	Task oriented training, repetitive training, postural alignment, reaching, grasping, object manipulation, self-care activities	90 min, 2 x pw, 6w 18 h total	Baseline, 6w	ULC: "Motor performance skill"
Calabro et al. [52]	n = 25	1.4w (0.3)	65y (3.0)	Amadeo Tyromotion	n = 25	1.4w (0.3)	64y (3.0)	Hand therapy, finger movements, upper limb positioning and constraint, movement execution, video-acoustic cueing	45 min, 5 x pw, 8w 30 h total	Baseline, 8w	ULC: 9HPT
Carpinella et al. [53]	n = 19	28w (12.0)	67y (3.0)	Braccio di Ferro	n = 19	21.2w (87.7)	59y (5.8)	Passive and active mobilisation, task-oriented exercises, reach and grasp, moving objects	45 min, 5 x pw, 4w 15 h total	Baseline, 4w	ADL: FIM

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Sample size	Mean time since stroke (SD)	Mean age (SD)			
Chen et al. [54]	n = 10	10.7w (7.8)	47.1y (11.1)	n = 10	7.2w (5.5)	54.9y (14.5)	45 min, 5 x pw, 4w 4w 15 h total	Baseline, 4w	ULC: ARAT ADL: MBI
Conroy et al. [43]	n = 20	156w (104.0)	57y (12.0)	n = 19	208w (312.0)	56y (6.3)	60 min, 3 x pw, 6w 6w 18 h total	Baseline, 3w, 6w, 12w	ULC: WMFT (movement time) ADL: SIS (ADL score)
Conroy et al. [43]	n = 18	260w (416.0)	60y (13.0)	n = 19	208w (312.0)	56y (6.3)	60 min, 3 x pw, 6w 6w 18 h total	Baseline, 3w, 6w, 12w	ULC: WMFT (movement time) ADL: SIS (ADL score)

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Crema et al. [55]	n = 15	NR	49y (16.7)	Gloreha Sinfonia	n = 15	NR	61y (10.0)	Passive motion, arm ergometer, exercises using VR, active movement, reaching, grasping, elevation, spatial orientation, repetitive task training	30 min, 3x pw, 9w 13.5 h total	Baseline, 5w, 9w, 13w	ULC: ARAT
Dehem et al. [56]	n = 23	4w (0.6)	67.3y (11.1)	REApplan	n = 22	3.9w (0.9)	68.6y (19.1)	Motor rehabilitation (intervention not described)	45 min, 4x pw, 9w 27 h total	Baseline, 9w, 6 m	ULC: WMFT (FAS score) ADL: ABILHAND
Fischer et al. [57]	n = 5	231.4w (NR)	71.6y (NR)	Pneumatic orthosis	n = 5	582.4w (NR)	55.6y (NR)	Non-facilitated grasp and release of real and virtual objects, audio feedback	60 min, 3x pw, 6w 18 h total	Baseline, 6w, 10w	ULC: WMFT (movement time)
Frisoli et al. [58]	n = 11	130.4w (86.9)	62y (12.0)	L-EXOS	n = 11	160.8w (104.3)	70y (11.0)	Reaching and grasping tasks, passive movement and stretching, goal directed movement, voluntary action, manipulation of objects, 3D spatial movements	45 min, 3x pw, 6w 13.5 h total	Baseline, 6w	ULC: "Bimanual activity test"
Guo et al. [59]	n = 10	50.8w (23.5)	56.9y (6.1)	Soft Robotic Glove	n = 10	47.4w (34.3)	53.5y (8.3)	Conventional therapy (intervention not described)	60 min, 5x pw, 2w 10 h total	Baseline, 2w, 3 m	ULC: WMFT

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)	
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)
Hesse et al. [60]	n = 4	4.8w (1.0)	60.8y (8.4)	Reha-Digit	n = 4	4.5w (0.6)	60.3y (3.6)	20 min, 5 × pw, 4w 6.7 h total	Baseline, 4w	ULC: BBT ADL: BI
Hesse et al. [61]	n = 25	4.5w (1.0)	71.4y (15.5)	Bi-Manu-Track, Reha-Digit, Reha-Slide, Reha-Slide Duo	n = 25	4.5w (0.6)	69.7y (16.6)	Task oriented motor relearning programme, impairment-oriented arm ability training, repetitions of movements, shaping	Baseline, 4w, 3 m	ULC: ARAT ADL: BI
Hsieh et al. [44]	n = 6	85.3w (28.7)	56y (13.7)	Bi-Manu-Track	n = 6	113.3w (79.6)	54y (8.1)	Neurodevelopmental techniques, functional tasks, muscle strengthening, passive ROM, stretching, fine motor/dexterity training, gross motor training, ADLS	Baseline, 4w	ADL: MAL (AOU score)
Hsieh et al. [44]	n = 6	52w (28.2)	52.5y (2.0)	Bi-Manu-Track	n = 6	113.3w (79.6)	54y (8.1)	Neurodevelopmental techniques, functional tasks, muscle strengthening, passive ROM, stretching, fine motor/dexterity training, gross motor training, ADLS	Baseline, 4w	ADL: MAL (AOU score)

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Hsieh et al. [45]	n = 15	86.7w (47.5)	57.3y (12.9)	InMotion ARM (InMotion 2.0, or MIT-MANUS)	n = 12	101.3w (69.8)	55.3y (10.5)	Passive and active ROM, gross motor training, object manipulation, fine motor training, muscle strengthening, functional task practice	45 min, 5 x pw, 4w 15 h total	Baseline, 4w	ADL: MAL (AOU score)
Hsieh et al. [45]	n = 13	59.7w (26.4)	50.4y (16.7)	InMotion WRIST (InMotion 3.0)	n = 12	101.3w (69.8)	55.3y (10.5)	Passive and active ROM, gross motor training, object manipulation, fine motor training, muscle strengthening, functional task practice	45 min, 5 x pw, 4w 15 h total	Baseline, 4w	ADL: MAL (AOU score)
Hsu et al. [62]	n = 22	54.8w (34.4)	53.1y (13.9)	Bi-Manu-Track	n = 21	58.8w (52.8)	52.6y (12.5)	Sensorimotor stimulation programme, task-specific training, targeted motor performance components of hand grips/grasps, elbow flexion/extension and forearm pronation/supination during functional tasks	40 min, 3 x pw, 4w 8 h total	Baseline, 4w, 3 m	ADL: MAL (AOU score)

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)	
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)
Hsu et al. [63]	n = 17	102.5w (25.6)	55.5 (13.4)	TIGER	n = 15	157.7w (41.3)	56.3y (16.5)	Proprioceptive neuromuscular facilitation, passive ROM exercises, repetitive skill building for ADLs	20 min, 2 x pw, 9w 6 h total Baseline, 9w, 12w	ULC: BBT
Hung et al. [46]	n = 10	82w (94.8)	52y (7.1)	Bi-Manu-Track	n = 10	100w (51.9)	55.5y (9.0)	Muscle tone normalisation, fine motor training, gross motor training, muscle strengthening, functional activity practice	70–75 min, 5 x pw, 4w 24.2 h total Baseline, 4w	ADL: MAL (AOU score)
Hung et al. [46]	n = 10	104w (5.6)	57.5y (5.9)	InMotion WRIST (InMotion 3.0)	n = 10	100w (51.9)	55.5y (9.0)	Muscle tone normalisation, fine motor training, gross motor training, muscle strengthening, functional activity practice	70–75 min, 5 x pw, 4w 24.4 h total Baseline, 4w	ADL: MAL (AOU score)
Kahn et al. [64]	n = 10	303.2w (182.0)	55.6y (12.0)	ARM guide	n = 9	412.4w (192.8)	55.9y (12.3)	Free-reaching training; unconstrained, unassisted repetitive voluntary reaching	45 min, 3 x pw, 8w 18 h total Baseline, 12w, 6 m	ULC: RLAF (Time)
Kim et al. [65]	n = 23	48.9w (90.7)	57.2y (15.1)	Camillo	n = 24	116.2w (175.1)	62.1y (12.4)	Stretching, joint ROM exercises, strengthening exercises, goal-directed functional exercise	30 min, 5 x pw, 4w 10 h total Baseline, 4w	ULC: BBT

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)	
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)
Kim et al. [66]	n = 15	930.8w (302.1)	65.5y (8.4)	HEXO-UR30A	n = 15	915.1w (351.0)	64.5y (7.7)	30 min, 3–4 x pw, 3w 5 h total	Baseline, 3w	ADL: MBI
Kutner et al. [67]	n = 10	38.5w (15.9)	61.9y (13.4)	HandMentor Pro	n = 7	26.3w (18.1)	51y (11.3)	3w 30 h total	Baseline, 3w, 2 m	ULC: SIS (hand score) ADL: SIS (ADL score)
Lee et al. [68]	n = 25	2.2w (1.2)	55.8y (13.6)	Neuro-X	n = 25	2.1w (1.0)	57.9y (11.1)	30 min, 5 x pw, 2w 5 h total	Baseline, 2w	ULC = MFT ADL: K-MBI
Lee et al. [69]	n = 15	73.1w (23.9)	52.1y (14.1)	REJOYCE	n = 15	75.5w (22.0)	50.3y (11.2)	30 min, 5 x pw, 8w 20 h total	Baseline, 8w	ADL: MBI
Liao et al. [70]	n = 10	95.6w (53.6)	55.5y (11.2)	Bi-Manu-Track	n = 10	88.8w (69.9)	54.6y (8.2)	75–85 min, 5 x pw, 4w 26.7 h total	Baseline, 4w	ADL: FIM

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Lin et al. [71]	n = 82	20.3w (23.3)	59.4y (11.0)	FLEXO-Arm1	n = 86	22.6w (25.5)	58.7y (12.9)	Gentle stretching, ROM exercises, strengthening exercises, facilitation, active-assisted movements, activities of daily living, functional tasks	30 min, 5 x pw, 3w 7.5 h total	Baseline, 1w, 3w	ADL: MBI
Lo et al. [72]	n = 49	187.2w (208.0)	66y (11.0)	InMotion ARM (InMotion 2.0, or MIT-MANUS), InMotion HAND, InMotion Linear robot, InMotion WRIST (InMotion 3.0)	n = 50	322.4w (260.0)	63y (12.0)	Assisted stretching, shoulder stabilisation activities, arm exercise, functional reaching tasks	60 min, 3 x pw, 12w 36 h total	Baseline, 12w, 36w	ULC: WMFT (movement time)
Lum et al. [73]	n = 13	120.8w (89.4)	63.2y (13.0)	MIME	n = 14	115.2w (94.3)	65.9y (9.0)	Establishing postural base of support, shoulder alignment facilitation, graded arm use in functional leisure and self-care tasks, re-education of muscles using sensorimotor approach, progression of movements, robotic exposure	40 min, 3 x pw, 8w 16 h total	Baseline, 8w, 6 m	ADL: FIM

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)			
Lum et al. [47]	n = 10	13w (6.6)	62.3y (8.9)	MIME	n = 6	10.6w (6.6)	59.9y (13.5)	50 min, 3–4 x pw, 4w 12.5 h total	Baseline, 4w, 6 m ADL: FIM
Lum et al. [47]	n = 9	10w (5.7)	69.8y (12.0)	MIME	n = 6	10.6w (6.6)	59.9y (13.5)	50 min, 3–4 x pw, 4w 12.5 h total	Baseline, 4w, 6 m ADL: FIM

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Intervention description	Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)	
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Sample size	Mean time since stroke (SD)	Mean age (SD)					
Lum et al. [47]	n = 5	6.2w (2.2)	72.2y (26.2)	n = 6	10.6w (6.6)	59.9y (13.5)	MIME	50 min, 3–4 x pw, 4w 12.5 h total	Baseline, 4w, 6 m	ADL: FIM	
								Establishing postural base of support, shoulder alignment facilitation, graded arm use in functional leisure and self-care tasks, re-education of muscles using sensorimotor approach, progression of movements, robotic exposure, verbal feedback from clinician			
Ma et al. [74]	n = 10	10w (5.9)	59y (10.6)	n = 9	10.33w (6.2)	56.4y (8.8)	Exoskeletal Hand Device	60 min, 5 x pw, 4w 20 h total	Baseline, 2w, 4w	ULC: WMFT (FAS score)	
								active-assisted finger movements, bimanual training, task-oriented training, object manipulation			
Masiero et al. [75]	n = 14	1.2w (0.5)	65.6y (9.2)	n = 16	1.5w (0.3)	66.8y (7.9)	NeReBot	40 min, 5 x pw, 5w 16.7 h total	Baseline, 5w, 3 m, 7 m	ULC = BBT ADL: FIM (motor score)	
								Bobath techniques, proprioceptive exercises, functional re-education, passive and active assisted mobilisation for hand and wrist			

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Intervention description	Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Sample size	Mean time since stroke (SD)	Mean age (SD)				
Page et al. [76]	n = 8	178.8w (153.6)	59y (12.9)	n = 8	427.2w (458.4)	58.5y (9.5)	Myomo	30 min, 3 x pw, 8w 12 h total	Baseline, 8w	ULC: SIS (hand score) ADL: SIS (ADL score)
Rabadi et al. [77]	n = 10	2.7w (0.7)	79.5y (6.2)	n = 10	3.2w (2.6)	67.8y (12.7)	InMotion 2.0 (MIT-MANUS)	40 min, 5 x pw, 2-3w 8 h total	Baseline, 3w	ULC: ARAT ADL: FIM (motor score)
Ranzani, et al. [78]	n = 17	3.1w (1.5)	70y (12.8)	n = 16	3.1w (1.3)	67.5y (11.4)	ReHapticKnob	45 min, 3-4 x pw, 4w 11.3 h total	Baseline, 4w, 8w, 6 m	ULC: BBT

Repetitive task specific practice, unilateral and bilateral tasks, purposeful activity improving motor control, coordination, strength, endurance, and proprioception, tasks broken into component segments, grading Self-ROM exercises, self-directed movements, use of unaffected arm to actively assist paretic arm

Neurocognitive therapy approach, haptic and postural perception, object discrimination, grasping, reaching, pinch, texture identification, thumb/finger flexion/extension, forearm pronation/supination, passive and active training

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)	
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)
Reinkensmeyer et al. [79]	n = 13	260w (188.0)	60y (10.0)	Pneu-Wrex	n = 13	268w (224.0)	61y (13.0)	50 min, 3 x pw, 8w 20 h total	Baseline, 8w, 3 m	ULC: BBT ADL; MAL (AOU score)
Rodgers et al. [80]	n = 257	32.5w (13.6)	59.9y (13.5)	InMotion ARM (InMotion 2.0, or MIT-MANUS), InMotion HAND, InMotion WRIST (InMotion 3.0)	n = 259	33.5w (12.9)	59.4y (14.3)	45 min, 3 x pw, 12w 27 h total	Baseline, 12w, 6 m	ULC: ARAT ADL; BI (ADL score)
Sale et al. [81]	n = 11	4.3w (1.0)	67y (12.4)	Amadeo Tyromotion	n = 9	4.3w (1.0)	72.6y (9.0)	40 min, 5 x pw, 4w 13.3 h total	Baseline, 4w, 3 m	ULC: BBT
Şenocak et al. [82]	n = 19	17.4w (6.9)	60.2y (10.5)	ExoRehab X	n = 22	23.7w (4.6)	63.7y (9.1)	60 min, 5 x pw, 6w 30 h total	Baseline, 6w	ULC: WMFT (FAS score)

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Singh et al. [83]	n = 13	60w (89.5)	41.1y (12.8)	Electromechanical robotic exoskeleton	n = 14	44.8w (21.7)	42.7y (9.3)	Passive stretching, fist making, ball squeezing and releasing, lock and key movements, muscle facilitation techniques, task-oriented training, reaching and grasping objects	45 min, 5 x pw, 4w 15 h total	Baseline, 4w	ADL: BI
Susanto et al. [84]	n = 9	65.6w (23.2)	50.7y (9.0)	Hand exoskeleton robot	n = 10	64.4w (20.4)	55.1y (10.6)	Passive stretching, reaching, finger flexion/extension, grasp/pinch practice while moving sponge, robotic exposure	50 min, 4 x pw, 5w 16.7 h total	Baseline, 5w, 6 m	ULC: WMFT (functional score)
Takahashi et al. [36]	n = 30	6.8w (1.0)	65.2y (10.9)	ReoGo	n = 26	6.7w (1.2)	64.6y (11.5)	Upper limb exercises for stretching, ROM, reaching, grasping/releasing, pinching, ADL training	40 min, 7 x pw, 6w 28 h total	Baseline, 6w	ULC: WMFT (movement time) ADL: FIM (motor score)
Takebayashi et al. [85]	n = 44	163.4w (242.5)	59y (12.0)	ReoGo-J	n = 37	149w (164.3)	58y (10.0)	Sanding, pinching, stretching, repetitive reaching/grasping/releasing practice, stretching, joint ROM exercises, correct-movement exercises, ADLs	40 min, 3 x pw, 10w 20 h total	Baseline, 5w, 10w	ULC: ARAT

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)	
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)
Thielbar et al. [86]	n = 11	380w (456.0)	61y (12.0)	VAEDA	n = 11	192w (188.0)	56y (10.0)	60 min, 3 x pw, 6w 18 h total	Baseline, 6w, 10w	ULC: WMFT (movement time)
Timmermans et al. [87]	n = 11	145.6w (150.8)	61.8y (6.8)	Haptic Master	n = 11	192.4w (156.0)	56.8y (6.4)	60 min, 4xpw, 8w 32 h total	Baseline, 8w, 3 m	ULC: ARAT ADL: MAL
Tomicić et al. [88]	n = 13	5w (1.4)	56.5y (7.4)	Arm Assist	n = 13	5.3w (1.1)	58.3y (5.2)	30 min, 5 x pw, 3w 7.5 h total	Baseline, 3w	ULC: WMFT (FAS score) ADL: BI
Vanoglio et al. [89]	n = 15	2.2w (1.0)	72y (11.0)	Gloreha Professional	n = 15	2.5w (1.1)	73y (14.0)	40 min, 5 x pw 6w 20 h total	Baseline, 6w	ULC: 9HPT ADL: Quick-DASH

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Villafañe et al. [90]	n = 16	NR	67y (11.0)	Glireha Professional	n = 16	NR	70y (12.0)	Assisted stretching, shoulder and arm exercises, functional reaching tasks	30 min, 5 x pw, 3w 4.5 h total	Baseline, 3w	ADL: BI
Volpe et al. [91]	n = 30	3.2w (0.2)	62y (2.0)	InMotion 2.0 (MIT-MANUS)	n = 26	3.7w (0.2)	67y (2.0)	Goal-directed movement, use of unimpaired upper limb to assist task, facilitation, robotic exposure	60 min, 5 x pw, 5w 2.5 h total	Baseline, 5w	ADL: FIM (motor score)
Volpe et al. [92]	n = 11	140w (28.0)	62y (3.0)	InMotion 2.0 (MIT-MANUS)	n = 10	160w (44.0)	60y (3.0)	Active assisted arm exercise with Monark Rehab Trainer, scapular stabilisation drills, static stretching, goal-directed movements, Bobath-based treatment activities	60 min, 3 x pw, 6w 18 h total	Baseline, 3w, 6w, 3 m	ULC: ARAT
Wolf et al. [93]	n = 51	16.5w (7.6)	59.1y (14.1)	Hand Mentor Pro	n = 48	18.2w (6.6)	54.7y (12.2)	Self-ROM, weight-bearing activities, active assisted exercises with a cane, shoulder exercises, elbow/forearm exercises, wrist/hand exercises, task-based activities	120 min, 5 x pw, 8w 80 h total	Baseline, 8w	ULC: WMFT (FAS score)

**Table 4** (continued)

Author	Experimental intervention (RT)			Conventional intervention (CT)			Dose-matched intervention amount	Outcome time points	Outcomes (construct: measurement name)		
	Sample size	Mean time since stroke (SD)	Mean age (SD)	Intervention description	Sample size	Mean time since stroke (SD)				Mean age (SD)	Intervention description
Wu et al. [94]	n = 14	72w (34.6)	55.1y (12.7)	Bi-Manu-Track	n = 14	70.3w (39.2)	51.3y (6.2)	Weight bearing, stretching, strengthening of the paretic arm, coordination, unilateral and bilateral fine motor tasks, balance, compensatory practice of functional tasks	70–80 min, 5x pw, 4w 25 h total	Baseline, 4w	ULC: SIS (hand score)
Wu et al. [48]	n = 18	76w (62.0)	55y (9.9)	Bi-Manu-Track	n = 17	93.6w (61.0)	54.2y (9.8)	Weight bearing, stretching, strengthening of the paretic arm, coordination tasks, unilateral and bilateral fine motor tasks, balance activities	75–85 min, 5x pw, 4w 26.7 h total	Baseline, 4w	ULC: WMFT (FAS score) ADL: MAL (AOU score)
Wu et al. [48]	n = 18	93.1w (61.5)	52.2y (12.2)	Bi-Manu-Track	n = 17	93.6w (61.0)	54.2y (9.8)	Weight bearing, stretching, strengthening of the paretic arm, coordination tasks, unilateral and bilateral fine motor tasks, balance activities	75–85 min, 5x pw, 4w 26.7 h total	Baseline, 4w	ULC: WMFT (FAS score) ADL: MAL (AOU score)

Outcome measures were presented as total scores unless specified otherwise

9HPT 9 hole peg test, ADL activities of daily living, AOU amount of use, ARAT action research arm test, BBT box and block test, BI barthel index, FAS functional ability scale, FIM functional independence measure, hrs hours, k-MBI korean modified barthel index, m, months, MAL motor activity log, MBI modified barthel index, MFT manual function test, MIME mirror-image motion enabler, mins minutes, NR not reported, pw per week, QOM quality of movement, Quick-DASH quick disabilities of arm, shoulder and hand, RLAFI rancho los amigos functional test, ROM range of movement, SD standard deviation, SIS stroke impact scale, TIGER Tenodesis-induced-grip exoskeleton robot, ULC upper limb capacity, VR virtual reality, w weeks, WMFT wolf motor function test, x times, y years

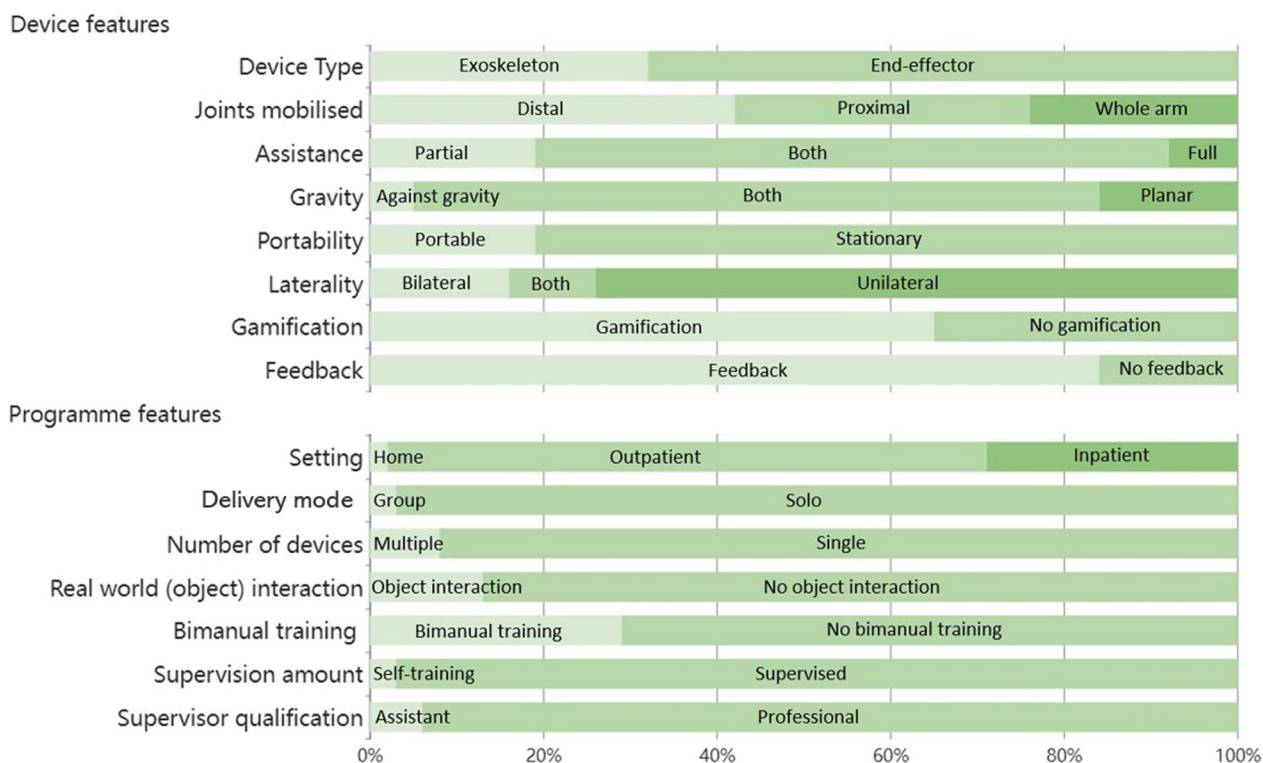


Fig. 5 Cumulate percentage of participants under successive category levels (discrete variables)

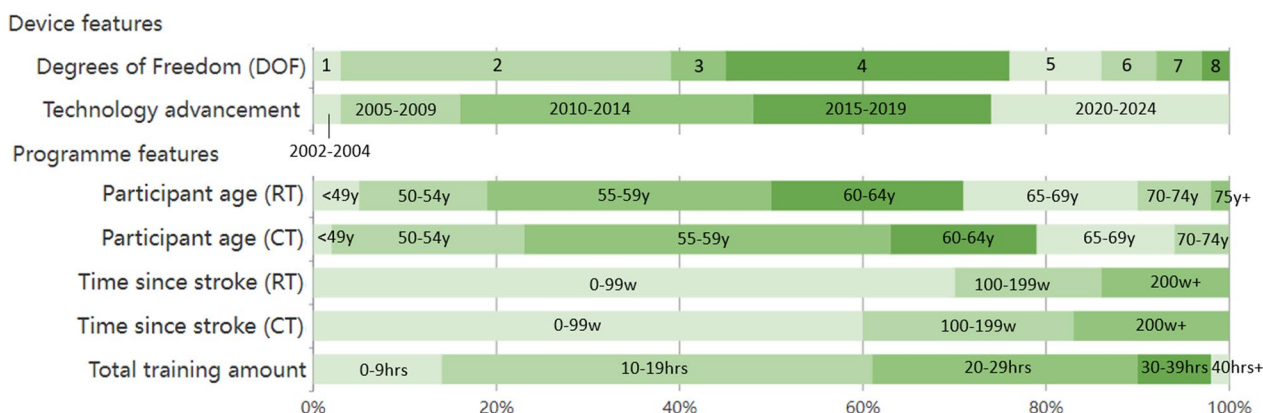


Fig. 6 Cumulate percentage of participants under successive category levels (continuous variables) RT experimental intervention CT control intervention

significant effects were observed in studies comparing robotics versus conventional rehabilitation where the device mobilised the ‘distal’ part of the upper limb (SMD 0.30, 95% CI [0.07, 0.53]), compared to smaller, non-significant effects in devices mobilising the ‘proximal’ upper limb (SMD 0.15, 95% CI [− 0.10, 0.40]), or the ‘whole arm’ (SMD − 0.03, 95% CI [− 0.13, 0.07]) (Fig. 10).

*Assistance provided by the device (partial, full, or both)*

There was a significant effect of the subgroup “assistance” ( $p = 0.0046$ ), as depicted in Fig. 11. This can be observed as larger and statistically significant effects in studies comparing robotics versus conventional rehabilitation where the wearer received ‘partial’ assistance (SMD 0.37, 95% CI [0.19, 0.55]), compared to smaller or insignificant effects where the wearer is being moved in ‘both’ assistance modes (SMD 0.05, 95% CI [− 0.08,

	Risk of bias domains							Risk of bias domains					
	D1	D2	D3	D4	D5	Overall		D1	D2	D3	D4	D5	Overall
Aprile, 2020	+	+	-	+	-	-	Lin, 2022	+	+	-	+	×	×
Budhota, 2021	+	+	+	+	×	×	Lo, 2010	+	+	+	+	+	+
Burgar, 2011	-	×	-	+	×	×	Lum, 2002	-	-	+	+	×	×
Byl, 2013	×	-	×	×	×	×	Lum, 2006	×	-	+	+	×	×
Calabro, 2019	+	+	+	+	×	×	Ma, 2022	+	+	-	+	×	×
Carpinella, 2020	+	+	+	+	×	×	Masiero, 2014	+	+	-	+	-	-
Chen, 2021	+	+	+	+	-	-	Page, 2012	-	+	+	-	-	-
Conroy, 2011 #	×	+	-	-	×	×	Rabadi, 2008 #	+	-	+	-	×	×
Crema, 2019	-	+	-	+	×	×	Ranzani, 2022	-	+	-	+	-	-
Dehem, 2019 #	+	-	×	-	×	×	Reikensmeyer, 2012 #	+	-	+	-	-	-
Fisher, 2007	×	×	×	×	×	×	Rodgers, 2019	+	+	×	×	-	×
Frisoli, 2022	×	+	-	×	-	×	Sale, 2014	-	+	+	+	×	-
Guo, 2022	-	+	+	×	×	×	Şenocak, 2023	+	+	+	×	-	×
Hesse, 2008	-	-	+	×	-	×	Singh, 2021	+	+	×	-	×	×
Hesse, 2014	+	+	+	×	-	×	Susanto, 2015	-	+	+	+	-	-
Hsieh, 2011	+	-	+	-	-	-	Takahashi, 2016	+	+	×	+	-	×
Hsieh, 2018	-	+	+	-	×	×	Takebayashi, 2022	+	-	+	+	×	×
Hsu, 2019	+	+	+	-	-	-	Thielbar, 2013	-	-	+	+	-	-
Hsu, 2022	-	+	-	+	-	-	Timmermans, 2014 #	+	+	+	-	-	-
Hung, 2019	-	+	+	-	×	×	Tomic, 2017	+	+	+	+	×	×
Kahn, 2006	-	-	+	+	-	-	Vangolio, 2017 #	+	+	-	-	-	-
Kim, 2021	-	-	×	+	×	×	Villafane, 2018	-	+	+	+	×	×
Kim, 2023	+	+	+	×	-	×	Volpe, 2000	×	-	+	+	-	×
Kutner, 2010	+	+	+	-	×	×	Volpe, 2008	-	-	+	+	-	-
Lee, 2017	-	+	-	×	-	×	Wolf, 2015	+	+	-	+	×	×
Lee, 2018	-	+	+	+	-	-	Wu, 2012	+	+	+	-	×	×
Liao, 2012	+	-	+	+	-	-	Wu, 2013 #	-	+	+	-	×	×

Domains:

D1: Bias arising from the randomization process.

D2: Bias due to deviations from intended intervention.

D3: Bias due to missing outcome data.

D4: Bias in measurement of the outcome.

D5: Bias in selection of the reported result.

Judgement

× High

- Some concerns

+ Low

Fig. 7 Cochrane ROB2 results for included studies

0.18]), or the ‘full’ assistance mode (SMD 0.52, 95% CI [-1.08, 2.12]).

**Laterality of the device (unilateral, bilateral, or both)**

There was a significant effect of the subgroup “laterality” ( $p= 0.0048$ ), where larger and statistically significant effects were observed in studies comparing robotics versus conventional rehabilitation where the device was applied ‘unilaterally’ (SMD 0.18, 95% CI [0.05, 0.31]), compared to smaller, non-significant effects in devices applied ‘bilaterally’ (SMD 0.17, 95% CI [-0.15, 0.48]), or utilising ‘both’ modes of application (SMD - 0.22, 95% CI [- 0.69, 0.25]) (Fig. 12).

**Programme features Delivery mode (solo, group)**

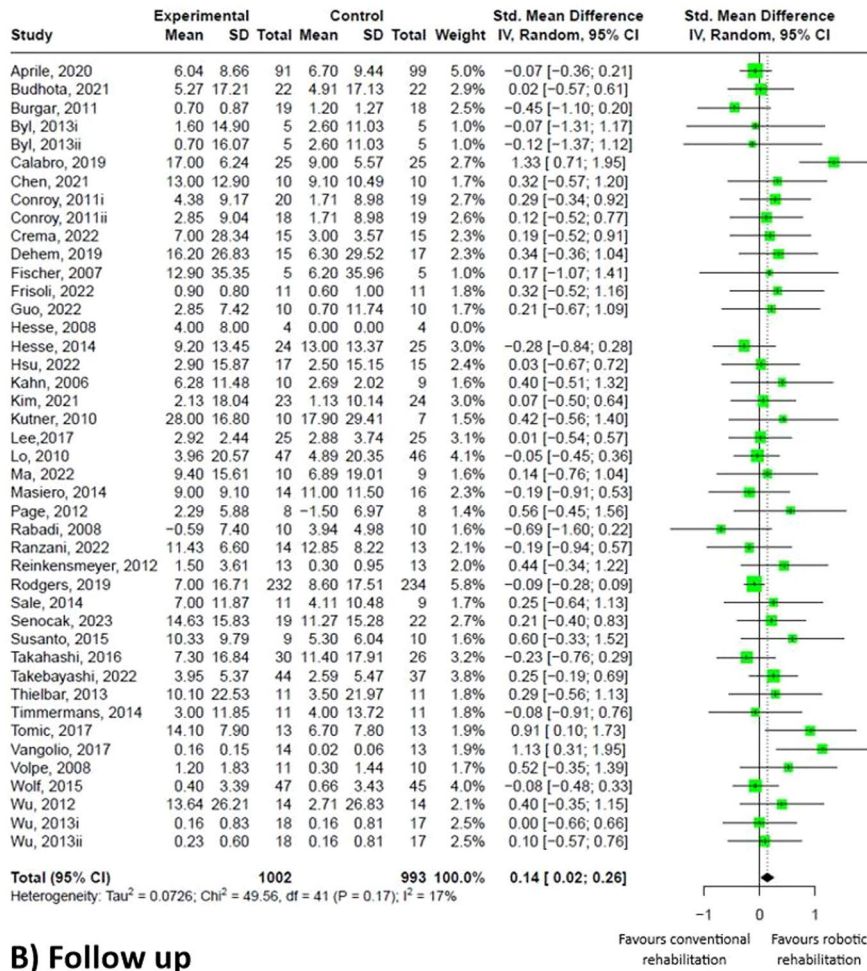
There was a significant effect of the subgroup “delivery mode” ( $p < 0.0067$ ), as depicted in Fig. 13. This can

be observed as larger and statistically significant effects in studies comparing robotics versus conventional rehabilitation where studies implemented robotic rehabilitation as ‘solo’ interventions (SMD 0.16, 95% CI [0.05, 0.28]), compared to smaller or insignificant effects where robotic rehabilitation was delivered in a ‘group’ setting (SMD - 0.15, 95% CI [- 1.42, 1.12]).

**Number of devices used in the intervention (single, multiple)**

There was a significant effect of the subgroup “number of devices” ( $p= 0.0001$ ), where larger and statistically significant effects were observed in studies comparing robotics versus conventional rehabilitation where a ‘single’ device was used (SMD 0.20, 95% CI [0.07, 0.33]), compared to an insignificant effect where ‘multiple’ devices were used (SMD - 0.08, 95% CI [- 0.18, 0.02]) (Fig. 14).

### A) Post intervention



### B) Follow up

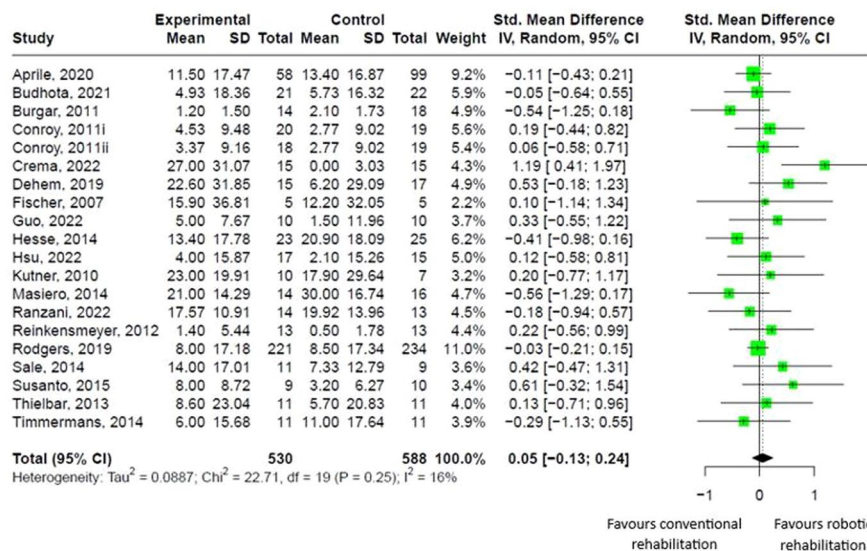
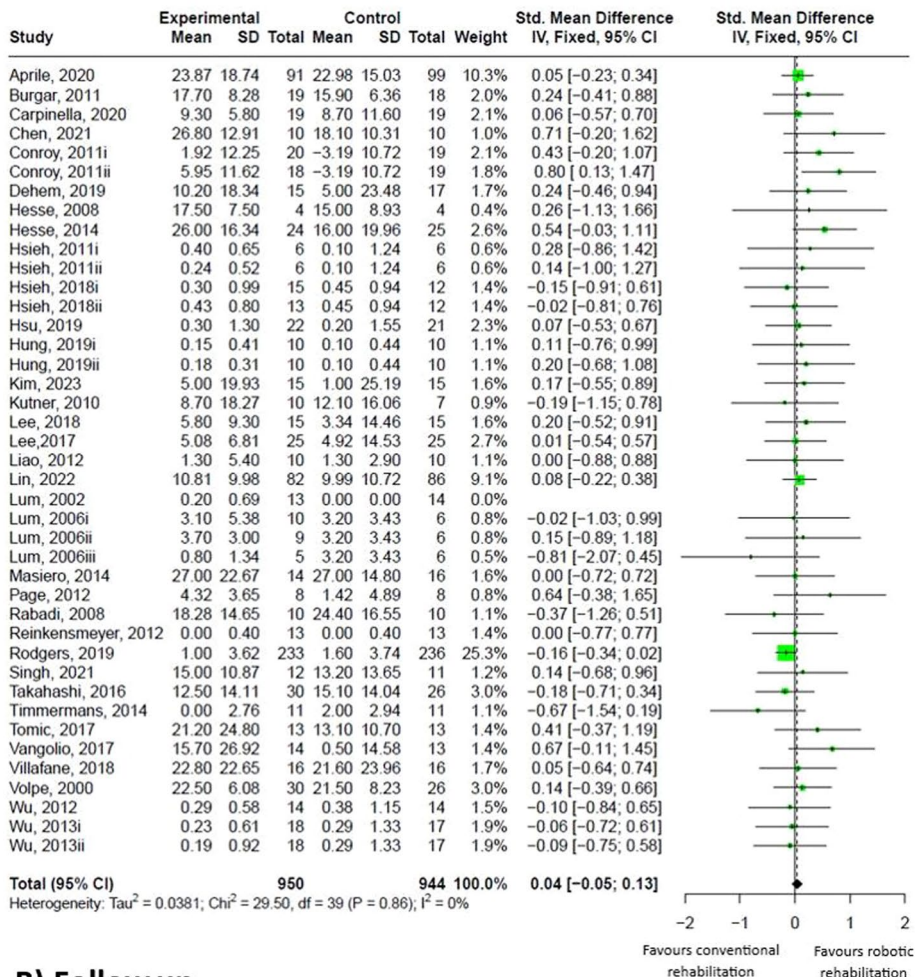


Fig. 8 Meta-analysis for effect of robotic rehabilitation on upper limb capacity outcomes post intervention (A) and follow up (B)

### A) Post intervention



### B) Follow up

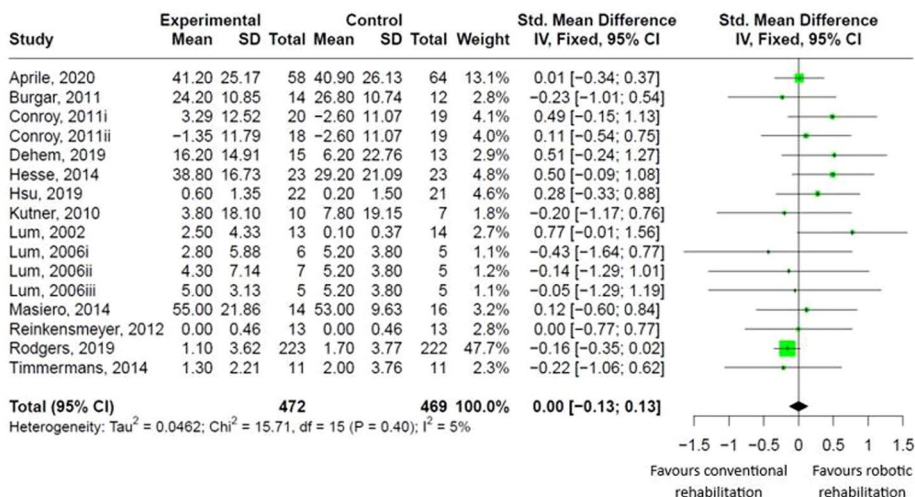


Fig. 9 Meta-analysis for effect of robotic rehabilitation on ADL outcomes post intervention (A) and follow up (B)

**Table 5** Subgroup analysis results for discrete variables

Subgroup category	Category options	Number of studies	Standardised mean difference [95% CI] for robotics versus conventional	Test for subgroup differences (trend observed)	
Device features	Device type	Exoskeleton	<b>0.24 [0.07 to 0.41]</b>	$p = 0.19$	
		End-effector	0.10 [- 0.06 to 0.26]		
	Joints mobilised	Distal	<b>0.30 [0.07 to 0.53]</b>		$p = 0.0133^*$
		Proximal	0.15 [- 0.10 to 0.40]		
		Whole arm	- 0.03 [- 0.13 to 0.07]		
	Assistance	Partial	<b>0.37 [0.19 to 0.55]</b>		$p = 0.0046^*$
		Both	0.05 [- 0.08 to 0.18]		
		Full	0.52 [- 1.08 to 2.12]		
	Gravity	Against gravity	0.32 [- 0.69 to 1.34]		$p = 0.14$
		Both	0.12 [- 0.01 to 0.25]		
		Planar	0.20 [- 0.21 to 0.61]		
	Portability	Stationary	0.10 [- 0.03 to 0.24]		$p = 0.38$
		Portable	<b>0.28 [0.01 to 0.55]</b>		
Laterality	Bilateral	0.17 [- 0.15 to 0.48]	$p = 0.0048^*$		
	Both	- 0.22 [- 0.69 to 0.25]			
	Unilateral	<b>0.18 [0.05 to 0.31]</b>			
Gamification	Gamification	0.13 [- 0.01 to 0.27]	$p = 0.71$		
	No gamification	0.18 [- 0.06 to 0.41]			
Feedback	Feedback	0.10 [- 0.02 to 0.23]	$p = 0.10$		
	No feedback	<b>0.36 [0.02 to 0.70]</b>			
Programme features	Setting	Home	- 0.08 [- 0.75 to 0.60]	$p = 0.81$	
		Outpatient	0.16 [- 0.17 to 0.48]		
		Inpatient	<b>0.15 [0.06 to 0.23]</b>		
	Delivery mode	Group	- 0.15 [- 1.42 to 1.12]		$p = 0.0067^*$
		Solo	<b>0.16 [0.05 to 0.28]</b>		
	Number of devices	Multiple	- 0.83 [- 0.18 to 0.02]		$p = 0.0001^*$
		Single	<b>0.20 [0.07 to 0.33]</b>		
	Real world (object) interaction	Object interaction	<b>0.21 [0.02 to 0.40]</b>		$p = 0.47$
		No object interaction	0.13 [0.00 to 0.27]		
	Bimanual training	Bimanual training	- 0.01 [- 0.23 to 0.21]		$p = 0.11$
		No bimanual training	<b>0.18 [0.04 to 0.32]</b>		
	Supervision	Self-training	0.08 [- 1.98 to 2.14]		$p = 0.71$
		Supervised	<b>0.15 [0.02 to 0.27]</b>		
	Supervisor qualification	Assistant	0.13 [- 0.62 to 0.89]		$p = 0.99$
		Professional	<b>0.14 [0.01 to 0.27]</b>		

\*Statistically significant test for subgroup differences  $p < 0.05$

Standardised mean differences that are statistically significant ( $p < 0.05$ ) are presented in bold

*Meta-regression (continuous variables)* The results from the subgroup analysis of continuous variables are summarised in Table 6, the full analysis can be found in the Supplementary File. There were statistically significant subgroup differences for the “degrees of freedom” variable ( $p = 0.012$ , Table 6). This is visualised in Fig. 15, which shows the fewer the degrees of freedom,

the more effective the robotic therapy intervention was for improving upper limb capacity.

#### Sensitivity analysis

Sensitivity analyses were conducted by excluding Aprile [49] and Rodgers [80], both of which had larger participant numbers ( $n = 224$  and  $n = 516$ ) in comparison to

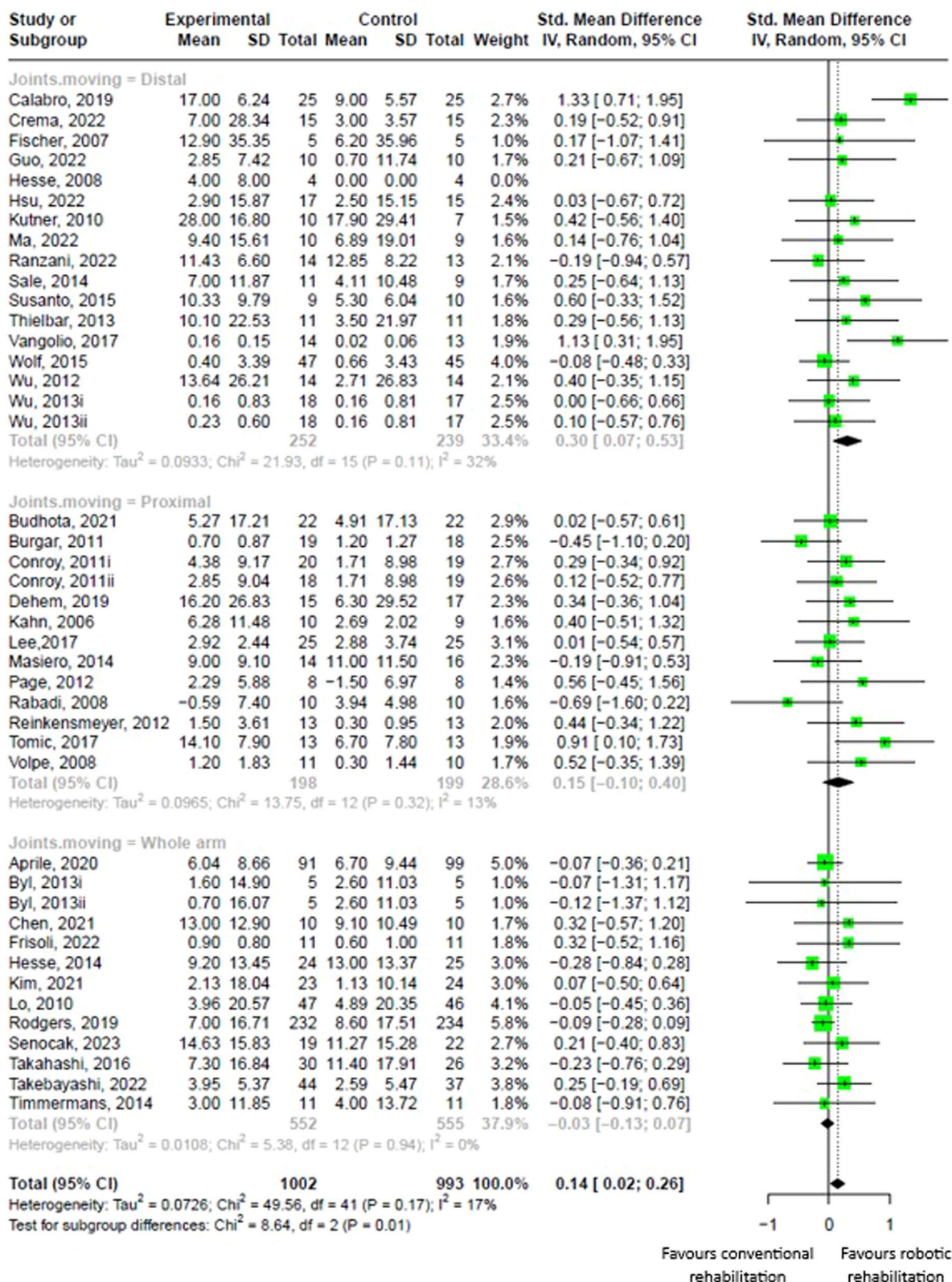


Fig. 10 “Joints mobilised” subgroup analysis

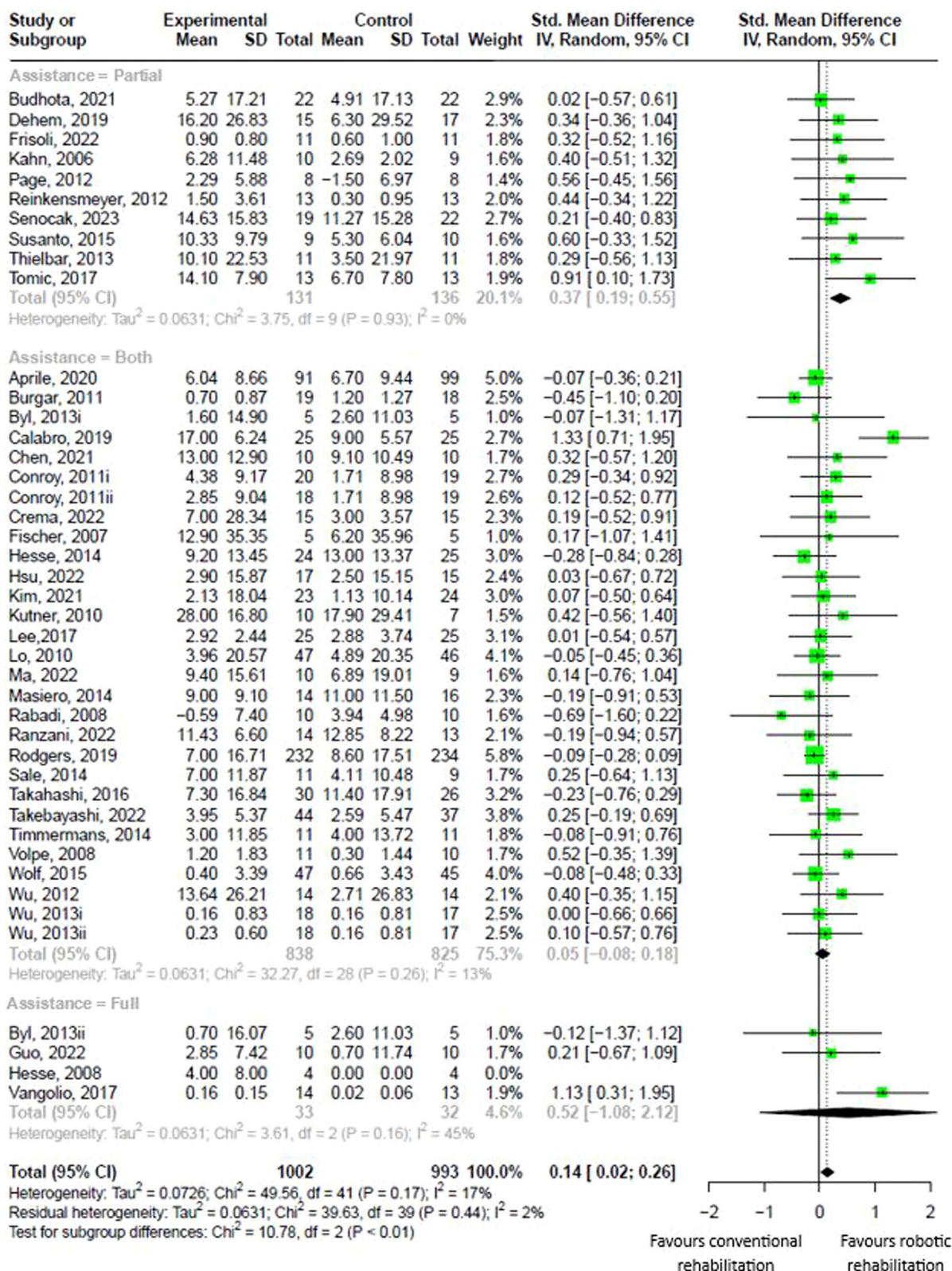


Fig. 11 “Assistance” subgroup analysis

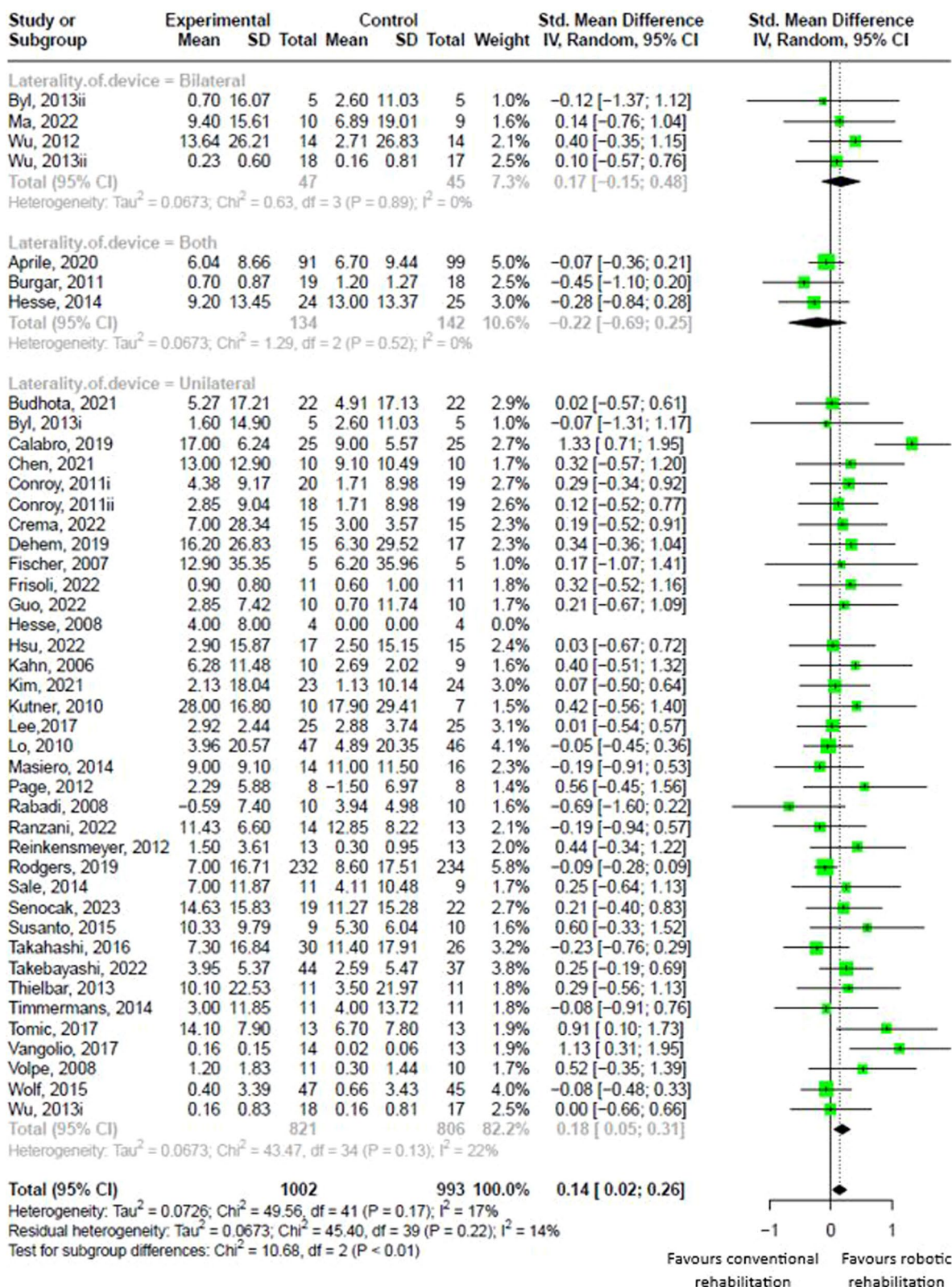


Fig. 12 “Laterality” subgroup analysis

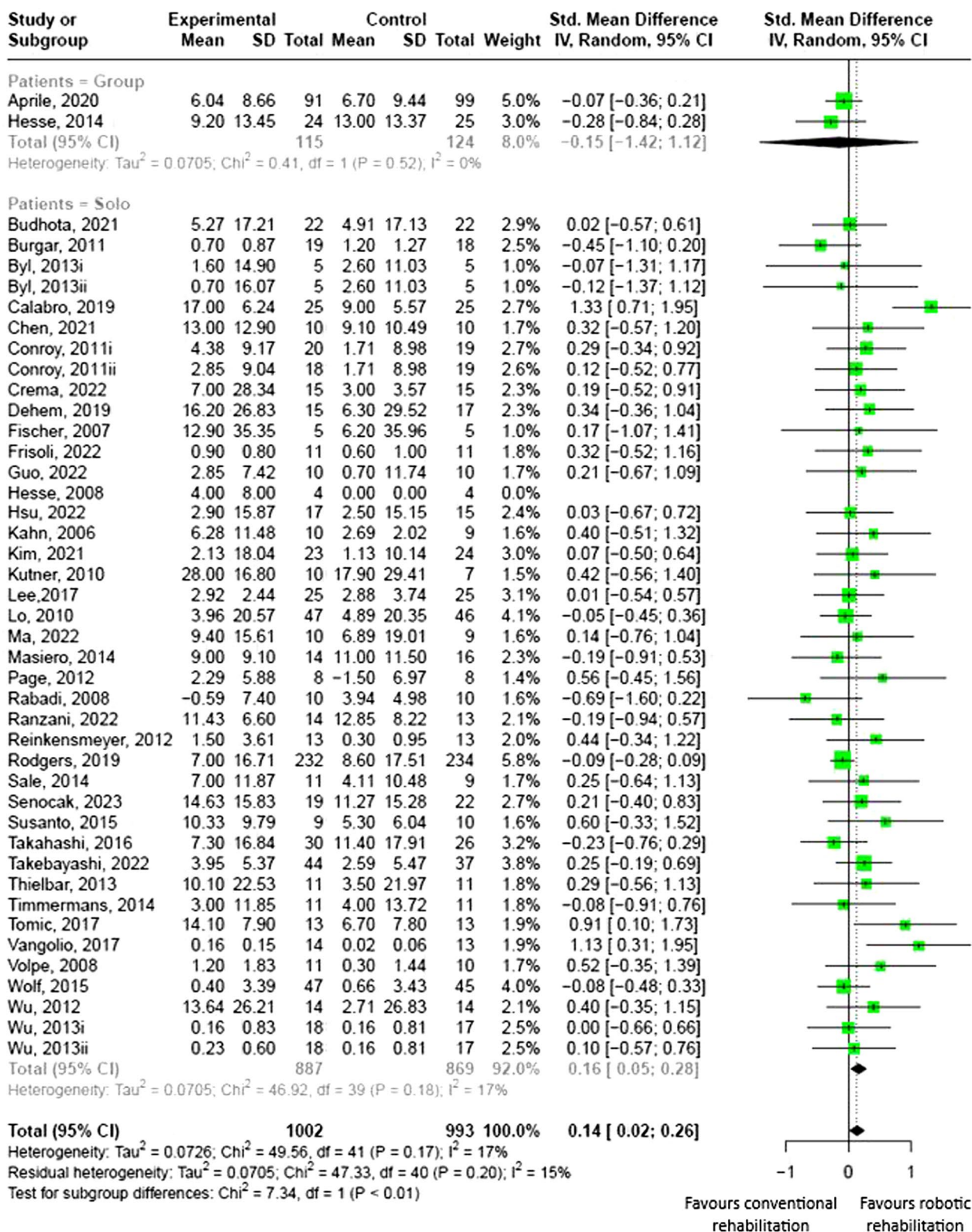


Fig. 13 “Delivery mode” subgroup analysis

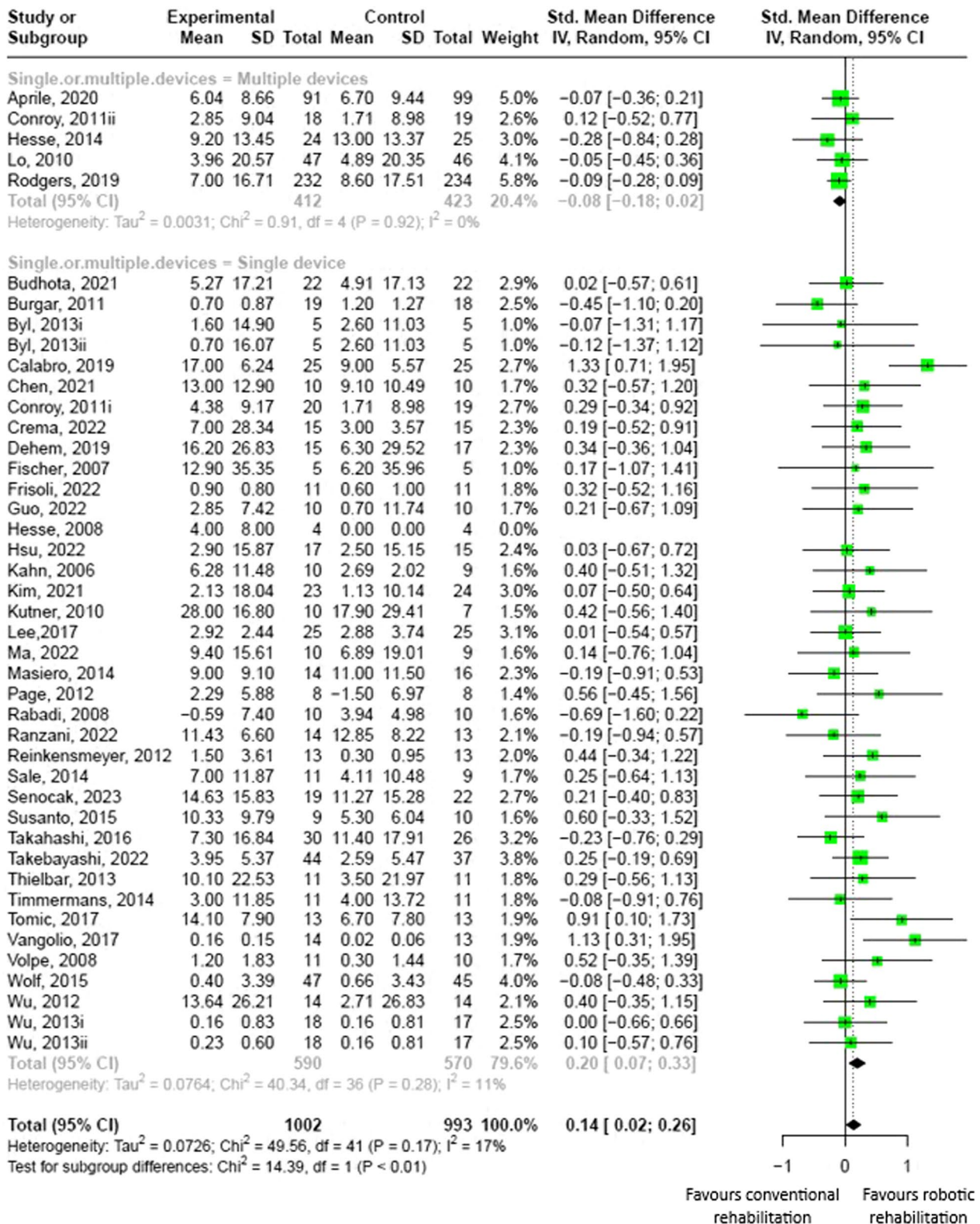
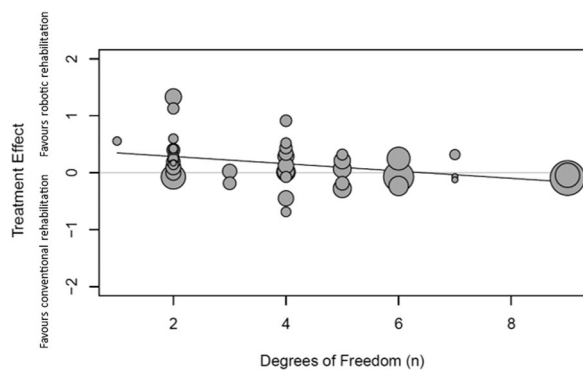


Fig. 14 “Number of devices” subgroup analysis

**Table 6** Subgroup analysis results for continuous variables

Subgroup category	Test for subgroup differences (trend observed)	Model coefficient
Device features		
Degrees of freedom (DOF)	0.012*	- 0.06, 95% CI [- 0.11, - 0.01]
Technology advancement	0.5902	0.007, 95% CI [- 0.02, 0.03]
Programme features		
Participant age	0.2744	- 0.01, 95% CI [- 0.03, 0.009]
Time since stroke	0.6719	- 0.06, 95% CI [- 0.34, 0.22]
Total training amount	0.7511	- 0.001, 95% CI [- 0.01, 0.007]

\*Statistically significant test for subgroup differences  $p < 0.05$



**Fig. 15** Visualisation of meta-regression analysis for “Degrees of Freedom”

the other studies. Given that the other 52 studies were relatively underpowered, these two studies had the potential to significantly overpower the data.

For upper limb capacity outcomes post-intervention, the effect of robotic rehabilitation compared to conventional rehabilitation was statistically significant (SMD 0.14, 95% CI [0.02, 0.26]). The significant effect of robotic rehabilitation compared with conventional rehabilitation was not maintained at follow-up (SMD 0.05, 95% CI [- 0.13, 0.24]). For ADL outcomes post-intervention, the overall effect of robotic rehabilitation was non-significant when compared to conventional rehabilitation (SMD 0.04, 95% CI [- 0.05, 0.13]). There were also no significant effects of robotic rehabilitation compared with conventional rehabilitation at follow up (SMD 0.001, 95% CI [- 0.13, 0.13]).

Results from the original meta-analysis were conserved and there were no changes to the pre-post, pre-follow-up, or subgroup analyses by conducting these sensitivity analyses.

## Discussion

### Summary of main results

This systematic review and meta-analysis presented an update on the efficacy of upper limb robotic rehabilitation compared with conventional rehabilitation for people with stroke, specifically focusing on ‘Activity’ level outcomes in dose-matched trials. Importantly, this is the first review to define device and programme features in robotic rehabilitation and investigate their effects on outcomes in people with stroke. Our review identified a large body of literature with 54 studies and 2,744 participants and has highlighted the exponential growth of rehabilitation research in robotics, with over 50% of the included studies being conducted within the last 10 years. Meta-analysis demonstrated that robotic rehabilitation had a statistically significant positive effect on upper limb capacity compared to dose-matched conventional rehabilitation (SMD 0.14, 95% CI [0.02, 0.26]). However, the magnitude of the positive effect was small [95] and the improvements seen were not maintained at follow-up (SMD 0.05, 95% CI [- 0.13, 0.24]). An SMD of 0.14 is equivalent to an increase of 13 on the FIM motor score and 8 on the ARAT, neither of which are considered clinically meaningful [96, 97]. These findings suggest that robotic rehabilitation may provide a small, short-term benefit in upper limb capacity over conventional rehabilitation, which is not substantial enough to be deemed clinically important [95]. Our findings also indicate that robotic rehabilitation does not result in improved ADL function compared to dose-matched conventional rehabilitation either post-intervention (SMD 0.04, 95% CI [- 0.05, 0.13]) or at follow-up (SMD 0.05, 95% CI [- 0.13, 0.24]). Previous meta-analyses by Veerbeek [17] and Norouzi-Gheidari [18] similarly concluded that robotic rehabilitation may not offer greater benefits for ADL function compared to conventional rehabilitation in dose-matched trials. Therefore, despite significant increases in the body of evidence over the past decade, robotic rehabilitation has yet to demonstrate substantial gains in upper

limb capacity or translate gains in upper limb capacity to ADL function, which is a priority for people with stroke [98] and a fundamental goal of rehabilitation [6]. Advancement of the field of robotic rehabilitation research may benefit from a clearer understanding of the device features and programme parameters likely to maximise recovery and positively influence outcomes.

### Tailoring rehabilitation

Review findings from the subgroup analyses may suggest that robotic rehabilitation is more effective at improving upper limb capacity when delivered in a targeted and specific manner. The evidence indicates that several device features appear critical in determining efficacy. Notably, the joints of the upper limb that were moving as a result of the action of the robotic device had a significant impact on the efficacy of robotic rehabilitation ( $p = 0.0133$ ). Devices that control the distal upper limb were more effective (SMD 0.30, 95% CI [0.07, 0.53]), compared to those targeting the proximal upper limb (SMD 0.15, 95% CI [- 0.10, 0.40]) or the whole arm (SMD - 0.03, 95% CI [- 0.13, 0.07]). Given that people with upper limb impairment following stroke often exhibit more distal weakness [99], robotic rehabilitation targeting distal upper limb deficits may be more likely to be effective [100]. The principle of training specificity is further supported by the finding that larger gains in upper limb capacity were seen with devices that control fewer degrees of freedom (DOF,  $p = 0.012$ , model coefficient - 0.06, 95% CI [- 0.11, - 0.01]). Additionally, a significant effect was observed based on the number of devices implemented in an intervention ( $p = 0.0001$ ), with a positive effect seen when utilising a single device (SMD 0.20, 95% CI [0.07, 0.33]) but not when employing multiple devices (SMD - 0.08, 95% CI [- 0.18, 0.02]). These results suggest that robotic rehabilitation focusing on specific movements within a limited number of degrees of freedom may be more effective for improving upper limb capacity than interventions which address multiple movements simultaneously. These findings reinforce the principle of training specificity in motor learning [101], suggesting that, where the aim is to improve upper limb capacity, device designers should prioritise the development of devices that enable targeting of specific movement deficits, particularly focusing on the distal upper limb. Furthermore, design device interfaces and intervention programmes that support clinicians to select the most appropriate device and intervention parameters for the individual is likely to yield greater gains [102, 103].

### Active engagement

Subgroup analysis findings underscored the critical role of active engagement in robotic rehabilitation for

achieving positive outcomes. Our findings illustrated that the level of assistance provided by the device significantly influenced upper limb capacity outcomes ( $p = 0.0046$ ). Specifically, devices which provided 'partial' assistance, where the person with stroke actively contributed to the movement, had significant effects on upper limb capacity compared to conventional rehabilitation (SMD 0.37, 95% CI [0.19, 0.55]). In contrast, full assistance devices, where the device entirely guided the movement yielded variable and non-significant effects (SMD 0.52, 95% CI [- 1.08, 2.12]) while devices which combined both modes had negligible effect (SMD 0.05, 95% CI [- 0.08, 0.18]). Collectively, these findings suggest that robotic rehabilitation is most effective when people with stroke actively initiate, control, and adapt their movements while the robotic device provides partial assistance, rather than when the device provides full assistance, even if the full assistance is just for part of the intervention programme. Caution is warranted when interpreting these findings due to the limited number of studies in the full-assistance category ( $n = 3$ ) and the overall lack of detailed reporting on how assistance levels were calibrated to each individual. However, the findings align with conventional rehabilitation practice, where passive movement of the affected limb is usually reserved for the maintenance of range of motion [104] and not expected to lead to improved functional outcomes [105], and active involvement in movement is emphasized to facilitate neural plasticity and promote recovery [106, 107].

Engagement includes not only physical participation in rehabilitation tasks but also relational aspects that foster active involvement in the rehabilitation process [108]. A primary rationale for implementing robotic devices in stroke rehabilitation is that features such as gamification [109] and objective feedback [110] may support motivation and meaningful engagement in rehabilitation tasks. Interestingly, our subgroup analyses did not reflect these benefits, where 'gamification' and 'feedback' did not appear to influence robotic rehabilitation effectiveness. Considering the clinical context in which these devices were implemented may offer an explanation. Of the 54 included studies, 52 implemented robotic rehabilitation with direct supervision from a clinician. Clinicians consistently employ extrinsic feedback approaches, including providing knowledge of performance and knowledge of results [111], positive reinforcement [112] and rewards [113] as fundamental elements of their role in rehabilitation. Therefore, the value of device features such as gamification and feedback may be confounded or obscured by input from clinicians. Importantly, to add value to rehabilitation, rehabilitation robotics either need to surpass outcomes seen in conventional rehabilitation or be implemented in a context with reduced direct

supervision by a clinician [107, 114]. The benefits of gamification and feedback in robotic rehabilitation may become more apparent over time as technology advances and devices are tested in minimally supervised rehabilitation contexts.

### ADL improvements

A key finding from our meta-analysis, and one consistently observed in the literature [17, 18], is that while robotic rehabilitation may enhance outcomes in upper limb capacity, these improvements do not appear to translate into greater gains real-world performance of complex tasks such as ADLs compared to conventional rehabilitation. This raises questions about whether current robotic rehabilitation devices and programmes are designed effectively to support gains in ADLs. Device capabilities such as ‘portability,’ ‘bimanual training,’ and ‘real world (object) interaction’ may be assumed to support gains in ADL performance [115–117], yet our subgroup analyses did not find statistically significant effects in these sub-group categories in regards to upper limb capacity. However, the number of trials and participants in each subgroup may have restricted the ability to detect subgroup differences. Nevertheless, the pooled effect estimates favoured robotic rehabilitation over conventional rehabilitation in studies using portable devices (SMD 0.28, 95% CI [0.01 to 0.55]) and those employing object interaction (SMD 0.21, 95% CI [0.02–0.40]) suggesting these features may be important and warrant further investigation [118]. In robotic rehabilitation, the principle of task specificity, where the most effective way to relearn a task is through focused practice of that task [119], likely extends to ADL performance [120]. Most devices in the review supported specific movements such as reaching and grasping [49, 53, 79], and were rarely employed in the context of complex ADL tasks such as grooming or dressing. In contrast, conventional rehabilitation often integrates compensatory approaches that enable behavioural, individual and environmental adjustments to facilitate learning alternative ways to perform a task [99, 121]. Robotic rehabilitation, however, typically focuses on retraining movement without accommodating compensatory strategies [17]. Therefore, exploring ways to integrate compensatory approaches within robotic rehabilitation may be critical to achieving improvements in ADLs. Designing devices that effectively facilitate ADLs likely demands different design priorities than those intended to solely address specific deficits in upper limb capacity. Based on the task characteristics of ADLs, devices designed to support ADL performance may need to target multiple joints of the upper limb, allow for compensatory strategies where appropriate, be portable and lightweight to enable engagement in a range of ADL tasks

while ensuring safety in a range of environments [21, 33, 122, 123]. While robotic rehabilitation devices specifically designed to target ADL performance could improve outcomes, achieving the necessary technological and design advancements may take time.

### Strengths and limitations

This systematic review and meta-analysis employed a rigorous approach to analyse the existing research evidence. The work was supported by the development of a novel classification system for describing robotic device and programme features to enable subgroup analyses. This system, although independently developed by our research team, aligns with other literature categorising these features [24]. Nevertheless, the review method had some limitations. While we conducted an extensive literature search yielding 54 studies with 2744 participants, the potential pool of literature may have been limited by the inclusion of only English language articles. Screening and data extraction was performed by one reviewer in consultation with the broader research team. This limitation was mitigated by piloting a comprehensive data extraction process, and performing result validation checks. The scope of our review was primarily focused on robotic device and programme features, with limited exploration of clinical and patient characteristics primarily due to inconsistent reporting of these characteristics in the included research [124]. Given that recovery of upper limb function following stroke is influenced by a range of clinical, demographic, and sociocultural factors [125] improved reporting of patient characteristics would enable exploration of the effectiveness of robotic rehabilitation in specific population subgroups [30, 123, 124].

The body of evidence included in this review had several limitations. A high risk or some concerns of bias were identified in most of the included studies. This potential for bias related to outcome measurement and reporting of results, offering low to moderate certainty of results. Many of the included studies also failed to report device features and programme parameters adequately, potentially limiting both the scope and reliability of the subgroup analysis findings due to insufficient detail. For example, some studies did not thoroughly report the amount of training or level of supervision, while in others the description of the device hindered precise classification of the level of ‘assistance’ provided, resulting in broader categorizations. Parameters such as training amount [8, 126] and clinician input [127] are known to influence upper limb outcomes after stroke. More comprehensive intervention reporting would support a more robust exploration of the influence of device features and programme features on outcomes. Concerns about intervention reporting quality have been noted across

the wider rehabilitation literature [128], emphasising the importance of employing tools such as the TIDieR-Rehab checklist to systematically describe robotic rehabilitation interventions [35, 129]. The outcome measures utilised to assess the efficacy of robotic rehabilitation also present a potential limitation. For example, studies investigating devices with more degrees of freedom tended to select global measures of upper limb capacity, such as the ARAT [49, 54], and the WMFT [72]. These measures are likely less sensitive to change than outcomes which focus on a specific body part of the upper limb such as the BBT [60], or the 9HPT [52], which were commonly used in studies with devices having fewer degrees of freedom. Consequently, the smaller effects sizes observed in studies with devices which have more degrees of freedom may reflect the use of less sensitive measures rather than the efficacy of the devices themselves.

## Conclusions

As the field of upper limb rehabilitation robotics evolves, it is important to understand the efficacy of robotic rehabilitation in comparison to conventional rehabilitation, as well as the device and programme features that support improved outcomes. This systematic review and meta-analysis evaluated the efficacy of upper limb robotic rehabilitation compared to dose-matched conventional rehabilitation in people with stroke. The findings revealed that while robotic rehabilitation offers a small but statistically significant improvement in upper limb capacity immediately post-intervention, these gains are not considered clinically meaningful and are not maintained at follow-up. Despite improvements in upper limb capacity, no significant differences were observed in ADL outcomes either post-intervention or at follow-up. Our findings align with prior research, indicating that the efficacy of robotic rehabilitation remains unclear despite an increasing body of evidence and technological advancements in the field. Our subgroup analyses identified several device and programme features that impacted efficacy, including the level of assistance provided by the device, the degrees of freedom and joints being moved, and the number of devices implemented in the intervention. However, features like gamification and feedback did not show benefits, possibly due to devices being implemented in contexts with high levels of clinician involvement. These results infer several clinical and design considerations that may enhance the efficacy of robotic rehabilitation, including tailoring interventions to address specific individual impairments, promoting active engagement in rehabilitation, and implementing devices in the context of daily task performance. Further research should prioritise the purposeful exploration of the device features and programme parameters that

influence outcomes and investigate the efficacy of robotic rehabilitation with reduced clinical supervision.

## Supplementary Information

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Additional file 1.

### Author contributions

Conceptualisation, K.B., N.S., G.A., E.R.R., and W.B.; methodology, K.B., N.S., U.R., G.A., E.R.R., and W.B.; validation, K.B., N.S., U.R., S.O.; formal analysis, U.R., investigation, K.B., N.S., U.R., G.A., S.O., E.R.R., and W.B.; data curation, K.B., writing-original draft preparation, K.B., S.O., and N.S., writing-review and editing, U.R., G.A., E.R.R., and W.B.; visualisation, K.B., N.S., U.R., and S.O.; supervision, N.S. and S.O., project administration, K.B.

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### Data availability

Data is provided within the manuscript or supplementary information files.

### Declarations

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

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#### Competing interests

The authors declare no competing interests.

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