Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Comparison of Upper Limb Motor Therapy Outcomes in Post-Stroke Patients: A Randomized Controlled Trial of Therapist-Led Versus Robot-Assisted Rehabilitation

Denis Moskiewicz
Wroclaw University of Health and Sport Sciences
Małgorzata Kołodziej
Wroclaw University of Health and Sport Sciences
Michał Mikulski
EGZOTech Sp. z o.o.
Anna Poświata
EGZOTech Sp. z o.o.
Iwona Sarzyńska-Długosz
isarzynska@ipin.edu.pl

Institute of Psychiatry and Neurology

Article

Keywords: stroke, upper limb rehabilitation, robot-assisted therapy, EMG-triggered therapy, Luna EMG, motor recovery, spasticity, pain, quality of life

Posted Date: February 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8795941/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

High-dose, task-specific upper limb training is essential for post-stroke motor recovery. EMG-triggered robot-assisted therapy enables intention-driven, high-repetition practice; however, evidence from randomized trials directly comparing this approach with dose-matched conventional rehabilitation remains limited. This single-blind randomized controlled trial compared short-term outcomes of EMG-triggered robot-assisted upper limb training using the Luna EMG system with standardized therapist-led therapy in patients after stroke.

Fifty-eight patients in the early post-stroke phase were randomly assigned to robot-assisted therapy (n = 29) or therapist-assisted therapy (n = 29). Both groups received identical upper limb training with respect to duration, intensity, frequency, and number of repetitions over six weeks within the same inpatient rehabilitation program. Outcomes were assessed at baseline, weeks three and six, and at three-week follow-up using the Fugl–Meyer Assessment for Upper Extremity, Box and Block Test, Modified Ashworth Scale, Numerical Rating Scale, and EQ-5D-5L.

Both groups showed significant within-group improvements in motor function, pain, and quality of life over time. When therapy dose is strictly controlled, no statistically significant between-group differences were observed. A single between-group difference was observed in the EQ-5D-5L domain of usual activities at follow-up, favoring the robot-assisted group.

Trial registration: ClinicalTrials.gov, NCT07002463. Registered May 30, 2025 (retrospectively registered)

Introduction

Stroke remains one of the leading causes of long-term disability worldwide, affecting millions of people each year and leaving a substantial proportion of survivors with persistent impairments of upper limb function [1–3]. Upper limb (UL) paresis is present in approximately 70–80% of individuals during the acute stage of stroke and continues to restrict motor performance and independence in the majority of survivors months or years after the event [2,4]. Because only 10–20% of patients achieve complete recovery of arm function, even small improvements in reaching, grasping, and manipulation can have a meaningful impact on independence in daily activities [5]. Consequently, optimizing motor rehabilitation strategies for the paretic upper limb remains a critical clinical priority.

Among the most common barriers to recovery are spasticity and post-stroke pain. Spasticity affects approximately 25–40% of stroke survivors and is associated with reduced range of motion, abnormal synergies, and difficulties performing voluntary movements [6]. Pain—including hemiplegic shoulder pain—affects nearly one-third of patients, limiting participation and negatively influencing therapy outcomes. [7] These complications further highlight the importance of structured, intensive, and task-specific rehabilitation, which is known to promote neuroplasticity and support functional reorganization of the motor system [8,9].

A central element of motor learning research is the recognition that a high number of task-specific repetitions is required to induce and sustain neuroplastic change. Experimental models indicate that hundreds of repetitions per day are needed to achieve meaningful cortical reorganization, yet observational studies show that typical clinical practice provides far fewer repetitions—often fewer than 30–40 per session [10]. This “dose gap” represents a major challenge in modern neurorehabilitation and has contributed to growing interest in technologies capable of delivering high-intensity, standardized movement training.

Robot-assisted therapy has emerged as a promising solution to this challenge, particularly in upper limb rehabilitation. Robotic systems can provide large numbers of repetitions with consistent movement parameters, objective monitoring, and enriched feedback, which may increase patient motivation and engagement [11]. Systematic reviews and meta-analyses support these benefits: Chien et al. demonstrated significant improvements in upper limb function with robot-assisted therapy compared with usual care [12], while Zhang et al. reported that longer and more intensive robotic interventions are associated with improved activities of daily living and motor recovery [13]. Recent evidence suggests that end-effector robots may yield the largest gains in arm function across multiple motor domains [14], and meta-analytic findings from 2025 confirm significant improvements in Fugl-Meyer Assessment for Upper Extremity (FMA-UE) scores among patients receiving robot-assisted training [15].

One promising subgroup of robotic devices uses electromyography (EMG) to detect voluntary muscle activation and trigger movement. EMG-triggered therapy enables active participation even in patients with minimal residual motor output and has been shown to enhance motor intention, cortical activation, and training specificity [15–17]. Dipietro et al. demonstrated that EMG-triggered robotic therapy improves engagement and functional motor performance [18], while more recent studies confirm the feasibility and functional benefits of EMG-driven robotic rehabilitation in both subacute and chronic stroke populations [19,20].

Despite the promising evidence, important knowledge gaps remain. Many previous trials have compared robotic therapy with usual care or heterogeneous conventional programmes, but only a minority have directly compared robot-assisted and therapist-assisted training using identical movement dosage, intensity, repetition count, and session duration [12,21]. This distinction is

crucial because differences in therapeutic outcomes may be driven by discrepancies in training dose rather than the treatment modality itself [22]. Furthermore, relatively few randomized trials have evaluated EMG-triggered end-effector devices such as Luna EMG or comparable EMG-based systems, and their role within structured, protocolled upper limb rehabilitation programmes remains insufficiently explored [20,23–25] Although growing evidence suggests that EMG-based robotic therapy may enhance motor control and functional activity, the literature remains limited, and findings regarding secondary outcomes—such as spasticity, pain, and QoL—are still inconsistent [26].

Given these considerations, a direct comparison of robot-assisted and therapist-led upper limb therapy under strictly controlled dosing conditions is warranted. The present study addresses this gap by comparing the effects of EMG-triggered robot-assisted therapy with conventional therapist-assisted training in post-stroke patients, while carefully standardizing the number of repetitions, movement intensity, and treatment duration. In this study, *motor function* is defined as motor performance measured by the FMA-UE and manual dexterity assessed using the Box and Block Test (BBT) [27]. Secondary outcomes include muscle tone, pain levels, and QoL.

This approach provides a rigorous test of the relative effectiveness of robot-assisted versus therapist-led rehabilitation and contributes new clinical evidence regarding the potential role of EMG-triggered robotic systems in structured upper limb therapy after stroke.

Methods

Patient population (P)

A total of 58 patients treated in the Rehabilitation Department of the T. Marciniak Lower Silesian Specialist Hospital, Emergency Medicine Center in Wrocław, Poland were enrolled in the study, according to predefined eligibility criteria. Participants were randomly assigned to two equally sized groups (29 participants each): an experimental group and a control group.

Participants were recruited consecutively between April 3, 2023 (date of first patient enrolment) and February 12, 2024 (date of primary completion), corresponding to the predefined recruitment period at the study site. The groups were homogeneous in terms of age, sex, type of stroke, time since stroke onset, and severity of neurological deficit (Table 1).

Table 1
Descriptive characteristics of study participants

	Experimental group (n = 29)	**Control group (n = 29)**	**p**
Age, years Mdn (IQR)	66.0 (13.0)	67.0 (14.0)	0.534
Sex **n (%)**			0.791
men	17 (58.6%)	16 (55.2%)	
women	12 (41.4%)	13 (44.8%)	
Stroke type **n (%)**			0.780
hemorrhagic	9 (31.0%)	10 (34.5%)	
ischemic	20 (69.0%)	19 (65.5%)	
Side of paresis **n (%)**			0.791
right	17 (58.6%)	16 (55.2%)	
left	12 (41.4%)	13 (44.8%)	

Mdn – median, IQR – interquartile range, n (%) – frequency in the experimental and control groups, p – p-value for the Mann–Whitney U test (for age) and for the χ^2 test (for sex, type of stroke, and side of paresis)

Inclusion criteria

The inclusion criteria were as follows: individuals aged 18 to 90 years who had experienced an ischemic or hemorrhagic stroke no more than 6 weeks prior to the start of the study, confirmed by a hospital discharge summary. Only patients for whom this was the first and only cerebrovascular event were eligible. Participants were required to have a stable medical condition that allowed for active rehabilitation, as well as a moderate, marked, or severe motor deficit of the directly affected upper limb, defined by a FMA-UE score of ≤ 94 [28]. Additional criteria included the absence of severe cognitive impairment, indicated by a score of 23 or higher on the Mini-Mental State Examination [29], and written informed consent to participate in both the study and therapy.

Although no formal lower FMA-UE limit was defined, all participants admitted to the study presented with moderate motor impairment. In our clinical setting, patients with extremely low FMA-UE scores or absent voluntary movement are not referred for active upper-limb rehabilitation, which explains why no such cases appeared in the enrolled sample.

Exclusion criteria

Exclusion criteria included: fixed, permanent contractures in the upper limb; significant spasticity in upper limb muscles, defined as a score of ≥ 3 on the Modified Ashworth Scale (MAS) in at least one muscle group [30]; substantial visual or hearing impairments; severe swallowing and breathing disorders; and a confirmed diagnosis of myasthenia or myasthenic syndrome.

Participant flow through the study is presented in Fig. 1, following CONSORT 2010 reporting guidelines.

n- number of subjects

Randomization and allocation concealment

Participants were randomly assigned to the experimental (robot-assisted therapy) or control (therapist-led therapy) group in a 1:1 ratio using simple randomization. The random allocation sequence was generated by an independent researcher who was not involved in patient recruitment, treatment, data collection, or outcome assessment. Group assignments were placed in sequentially numbered, opaque, sealed envelopes to ensure allocation concealment. After completion of the baseline assessment, each participant was assigned to a group by opening the next consecutively numbered envelope. Outcome assessors were blinded to group allocation throughout the study in order to minimize the risk of detection bias.

Ethics approval and trial registration

The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. The study protocol, including predefined objectives, eligibility criteria, intervention procedures, outcome measures, and statistical analysis plan, was reviewed and approved by the Senate Committee on Ethics at Wroclaw University of Health and Sport Sciences (Approval No. 4/2023) prior to enrolment of the first participant. Written informed consent was obtained from all participants before inclusion in the study.

The trial was registered at ClinicalTrials.gov (Identifier: NCT07002463) on May 30, 2025. Registration was completed retrospectively due to administrative delay. No changes were made to the predefined protocol, outcomes, or statistical analysis plan after recruitment commenced.

Therapeutic protocol

The therapeutic protocol was carried out by physiotherapists and occupational therapists in the Rehabilitation Department of the T. Marciniak Lower Silesian Specialist Hospital, Emergency Medicine Center in Wrocław, Poland. The total duration of the implemented therapy was 2 hours per day, 5 days a week, for 6 weeks. Diagnostic assessments were conducted on the following time-points: on the first day of the therapeutic protocol, after 3 weeks from baseline, after 6 weeks from baseline, and 3 weeks after the completion of the protocol. The end-of-intervention assessment at week 6 was considered the main time point for evaluation of treatment effects. There were no expectations regarding the magnitude of the improvement achieved.

The PICO framework was used to formulate the clinical questions and design the study protocol [31]. The CONSORT 2010 statement was used to support the study protocol development and reporting [32].

Intervention (I)

The LUNA EMG system uses surface electrodes placed over the muscle belly of the anterior deltoid, infraspinatus, triceps brachii, and brachioradialis, following SENIAM recommendations for EMG electrode placement [33]. Before each session, electrode impedance and signal quality were verified to ensure reliable EMG acquisition.

An individualized activation threshold was established at the beginning of each training session. In line with protocols applied in EMG-triggered robotic therapy, the threshold typically corresponded to approximately 30% of the patient's maximum voluntary EMG amplitude for the target muscle [18]. When the EMG signal exceeded this threshold, the robot initiated the predefined movement trajectory.

The control algorithm is EMG-triggered rather than EMG-proportional: exceeding the threshold activates a full robotic movement with constant velocity and a patient-specific, safe range of motion determined during calibration. This method is commonly used to enhance active participation in upper-limb robotic rehabilitation [18,19].

The system provides real-time visual biofeedback displaying EMG amplitude and movement progression, supporting motor intention, motivation, and motor learning, consistent with established principles of biofeedback-supported neurorehabilitation [34].

The number of repetitions was determined based on the study by Lang et al.[10], in which the researchers concluded that high repetition counts are necessary to stimulate motor learning after stroke. With regard to the upper limb, a minimum of 100 movements is required.

To ensure a valid comparison between the intervention modalities, the number of therapist-assisted repetitions was intentionally standardized. Controlling movement dose and session intensity is essential, because variability in the amount of practiced movement can independently influence motor outcomes and bias treatment effects [6,9,10,35].

Standard rehabilitation program

The standard rehabilitation program individualized kinesiotherapy and occupational therapy tailored to the patient's specific needs and abilities, based on guidelines for the rehabilitation of adults after stroke (60 minutes), as well as classical upper limb massage (15 minutes) [36–38].

Rehabilitation program using the LUNA EMG robot

A single session lasted approximately 45 minutes and consisted of the following:

- 50 repetitions of an EMG-triggered exercise utilizing EMG activity from the anterior deltoid muscle, resulting in movement of the end-effector and limb toward shoulder flexion,
- 50 repetitions of an EMG-triggered exercise utilizing EMG activity from the infraspinatus muscle, resulting in movement of the end-effector and limb toward shoulder external rotation,
- 50 repetitions of an EMG-triggered exercise utilizing EMG activity from the triceps brachii muscle, resulting in movement of the end-effector and limb toward elbow extension,
- 50 repetitions of an EMG-triggered exercise utilizing EMG activity from the brachioradialis muscle, resulting in movement of the end-effector and limb toward elbow supination.

Rehabilitation program with a physiotherapist

A single session lasted approximately 45 minutes and consisted of the following:

- 50 repetitions of assisted exercises involving shoulder flexion movement,
- 50 repetitions of assisted exercises involving external rotation of shoulder joint,
- 50 repetitions of assisted exercises involving elbow extension,
- 50 repetitions of assisted exercises involving elbow supination.

The selection of four proximal upper-limb movements was based on safety considerations and the technical capabilities of the device. The LUNA EMG robot supports controlled, single-joint proximal movements and does not allow isolated wrist or hand exercises. Focusing on proximal segments is also consistent with classical and contemporary models of post-stroke motor recovery, which describe a characteristic proximal-to-distal sequence of functional return [39,40] Moreover, modern evidence indicates that regaining proximal control is essential for enabling the later re-emergence of distal dexterity and functional hand use [41].

Comparison (C)

Both groups were assigned to the same standard rehabilitation program. In addition, the experimental group participated in a rehabilitation program using the LUNA EMG robot, while the control group participated in a rehabilitation program led by a physiotherapist. The duration, intensity, and dosage of the therapeutic procedures were identical in both groups; the only

difference was the method of implementing assisted exercises: robot-assisted in the experimental group (LUNA EMG) and therapist-assisted in the control group.

Outcome measures (O)

Several outcome measures were used for the quantitative assessment of the research objectives.

Assessment of motor function of the paretic upper limb

- FMA-UE [28] - a widely validated, stroke-specific measure of upper-limb motor impairment and is considered the gold standard for quantifying motor recovery.
- B&BT was used to assess gross manual dexterity. The participant is instructed to move as many small wooden blocks as possible, one at a time, from one compartment of a divided box to the other within 60 seconds. The final score represents the total number of blocks transferred with the tested hand. [42].

Assessment of muscle tone in the paretic upper limb

Muscle tone was assessed using the MAS. The MAS is a six-level ordinal scale, where 0 = no increase in muscle tone; 1 = slight increase manifested by a catch and release; 1 + = slight increase with a catch followed by minimal resistance through less than half of the available range of motion; 2 = more marked increase through most of the range; 3 = considerable increase in tone; and 4 = affected part rigid in flexion or extension. For statistical analysis, MAS scores of 1 + were converted to 1.5, following commonly used procedures for handling this intermediate ordinal category [43].

Assessment using the MAS [44] was conducted for the following muscle groups: shoulder girdle elevators (mainly *musculus trapezius pars descendens*, *musculus levator scapulae*), shoulder adductors, internal rotators, and extensors (mainly *musculus latissimus dorsi*), shoulder external rotators (mainly *musculus infraspinatus*), shoulder abductors (mainly *musculus deltoideus pars media*), elbow flexors in forearm supination (mainly *musculus biceps brachii*), elbow flexors in neutral forearm position (mainly *musculus brachioradialis*), elbow extensors (mainly *musculus triceps brachii*), forearm pronators (mainly *musculus pronator teres*), wrist flexors (*musculus flexor carpi radialis, musculus flexor carpi ulnaris*), and finger flexors (mainly *musculus flexor digitorum superficialis, musculus flexor digitorum profundus*).

Pain assessment

Pain intensity was assessed using the Numerical Rating Scale (NRS, 0–10) [45] during a standardized reaching task at each assessment time point. Participants were instructed to reach forward toward an object placed at shoulder height and at a comfortable arm's-length distance. After completing the movement, they rated their shoulder pain on the NRS, where 0 indicated "no pain" and 10 indicated "worst imaginable pain". Only activity-related pain during this standardized reaching task was recorded and included in the analysis.

QoL assessment

The EQ-5D-5L instrument [46] was used to evaluate five key dimensions: mobility, self-care, usual activities, pain/discomfort, and anxiety/depression. Each dimension is rated on a five-level scale, where level 1 indicates no problems and level 5 indicates extreme difficulty or complete inability to perform the activity. In addition to these five descriptive dimensions, participants also completed the EQ-VAS ("% health today"), a vertical visual analogue scale ranging from 0 ("the worst health you can imagine") to 100 ("the best health you can imagine"). This score reflects the participant's overall perceived health status on the day of assessment and was analysed as an additional quality-of-life indicator.

Sample size

No formal a priori sample size calculation was performed. The final sample comprised all eligible post-stroke patients consecutively admitted to the rehabilitation department during the predefined recruitment period.

Statistical analysis

The distribution of data across four measurements in the experimental and control groups was assessed using the Shapiro–Wilk W test. For most variables, the assumption of normality was not confirmed; therefore, non-parametric methods were applied. For all variables, the median (Mdn) and interquartile range (IQR) were calculated.

Differences between the experimental and control groups with respect to sex, type of stroke, and side of paresis were examined using the chi-square (χ^2) test, and their potential differentiating effect on quantitative variables was assessed using the Mann–Whitney U test. Correlations between variables and age were evaluated using Spearman's rho (ρ). Differences between the four measurements (changes over time) were analysed using the Friedman rank test followed by the Nemenyi post-hoc test. When necessary, Bonferroni correction was applied in the analyses to account for the number of group comparisons.

Results

No statistically significant differences between the experimental and control groups were observed at any measurement time point for any of the analysed variables, including motor performance parameters, upper limb muscle tone, pain intensity, and quality of life. No serious adverse events or therapy-related complications were observed, and no participants discontinued the intervention due to safety concerns.

For all parameters, except FMA-UE-PJM in the control group, significant changes across the four measurement points were observed; however, for some variables, the pattern in which each subsequent measurement differed significantly from the previous one was not maintained (see the notation “(1)–(2)–(3)–(4)” in Table 2). For many parameters (except those for which all possible pairwise differences between measurements “(1)–(2)–(3)–(4)” were significant), no statistically significant changes were found between the third and fourth measurements.

Changes between consecutive measurements for most variables were independent of group allocation. A statistically significant interaction between time and group was observed in only three cases:

– changes in FMA-UE-PJM were statistically significant only in the experimental group;

– the difference between the first and third measurements of EQ-5L-B/D was significantly greater in the control group than in the experimental group;

– the difference between the second and third measurements of EQ-5L-N/P was significantly greater in the control group than in the experimental group.

Table 2. Differences among four measurements of motor performance parameters, upper-limb muscle tone, and assessments of pain intensity and quality of life in post-stroke patients undergoing robot-assisted (Experimental) and non-assisted (Control) rehabilitation.

	Experimental Group (n = 29)						Control Group(n = 29)					
	Mdn (IQR)						Mdn (IQR)					
	(1)	(2)	(3)	(4)	p	Differences	(1)	(2)	(3)	(4)	p	Differences
FMA-UE-UE	18.0 (6.0)	20.0 (7.0)	23.0 (6.0)	24.0 (5.0)	< 0.001	(1)−(2)−(3)−(4)	18.0 (8.0)	21.0 (9.0)	24.0 (9.0)	26.0 (8.0)	< 0.001	(1)−(2)−(3)−(4)
FMA-Wr	4.0 (3.0)	5.0 (1.0)	6.0 (2.0)	6.0 (1.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)	4.0 (4.0)	5.0 (3.0)	6.0 (3.0)	7.0 (2.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)
FMAUE-Hnd	4.0 (3.0)	6.0 (3.0)	7.0 (3.0)	7.0 (2.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)	5.0 (6.0)	6.0 (5.0)	7.0 (4.0)	7.0 (3.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)
FMA-UE-C/S	2.0 (3.0)	3.0 (3.0)	3.0 (1.0)	3.0 (1.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)	2.0 (3.0)	3.0 (3.0)	3.0 (2.0)	4.0 (1.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)
FMA-UE-Ttl	27.0 (14.0)	32.0 (10.0)	40.0 (11.0)	42.0 (9.0)	< 0.001	(1)−(2)−(3)−(4)	29.0 (21.0)	38.0 (22.0)	41.0 (18.0)	45.0 (12.0)	< 0.001	(1)−(2)−(3)−(4)
FMAUE-Sen	6.0 (5.0)	8.0 (4.0)	9.0 (4.0)	9.0 (3.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)	6.0 (4.0)	7.0 (4.0)	8.0 (2.0)	8.0 (2.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)
FMA-UE-PJM	22.0 (2.0)	21.0 (2.0)	20.0 (3.0)	20.0 (3.0)	0.038	(1)−(3); (1)−(4)	22.0 (1.0)	21.0 (2.0)	21.0 (2.0)	21.0 (2.0)	0.187	-
FMAUE-J.Pa	20.0 (5.0)	19.0 (4.0)	21.0 (3.0)	21.0 (3.0)	< 0.001	(2)−(3); (2)−(4)	20.0 (5.0)	19.0 (3.0)	20.0 (3.0)	21.0 (2.0)	< 0.001	(1)−(4); (2)−(4)
FMAUE-sum	73.0 (18.0)	82.0 (16.0)	90.0 (20.0)	93.0 (14.0)	< 0.001	(1)−(2)−(3)−(4)	72.0 (22.0)	82.0 (24.0)	89.0 (20.0)	92.0 (17.0)	< 0.001	(1)−(2)−(3)−(4)
Box n Blocks	3.0 (10.0)	8.0 (9.0)	13.0 (6.0)	15.0 (8.0)	< 0.001	(1)−(2)−(3)−(4)	3.0 (12.0)	7.0 (18.0)	12.0 (19.0)	18.0 (20.0)	< 0.001	(1)−(2)−(3)−(4)
MAS-Bic	1.0 (1.0)	1.5 (0.5)	1.5 (0.0)	1.5 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	1.0 (1.0)	1.0 (0.5)	1.5 (1.0)	1.5 (1.0)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)
MAS-Tric	0.0 (1.0)	1.0 (1.5)	1.0 (0.0)	1.0 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	0.0 (1.0)	1.0 (1.5)	1.0 (0.5)	1.0 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)
MAS-Brarad	0.0 (1.0)	1.0 (1.0)	1.0 (0.5)	1.0 (0.5)	< 0.001	(1)−(2)−(3); (1)−(2)−(4)	0.0 (1.0)	1.0 (0.0)	1.0 (0.5)	1.0 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)
MAS-Delt	0.0 (0.0)	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	0.0 (0.0)	0.0 (1.0)	1.0 (1.0)	0.0 (1.0)	< 0.001	(1)−(2); (1)−(3); (1)−(4)
MAS-Lat/Do	1.0 (0.5)	1.5 (0.5)	1.5 (0.5)	1.5 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	1.5 (0.5)	1.5 (0.5)	1.5 (0.5)	1.5 (0.5)	0.004	(1)−(2); (1)−(3); (1)−(4)
MAS-Infra	0.0 (1.0)	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	0.0 (0.0)	1.0 (1.0)	1.0 (0.5)	1.0 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)
MAS-Up.Tra	1.5 (0.5)	1.5 (0.5)	1.5 (0.0)	1.5 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	1.0 (0.5)	1.5 (0.5)	1.5 (0.5)	1.5 (0.5)	0.005	(1)−(2); (1)−(3); (1)−(4)
MAS-FDS	1.0 (0.0)	1.5 (0.5)	1.5 (0.5)	1.5 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	1.0 (0.0)	1.5 (0.5)	1.5 (0.5)	1.5 (0.5)	0.006	1)−(2); (1)−(3); (1)−(4)
MAS-Pro-Te	1.0 (1.0)	1.5 (0.5)	1.0 (0.5)	1.5 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	1.0 (1.0)	1.0 (0.5)	1.5 (0.5)	1.5 (0.5)	< 0.001	1)−(2); (1)−(3); (1)−(4)
MAS-F.Ca	1.0 (1.0)	1.5 (0.5)	1.5 (1.0)	1.5 (1.0)	< 0.001	(1)−(2); (1)−(3); (1)−(4)	1.0 (1.0)	1.0 (0.5)	1.5 (1.0)	1.5 (0.5)	< 0.001	(1)−(2); (1)−(3); (1)−(4)
EQ-5L-Por	3.0 (1.0)	3.0 (2.0)	3.0 (1.0)	2.0 (1.0)	< 0.001	(1)−(3); (1)−(4); (2)−(4)	4.0 (1.0)	3.0 (2.0)	3.0 (1.0)	2.0 (2.0)	< 0.001	(1)−(2)−(3)−(4)
EQ-5L-Sam	3.0 (1.0)	3.0 (1.0)	3.0 (1.0)	2.0 (1.0)	< 0.001	(1)−(3)−(4); (1)−(2); (2)−(4)	3.0 (1.0)	3.0 (0.0)	3.0 (1.0)	2.0 (1.0)	< 0.001	(1)−(3)−(4); (1)−(2); (2)−(4)

	Experimental Group (n = 29)						Control Group(n = 29)					
	Mdn (IQR)						Mdn (IQR)					
	(1)	(2)	(3)	(4)	p	Differences	(1)	(2)	(3)	(4)	p	Differences
EQ-5L-Z/C	4.0 (1.0)	3.0 (1.0)	3.0 (1.0)	2.0 (1.0)	< 0.001	(1)−(2)−(3)−(4)	4.0 (1.0)	3.0 (1.0)	3.0 (1.0)	3.0 (1.0)	< 0.001	(1)−(3)−(4); (1)−(2); (2)−(4)
EQ-5L-B/D	2.0 (1.0)	2.0 (1.0)	2.0 (1.0)	2.0 (0.0)	0.017	(1)−(3)	3.0 (1.0)	3.0 (1.0)	2.0 (2.0)	2.0 (2.0)	< 0.001	(1)−(3); (1)−(4)
EQ-5L-N/P	3.0 (1.0)	2.0 (1.0)	2.0 (2.0)	2.0 (1.0)	< 0.001	(1)−(3)−(4); (1)−(2); (2)−(4)	3.0 (1.0)	3.0 (1.0)	2.0 (2.0)	2.0 (1.0)	< 0.001	(1)−(3)−(4); (2)−(3); (2)−(4)
EQ-5L-%Zd	40.0 (20.0)	50.0 (15.0)	65.0 (23.0)	75.0 (20.0)	< 0.001	(1)−(2)−(3)−(4)	40.0 (12.0)	50.0 (20.0)	60.0 (15.0)	70.0 (15.0)	< 0.001	(1)−(2)−(3)−(4)
NRS	5.0 (4.0)	5.0 (3.0)	4.0 (2.0)	3.0 (2.0)	< 0.001	(1)−(4); (2)−(4)	6.0 (2.0)	5.0 (3.0)	4.0 (2.0)	3.0 (3.0)	< 0.001	(1)−(4); (2)−(4)

There were no significant differences between the Experimental and Control groups (p > 0.05 for all variables), Mdn – median, IQR – interquartile range, n (%) – frequency in the experimental and control groups, p – value of statistical significance; FMA – Fugl-Meyer Assessment; UE – Upper Extremity; FMA-UE-UE – shoulder and upper arm function; FMA-Wr – wrist function; FMAUE-Hnd – hand function; FMA-UE-C/S – coordination and speed; FMA-UE-Ttl – total upper extremity motor score; FMAUE-Sen – sensation; FMA-UE-PJM – passive joint motion; FMAUE-J.Pa – joint pain; FMAUE-sum – total FMA upper extremity score; Box n Blocks – Box and Block Test; MAS – Modified Ashworth Scale: MAS-Bic – biceps brachii; MAS-Tric – triceps brachii; MAS-Brarad – brachioradialis; MAS-Delt – deltoid; MAS-Lat/Do – latissimus dorsi; MAS-Infra – infraspinatus; MAS-Up.Tra – upper trapezius; MAS-FDS – flexor digitorum superficialis; MAS-Pro-Te – pronator teres; MAS-F.Ca – wrist flexors (flexor carpi); EQ-5L – EuroQol 5 Dimensions, 5 Levels: EQ-5L-Por – mobility; EQ-5L-Sam – self-care; EQ-5L-Z/C – usual activities; EQ-5L-B/D – pain/discomfort; EQ-5L-N/P – anxiety/depression; EQ-5L-%Zd – self-rated health; NRS – Numeric Rating Scale; (1)–(2)–(3)–(4) – significant differences between all four consecutive measurements; (1)–(2) differences between measurements (1) and (2)FMA – Fugl-Meyer Assessment; UE – Upper Extremity; FMA-UE-PJM – passive joint motion; EQ-5L-B/D – pain/discomfort; FMA-UE-Ttl – total upper extremity motor score; Box n Blocks – Box and Block Test; EQ-5L-%Zd – self-rated health; MAS-Tric – triceps brachii spasticity assessed using the Modified Ashworth Scale

The parameters at each measurement point did not correlate with participants' age and did not differ by sex or by the side of paresis. A differentiating effect of stroke type was detected for FMA-Wr, FMAUE-Hnd, FMAUE-J.Pa, FMAUE-sum, and the Box and Blocks Test; these parameters had higher values in participants after hemorrhagic stroke than in those after ischemic stroke. Only the changes in FMAUE-J.Pa differed by stroke type. In participants after ischemic stroke, the changes in FMAUE-J.Pa were greater than in participants after hemorrhagic stroke (Fig. 3).

Figure 3. Changes in FMAUE-J.Pa between measurements (1)–(4) according to stroke type.

FMA – Fugl-Meyer Assessment; UE – Upper Extremity; FMA-UE-J.Pa – joint pain component of the Fugl-Meyer Assessment Upper Extremity.

Discussion

This randomized controlled trial compared EMG-triggered robot-assisted upper limb therapy using the Luna EMG system with therapist-led rehabilitation in post-stroke patients under strictly standardized conditions of movement dose, repetition count, and session duration. The present findings suggest that both interventions were associated with significant improvements in upper limb motor function, muscle tone, pain intensity, and QoL. No statistically significant between-group differences were observed for FMA-UE, Box and Block Test, MAS, or NRS outcomes at any of the examined time points, while a single significant difference was detected in the EQ-5D-5L "usual activities" domain at follow-up, in favor of the robot-assisted group.

The absence of statistically significant between-group differences in motor outcomes is consistent with previous randomized trials and recent meta-analyses demonstrating that robot-assisted upper limb therapy improves motor impairment but does not consistently outperform dose-matched conventional therapy [12,13,15,17,21,47–49]. This supports the interpretation that robotic assistance may represent an alternative method of delivering intensive motor training rather than an inherently superior therapeutic modality.

The within-group improvements in both FMA-UE and Box and Block Test scores observed in the experimental and control groups confirm that intensive, task-oriented upper limb training in the early post-stroke phase can effectively enhance motor performance irrespective of whether movement assistance is provided by a therapist or a robotic device. This finding is consistent with the

concept that the *dose of active movement practice* is a critical driver of post-stroke recovery [8–10]. Observational studies have demonstrated that the number of purposeful upper limb repetitions typically achieved during routine clinical rehabilitation is often insufficient to optimally stimulate neuroplastic reorganization [9,10]. In the present trial, movement dose was deliberately controlled and equalized between the study arms, which likely minimized any potential advantage of robotic technology related solely to repetition volume.

The present study also contributes to the growing literature on EMG-based robotic rehabilitation. EMG-triggered devices initiate movement only when voluntary muscle activation exceeds a predefined threshold, thereby reinforcing motor intention and active participation [18,19,26].

Recent meta-analyses have reported improvements in upper limb motor outcomes associated with EMG-based robotic systems after stroke; however, superiority over dose-matched conventional therapy remains uncertain [20]. Our findings extend this evidence by suggesting that EMG-triggered robot-assisted training can achieve similar short-term motor improvements under carefully standardized dosing conditions.

Regarding muscle tone, no significant between-group differences in MAS scores were observed across any of the examined muscle groups or time points. This suggests that, within the six-week intervention period and under standardized movement conditions, both robot-assisted and therapist-led rehabilitation exerted a similar influence on spasticity. Previous trials and systematic reviews have reported heterogeneous effects of robotic rehabilitation on upper limb spasticity, with some studies demonstrating modest reductions and others reporting no significant differences relative to conventional therapy [50–52]. The available evidence therefore supports the interpretation that robotic assistance is not inherently superior to therapist-led exercises for spasticity modulation when movement dose and structure are comparable.

Both study groups exhibited a significant reduction in pain intensity between baseline and the final follow-up measurement. Importantly, the reduction in pain became statistically significant primarily at later measurement points rather than immediately after therapy initiation. This delayed pattern suggests that pain relief was most likely mediated by cumulative improvements in neuromuscular control, joint mobility, and soft tissue flexibility, as well as by the additive effects of comprehensive multidisciplinary rehabilitation. Exercise-based interventions such as strengthening, stretching, and task-oriented functional training have been consistently shown to reduce post-stroke shoulder pain and improve movement tolerance [53–55]. Massage and manual techniques, which were part of the standard rehabilitation program in both groups, have also been associated with clinically meaningful pain reduction [54].

Hemiplegic shoulder pain is a common complication after stroke and is widely recognized as a multifactorial condition influenced by biomechanical, neuromuscular, and psychosocial factors [7,56]. As both groups in the present study received similar adjunctive therapies, the observed reduction in pain intensity is best explained by the cumulative effect of comprehensive rehabilitation rather than by a specific analgesic effect of either robot-assisted or therapist-led upper limb training alone.

QoL, as assessed by the EQ-5D-5L, improved in several domains in both groups, including mobility, self-care, pain/discomfort, and anxiety/depression, reflecting the overall functional gains achieved during intensive inpatient neurorehabilitation [46,57,58]. The only statistically significant between-group difference was detected in the “usual activities” dimension at follow-up, favoring the robot-assisted group. However, this finding must be interpreted with caution. The Luna EMG protocol focused exclusively on proximal upper limb movements and did not directly train activities of daily living. Therefore, it is unlikely that this difference reflects a direct task-specific transfer effect from robotic exercises to everyday functional performance.

A more plausible explanation is that the observed improvement in “usual activities” reflects the combined effects of high-dose upper limb training and the broader standard rehabilitation program, including functional kinesiotherapy and occupational therapy. Previous studies indicate that robot-assisted training is most likely to translate into improvements at the activity and participation levels when it is embedded within comprehensive multidisciplinary rehabilitation rather than delivered as a standalone modality [15,57,58].

The potential contribution of motivational and engagement-related mechanisms should also be considered. Robotic systems provide real-time visual feedback and objective performance monitoring, which may enhance patient engagement [11,34]. Although these factors were not directly assessed in the present study, their potential influence on subjective perceptions of functional ability and daily activity performance cannot be excluded.

Although some differences related to stroke aetiology were observed, the interpretation of analyses according to stroke aetiology should be made with caution because the hemorrhagic stroke subgroup was relatively small (9 and 10 participants) compared with the ischemic subgroup (20 and 19 participants).

From a clinical perspective, the present findings indicate that EMG-triggered robot-assisted therapy using the Luna EMG system represents a viable alternative to therapist-led rehabilitation for delivering high-repetition upper limb training in the early post-

stroke phase. When movement dose, repetition count, and session duration are tightly controlled, robot-assisted therapy appears to be as effective as standardized therapist-led rehabilitation in improving motor function, reducing pain, and enhancing QoL over a six-week period [48,49].

These results should not be interpreted as evidence that robotic rehabilitation is unnecessary or clinically redundant. Instead, they support a model in which EMG-based robotic systems such as Luna are integrated as complementary tools within structured rehabilitation programs. Once clinical equivalence between robotic and conventional upper limb rehabilitation has been demonstrated, recent economic evaluations suggest that future analyses should focus on optimizing resource utilization, accessibility, and long-term sustainability rather than on seeking superiority in short-term clinical outcomes [59].

In summary, this randomized controlled trial demonstrated that both EMG-triggered robot-assisted therapy using the Luna EMG system and standardized therapist-led rehabilitation were associated with significant short-term improvements in upper limb motor function, muscle tone, pain, and QoL under rigorously controlled dosing conditions. No statistically significant between-group differences were detected. These findings suggest that EMG-based robotic systems may serve as an alternative modality for delivering high-repetition upper limb rehabilitation within comprehensive post-stroke programs.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, although 58 participants were included, no formal a priori sample size calculation was performed. The final sample comprised all eligible post-stroke patients consecutively admitted to the rehabilitation department during the predefined recruitment period. This may limit the statistical power of the study and increase the risk of type II error, which may partly explain the lack of statistically significant between-group differences in several outcome measures. Although both groups demonstrated clinically meaningful improvements over time, subtle between-group effects may have remained undetected.

Second, the absence of long-term follow-up prevents conclusions regarding the durability and sustainability of the observed functional improvements beyond the short post-intervention period.

Third, although movement dose and session duration were rigorously standardized, other potentially influential factors—such as individual motivation, therapist–patient interaction, and psychosocial variables—were not formally controlled or quantified and may have affected the outcomes.

Fourth, the intervention focused exclusively on proximal upper limb movements due to the technical constraints of the robotic device. Consequently, the results cannot be directly generalized to distal hand function or fine motor recovery.

Another important limitation is that clinical trial registration at ClinicalTrials.gov was performed retrospectively due to administrative delays. Although the full study protocol had been developed and approved by the institutional ethics committee prior to patient enrolment, prospective registration was not completed in time. No modifications were made to the protocol after data collection or statistical analysis. Nevertheless, retrospective registration may reduce the transparency of the study, and future trials should ensure prospective registration in accordance with CONSORT recommendations.

Conclusions

This randomized controlled trial showed that EMG-triggered robot-assisted upper limb therapy using the Luna EMG system and standardized therapist-led rehabilitation were associated with significant short-term improvements in upper limb motor function, muscle tone, pain intensity, and quality of life in patients after stroke when movement dose and session duration were strictly controlled.

No statistically significant between-group differences were detected under matched dosing conditions. These findings suggest that robot-assisted therapy may represent an alternative method for delivering high-repetition upper limb training in early post-stroke rehabilitation rather than a superior therapeutic modality.

The single between-group difference observed in the “usual activities” domain of the EQ-5D-5L at follow-up should be interpreted with caution and is most likely attributable to the combined effects of comprehensive multidisciplinary rehabilitation rather than to a specific task-transfer effect of the robotic intervention alone.

Considering the lack of prospective sample size calculation and the relatively limited sample size, the findings of this study warrant cautious interpretation. Larger, adequately powered randomized controlled trials with extended follow-up periods are necessary to confirm these results, establish the durability of treatment effects, and better identify clinical predictors of response as well as patient subgroups who may derive the greatest benefit from EMG-based robotic rehabilitation.

Abbreviations

EQ-5L, EuroQoL-5 Dimensions-5 Levels Instrument

NRS, Numerical Rating Scale

VAS, Visual Analog Scale

QoL, quality of life

FMA-UE, Fugl-Mayer Upper Extremity Assessment

DALY, disability-adjusted life year

MAS, Modified Ashworth Scale

EMG, electromyography

B&BT, Box and Block test

Mdn, median

IQR, interquartile range

ρ, Spearman’s rank correlation coefficient

χ^2, chi-square test

Declarations

Acknowledgements

The authors would like to thank the staff of EGZOTech for their technical support. They were not involved in any direct activities related to the study protocol, such as patient recruitment, data collection, or data analysis. Their contribution was limited to providing consultations regarding the robotic technology developed by EGZOTech company.

Author contributions

Conceptualization; D.M., I.S.-D.; Methodology: D.M., I.S.-D., M.M., A.P.; Data acquisition: D.M.; Formal analysis: D.M., M.K; Data interpretation: D.M., I.S.-D., M.K.; Manuscript writing: D.M.; Manuscript reviewing and editing: D.M., I.S.-D., M.M., A.P., M.K All authors reviewed the manuscript and approved the final version to be published.

Funding

No funding was received to conduct the study.

Availability of data and materials

Data are available from the corresponding authors upon request.

Ethics approval and consent to participate:

The study has been conducted according to the principles expressed in the Declaration of Helsinki. The study protocol was approved by the Senate Committee on Ethics at Wrocław University of Health and Sport Sciences. Written informed consent was obtained from all patients to participate in both the study and therapy.

Consent for publication

Not applicable

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

Competing interests

Michal Mikulski and Anna Poświata are employees of EGZOTech Sp. z o.o., the manufacturer of the LUNA EMG system. The company had no influence on study design, data collection, analysis, or interpretation.

References

1. Feigin, V. L. *et al.* World Stroke Organization: Global Stroke Fact Sheet 2025. *Int J Stroke* **20**, 132–144 (2025).
2. Lawrence, E. S. *et al.* Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population. *Stroke* **32**, 1279–1284 (2001).
3. Hendricks, H. T., van Limbeek, J., Geurts, A. C. & Zwarts, M. J. Motor recovery after stroke: a systematic review of the literature. *Arch Phys Med Rehabil* **83**, 1629–1637 (2002).
4. Kuo, C.-L. & Hu, G.-C. Post-stroke Spasticity: A Review of Epidemiology, Pathophysiology, and Treatments. *International Journal of Gerontology* **12**, 280–284 (2018).
5. Paolucci, S. *et al.* Prevalence and Time Course of Post-Stroke Pain: A Multicenter Prospective Hospital-Based Study. *Pain Med* **17**, 924–930 (2016).
6. Pollock, A. *et al.* Interventions for improving upper limb function after stroke. *Cochrane Database Syst Rev* **2014**, CD010820 (2014).
7. Adey-Wakeling, Z. *et al.* Incidence and associations of hemiplegic shoulder pain poststroke: prospective population-based study. *Arch Phys Med Rehabil* **96**, 241-247.e1 (2015).
8. Schaechter, J. D. Motor rehabilitation and brain plasticity after hemiparetic stroke. *Prog Neurobiol* **73**, 61–72 (2004).
9. Lang, C. E., Lohse, K. R. & Birkenmeier, R. L. Dose and timing in neurorehabilitation: prescribing motor therapy after stroke. *Curr Opin Neurol* **28**, 549–555 (2015).
10. Lang, C. E. *et al.* Observation of amounts of movement practice provided during stroke rehabilitation. *Arch Phys Med Rehabil* **90**, 1692–1698 (2009).
11. Tomić, T. J. D. *et al.* ArmAssist Robotic System versus Matched Conventional Therapy for Poststroke Upper Limb Rehabilitation: A Randomized Clinical Trial. *Biomed Res Int* **2017**, 7659893 (2017).
12. Chien, W.-T., Chong, Y.-Y., Tse, M.-K., Chien, C.-W. & Cheng, H.-Y. Robot-assisted therapy for upper-limb rehabilitation in subacute stroke patients: A systematic review and meta-analysis. *Brain Behav* **10**, e01742 (2020).
13. Zhang, L., Jia, G., Ma, J., Wang, S. & Cheng, L. Short and long-term effects of robot-assisted therapy on upper limb motor function and activity of daily living in patients post-stroke: a meta-analysis of randomized controlled trials. *J Neuroeng Rehabil* **19**, 76 (2022).
14. Lee, S. H. *et al.* Comparisons between end-effector and exoskeleton rehabilitation robots regarding upper extremity function among chronic stroke patients with moderate-to-severe upper limb impairment. *Sci Rep* **10**, 1806 (2020).
15. Jin, C., Chen, Y. & Ma, Y. Effectiveness of robot-assisted task-oriented training intervention for upper limb and daily living skills in stroke patients: A meta-analysis. *PLoS One* **20**, e0316633 (2025).
16. Yang, S.-W., Ma, S.-R. & Choi, J.-B. Effect of 3-Dimensional Robotic Therapy Combined with Electromyography-Triggered Neuromuscular Electrical Stimulation on Upper Limb Function and Cerebral Cortex Activation in Stroke Patients: A Randomized Controlled Trial. *Bioengineering* **11**, 12 (2024).
17. Wang, H., Wu, X., Li, Y. & Yu, S. Efficacy of Robot-assisted Training on Upper Limb Motor Function After Stroke: A Systematic Review and Network Meta-analysis. *Archives of Rehabilitation Research and Clinical Translation* **7**, 100387 (2025).
18. Dipietro, L. *et al.* Customized interactive robotic treatment for stroke: EMG-triggered therapy. *IEEE Trans Neural Syst Rehabil Eng* **13**, 325–334 (2005).
19. Shi, X.-Q. *et al.* Task-Oriented Training by a Personalized Electromyography-Driven Soft Robotic Hand in Chronic Stroke: A Randomized Controlled Trial. *Neurorehabil Neural Repair* **38**, 595–606 (2024).
20. Huo, Y., Wang, X., Zhao, W., Hu, H. & Li, L. Effects of EMG-based robot for upper extremity rehabilitation on post-stroke patients: a systematic review and meta-analysis. *Front. Physiol.* **14**, (2023).
21. Veerbeek, J. M., Langbroek-Amersfoort, A. C., van Wegen, E. E. H., Meskers, C. G. M. & Kwakkel, G. Effects of Robot-Assisted Therapy for the Upper Limb After Stroke. *Neurorehabil Neural Repair* **31**, 107–121 (2017).
22. Hsieh, Y. *et al.* Dose-response relationship of robot-assisted stroke motor rehabilitation: the impact of initial motor status. *Stroke* **43**, 2729–2734 (2012).
23. Maciejasz, P., Eschweiler, J., Gerlach-Hahn, K., Jansen-Troy, A. & Leonhardt, S. A survey on robotic devices for upper limb rehabilitation. *J Neuroeng Rehabil* **11**, 3 (2014).

24. Leszczak, J. *et al.* Evaluation of Reliability of the Luna EMG Rehabilitation Robot to Assess Proprioception in the Upper Limbs in 102 Healthy Young Adults. *Med Sci Monit* **29**, e942439-1-e942439-9 (2024).
25. Leszczak, J. *et al.* Assessment of inter-rater and intra-rater reliability of the Luna EMG robot as a tool for assessing upper limb proprioception in patients with stroke-a prospective observational study. *PeerJ* **12**, e17903 (2024).
26. Chen, Y.-W., Chiang, W.-C., Chang, C.-L., Lo, S.-M. & Wu, C.-Y. Comparative effects of EMG-driven robot-assisted therapy versus task-oriented training on motor and daily function in patients with stroke: a randomized cross-over trial. *Journal of NeuroEngineering and Rehabilitation* **19**, 6 (2022).
27. Xu, Z., Chai, S. C., Chu, S. Y. & Li, K. Effects of pressure garments of varying designs on upper extremity sensorimotor functions and quality of life after stroke: Study protocol for a multicenter, double-blind, prospective randomized controlled trial. *PLoS One* **20**, e0326680 (2025).
28. Gladstone, D. J., Danells, C. J. & Black, S. E. The fugl-meyer assessment of motor recovery after stroke: a critical review of its measurement properties. *Neurorehabil Neural Repair* **16**, 232–240 (2002).
29. Folstein, M. F., Folstein, S. E. & McHugh, P. R. 'Mini-mental state'. A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res* **12**, 189–198 (1975).
30. Morris, S. Ashworth And Tardieu Scales: Their Clinical Relevance For Measuring Spasticity In Adult And Paediatric Neurological Populations. *Physical Therapy Reviews* https://doi.org/10.1179/108331902125001770 (2002) doi:10.1179/108331902125001770.
31. Huang, X., Lin, J. & Demner-Fushman, D. Evaluation of PICO as a knowledge representation for clinical questions. *AMIA Annu Symp Proc* **2006**, 359–363 (2006).
32. Schulz, K. F., Altman, D. G., Moher, D., & CONSORT Group. CONSORT 2010 Statement: updated guidelines for reporting parallel group randomised trials. *BMC Med* **8**, 18 (2010).
33. Hermens, H. J., Freriks, B., Disselhorst-Klug, C. & Rau, G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* **10**, 361–374 (2000).
34. Bertani, R. *et al.* Effects of robot-assisted upper limb rehabilitation in stroke patients: a systematic review with meta-analysis. *Neurol Sci* **38**, 1561–1569 (2017).
35. Veerbeek, J. M. *et al.* What is the evidence for physical therapy poststroke? A systematic review and meta-analysis. *PLoS One* **9**, e87987 (2014).
36. Stroke rehabilitation in adults.
37. Cabanas-Valdés, R. *et al.* The Effectiveness of Massage Therapy for Improving Sequelae in Post-Stroke Survivors. A Systematic Review and Meta-Analysis. *International Journal of Environmental Research and Public Health* **18**, 4424 (2021).
38. Hildebrand, M. W., Geller, D. & Proffitt, R. Occupational Therapy Practice Guidelines for Adults With Stroke. *Am J Occup Ther* **77**, 7705397010 (2023).
39. Sawner, K. A., LaVigne, J. M. & Brunnstrom, S. *Brunnstrom's Movement Therapy in Hemiplegia: A Neurophysiological Approach*. (Lippincott, Philadelphia, 1992).
40. Twitchell, T. E. The restoration of motor function following hemiplegia in man. *Brain* **74**, 443–480 (1951).
41. Lin, D. J. *et al.* Distinguishing Distinct Neural Systems for Proximal vs Distal Upper Extremity Motor Control After Acute Stroke. *Neurology* **101**, e347–e357 (2023).
42. Desrosiers, J., Bravo, G., Hébert, R., Dutil, E. & Mercier, L. Validation of the Box and Block Test as a measure of dexterity of elderly people: reliability, validity, and norms studies. *Arch Phys Med Rehabil* **75**, 751–755 (1994).
43. Bohannon, R. W. & Smith, M. B. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther* **67**, 206–207 (1987).
44. Ansari, N. N., Naghdi, S., Arab, T. K. & Jalaie, S. The interrater and intrarater reliability of the Modified Ashworth Scale in the assessment of muscle spasticity: limb and muscle group effect. *NeuroRehabilitation* **23**, 231–237 (2008).
45. Lundeberg, T. *et al.* Reliability and responsiveness of three different pain assessments. *J Rehabil Med* **33**, 279–283 (2001).
46. Herdman, M. *et al.* Development and preliminary testing of the new five-level version of EQ-5D (EQ-5D-5L). *Qual Life Res* **20**, 1727–1736 (2011).
47. Mehrholz, J., Pohl, M., Platz, T., Kugler, J. & Elsner, B. Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. *Cochrane Database Syst Rev* **9**, CD006876 (2018).
48. Boardsworth, K. *et al.* Upper limb robotic rehabilitation following stroke: a systematic review and meta-analysis investigating efficacy and the influence of device features and program parameters. *J Neuroeng Rehabil* **22**, 164 (2025).
49. Park, J. M. *et al.* Effects of Robot-Assisted Therapy for Upper Limb Rehabilitation After Stroke: An Umbrella Review of Systematic Reviews. *Stroke* **56**, 1243–1252 (2025).

50. Lee, H. Y. & Ryu, B. Effects of Repetitive Transcranial Magnetic Stimulation on Upper and Lower Limb Motor Function and Spasticity After Stroke: A Meta-Analysis. *Brain Neurorehabil* **18**, e5 (2025).
51. Demetrios, M., Khan, F., Turner-Stokes, L., Brand, C. & McSweeney, S. Multidisciplinary rehabilitation following botulinum toxin and other focal intramuscular treatment for post-stroke spasticity. *Cochrane Database Syst Rev* **2013**, CD009689 (2013).
52. Kwakkel, G., Kollen, B. J. & Krebs, H. I. Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. *Neurorehabil Neural Repair* **22**, 111–121 (2008).
53. Ma, Y., Luo, J. & Wang, X.-Q. The effect and mechanism of exercise for post-stroke pain. *Front Mol Neurosci* **15**, 1074205 (2022).
54. Gomez-Cuaresma, L. *et al.* Effectiveness of Stretching in Post-Stroke Spasticity and Range of Motion: Systematic Review and Meta-Analysis. *J Pers Med* **11**, 1074 (2021).
55. Geneen, L. J. *et al.* Physical activity and exercise for chronic pain in adults: an overview of Cochrane Reviews. *Cochrane Database Syst Rev* **1**, CD011279 (2017).
56. de Sire, A. *et al.* Efficacy of rehabilitative techniques in reducing hemiplegic shoulder pain in stroke: Systematic review and meta-analysis. *Ann Phys Rehabil Med* **65**, 101602 (2022).
57. Kutner, N. G., Zhang, R., Butler, A. J., Wolf, S. L. & Alberts, J. L. Quality-of-life change associated with robotic-assisted therapy to improve hand motor function in patients with subacute stroke: a randomized clinical trial. *Phys Ther* **90**, 493–504 (2010).
58. Dundar, U., Toktas, H., Solak, O., Ulasli, A. M. & Eroglu, S. A comparative study of conventional physiotherapy versus robotic training combined with physiotherapy in patients with stroke. *Top Stroke Rehabil* **21**, 453–461 (2014).
59. Gower, V. *et al.* Cost analysis of technological vs. conventional upper limb rehabilitation for patients with neurological disorders: an Italian real-world data case study. *Front. Public Health* **12**, (2024).

Figures

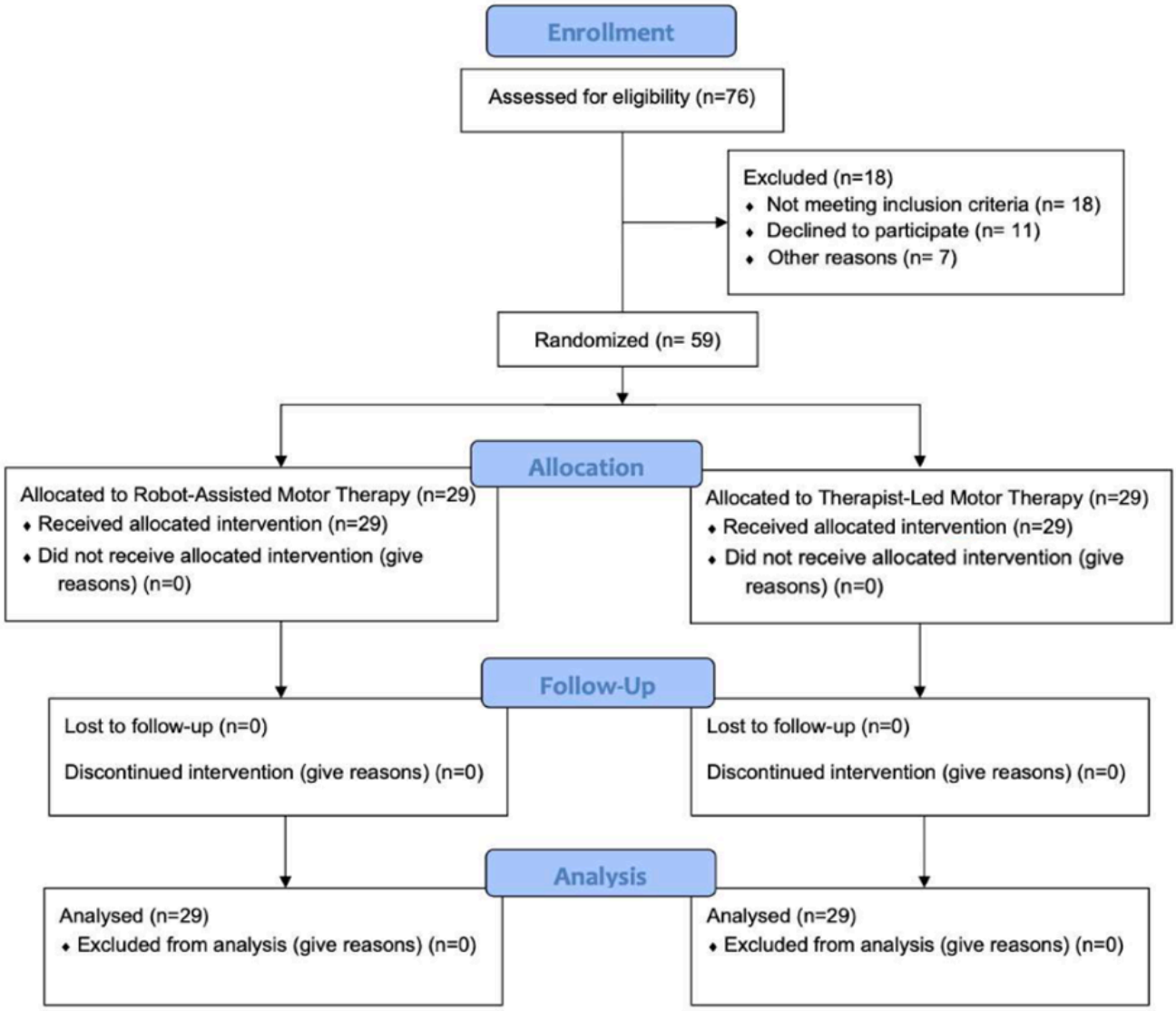


Figure 1

CONSORT 2010 Flow Diagram illustrating participant progress through enrolment, allocation, follow-up, and analysis n- number of subjects

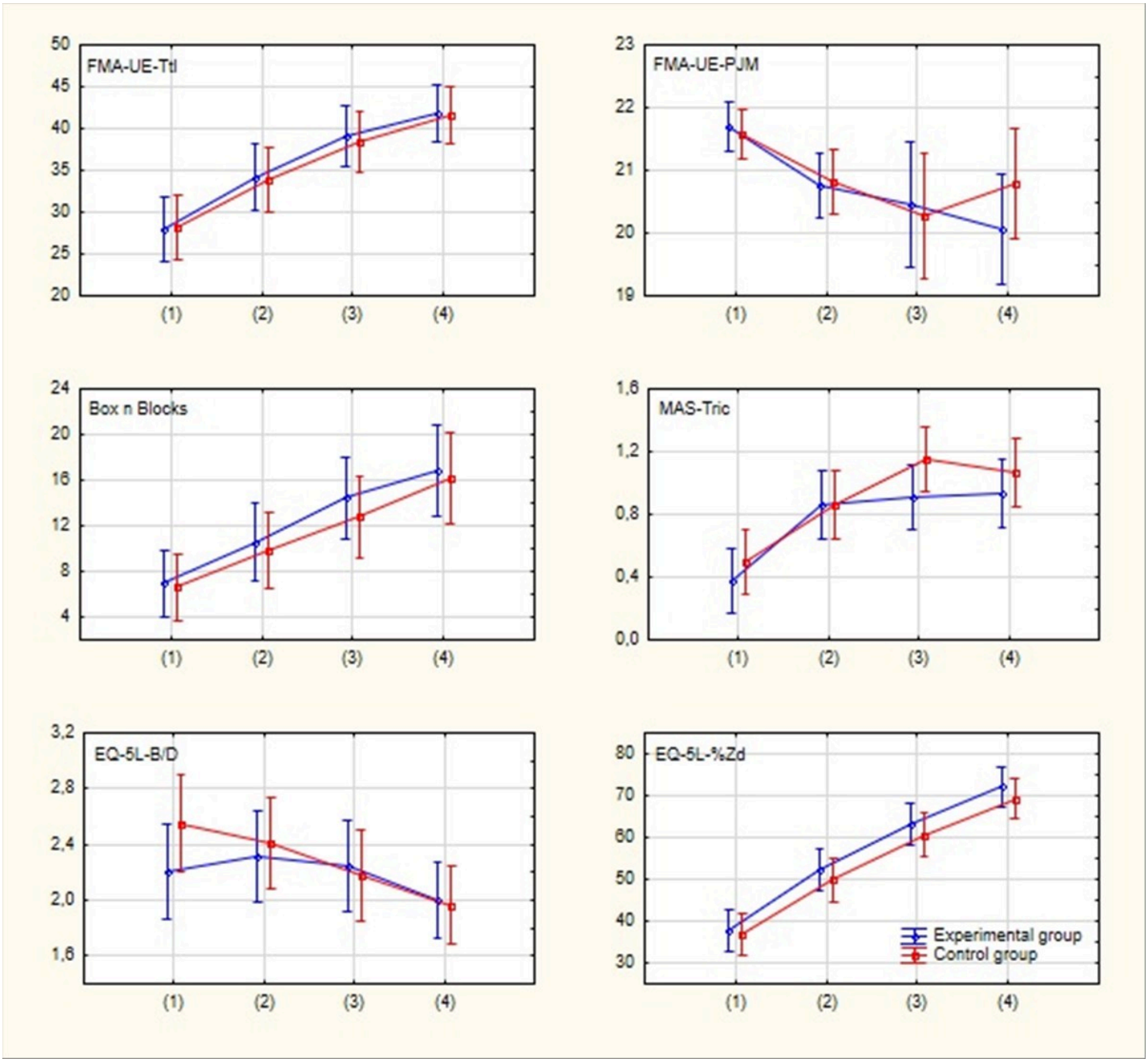


Figure 2

Changes in selected clinical parameters between measurements (1)–(4) in the Experimental and Control groups. FMA – Fugl-Meyer Assessment; UE – Upper Extremity; FMA-UE-PJM – passive joint motion; EQ-5L-B/D – pain/discomfort; FMA-UE-Ttl – total upper extremity motor score; Box n Blocks – Box and Block Test; EQ-5L-%Zd – self-rated health; MAS-Tric – triceps brachii spasticity assessed using the Modified Ashworth Scale

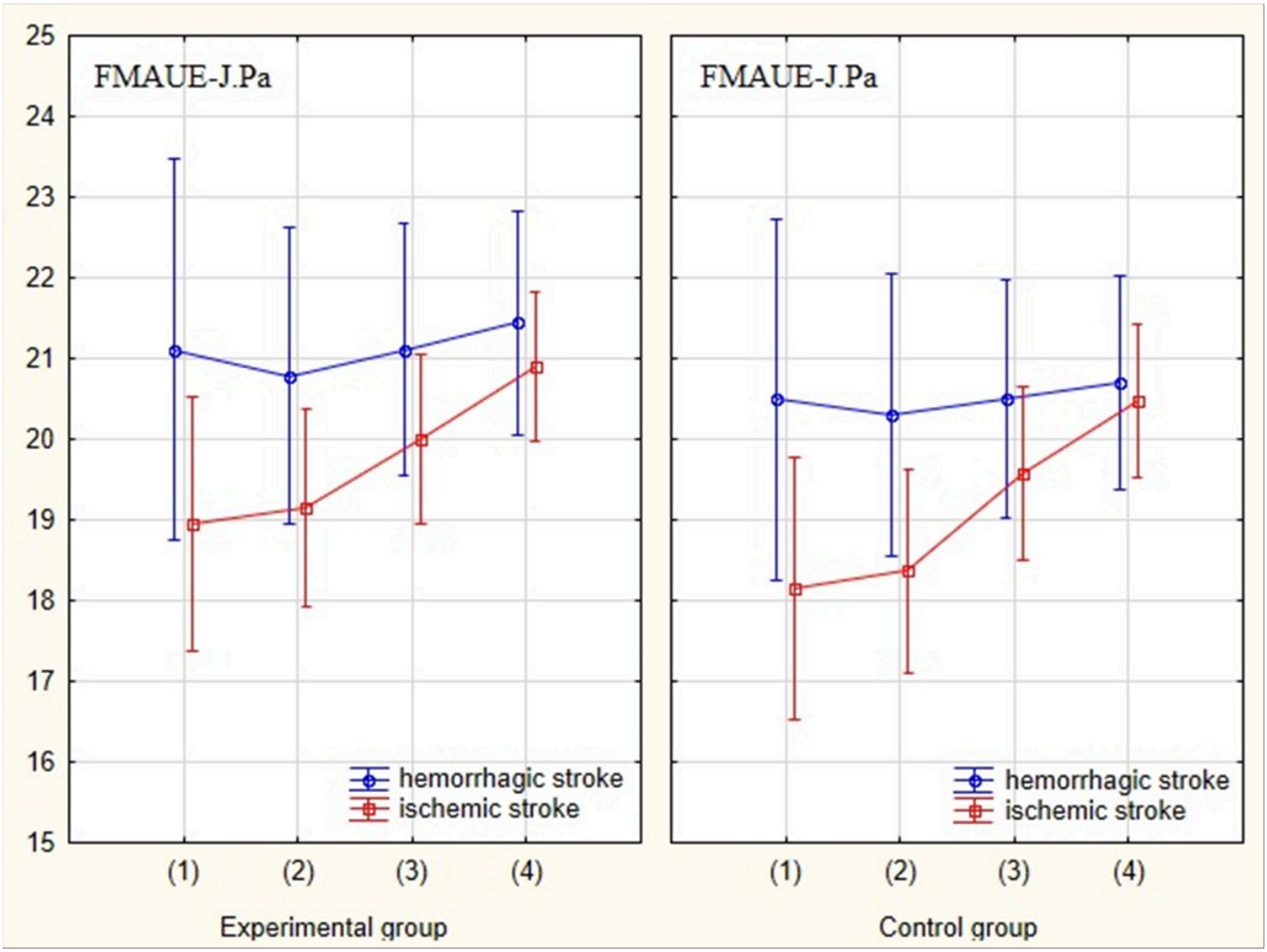


Figure 3

Changes in FMAUE-J.Pa between measurements (1)–(4) according to stroke type. FMA – Fugl-Meyer Assessment; UE – Upper Extremity; FMA-UE-J.Pa – joint pain component of the Fugl-Meyer Assessment Upper Extremity.