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# Extending reach: hybrid robotic-functional electrical stimulation training for post-stroke upper extremity rehabilitation

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## Abstract

**Background** Impaired upper extremity (UE) function is a major contributor to disability after stroke. Combining robotic devices with functional electrical stimulation (FES) has emerged as a promising hybrid approach to enhance post stroke UE function.

**Objective** To assess the preliminary efficacy of robotic training with the REACH+multi-muscle FES device compared to the REACH device alone on UE function in individuals with chronic stroke.

**Methods** This was a pilot non-blinded randomized control trial. Twenty individuals with chronic stroke were randomized to hybrid REACH + FES ($n = 10$) or REACH alone training ($n = 10$). All participants utilized the REACH device for training, which consisted of point-to-point reaching movements in response to a visually evoked task. The REACH + FES group additionally received multi-muscle FES during the REACH device training. Training consisted of 60 min sessions, 3 times/week for six weeks, totaling 18 sessions. The primary outcomes were the kinematic outcomes from the Kinereach/TrakStar virtual reality system. Secondary outcomes included Upper Extremity Fugl Meyer Assessment (UE-FMA), Action Research Arm Test (ARAT), Reaching Performance Scale for Stroke (RPSS), and Modified Ashworth Scale (MAS).

**Results** Both groups demonstrated improvements in kinematic and clinical outcomes post-training; but the REACH + FES group showed superior improvements in unconstrained reaching, including distance (midline, contralateral and ipsilateral directions; $p < 0.05$) and contralateral linearity($p < 0.05$). Additionally, REACH + FES also exhibited improvements in UE impairments (UE-FMA: $p < 0.025$, Far component of RPSS: $p < 0.05$, MAS: $p < 0.05$) and function (ARAT: $p < 0.025$).

**Conclusion** There is preliminary support for the use of an end-effector, uniaxial robotic device integrated with multi-muscle FES to maximize UE functional improvement in individuals with chronic stroke in a clinically meaningful way.

*Clinical Trial Registration* NCT05854485.

**Keywords** Stroke, Upper extremity, Robotics, FES, Rehabilitation, Reach

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## Introduction

Stroke is a significant public health issue, leading to substantial long-term disabilities among adults worldwide. In the United States alone, approximately 800,000 individuals experience a stroke annually, with over 80% exhibiting motor deficits in the paretic upper extremity (UE) [1, 2]. Despite completing standard rehabilitation protocols, about 50–60% of individuals continue to experience persistent motor impairments during the chronic phase, beyond six months post-stroke [3]. Evidence supports intensive, repetitive, goal-oriented rehabilitation delivered by interdisciplinary clinical providers with emphasis on active patient engagement to promote experience-dependent plasticity and motor recovery following stroke [4, 5]. However, a fundamental challenge exists for individuals with limited or no active movement in their UE, as they face significant barriers to engaging in effective task-oriented training. Barker et al. identified that having not enough movement to work with is perceived by individuals with stroke as the greatest barrier to recovery [6, 7].

In response, technological innovations such as UE robotics and/or functional electrical stimulation (FES) have emerged as potential solutions. These technologies enable repetitive, task-specific training that can support motor recovery even in individuals with minimal movement control [8–10]. Robotic training, particularly for planar reaching, has been established as a safe and modestly effective intervention, demonstrating improvements in arm function and strength [11], as well as functional cortical reorganization accompanied by persistent motor gains [12, 13]. Similarly, FES-assisted reaching training has been shown to enhance voluntary motor recovery through temporal coupling of attempted movement with peripheral muscle activation, promoting cortical reorganization [14], resulting in improved inter-joint coordination [15, 16]. However, each modality has distinct limitations when used in isolation. While robotics provide consistent, programmable assistance, they may not ensure proper or synchronized muscle activations necessary for coordinated movement [17–19]. Conversely, although FES can activate specific muscles to facilitate movement [15, 20], it presents challenges in precisely controlling muscle contractions to achieve desired kinematic properties particularly during multi-joint reaching. This limitation is exacerbated in joints with contractures or spasticity, restricting improvements in strength and range of motion [16, 21]. Consequently, the integration of these technologies into "Hybrid Rehabilitation Systems" has developed steadily over recent years, aiming to combine the benefits of each approach while mitigating their individual limitations [22].

Current research on hybrid systems for UE rehabilitation, especially for re-training reaching function reveals two important limitations. First, most existing randomized controlled trials (RCTs) have limited FES application to only one or two muscles [7, 23–25], despite the fact that functional reach requires coordinated activation across multiple muscle groups and joints. Furthermore, the robotic systems employed in some of these studies are passive systems [7, 25] rather than active, assist as-needed approaches to promote patient engagement and motor learning [26]. Even with assist as-needed robotic technologies, modest improvements in UE function have been reported in individuals with chronic stroke [27].

To address these limitations, we propose an innovative hybrid system that combines an "assist-as-needed" REACH robotic device with multi-muscle FES. The REACH is an end-effector robotic device that functions as both an assessment and intervention tool. Its assist-as-needed capability provides support for reaching movements only when participants cannot execute movements independently, thereby actively promoting patient engagement during training. Additionally, the space-efficient design of the REACH device makes it a viable option for translation into daily clinical routines. This hybrid system delivers tailored training designed to retrain arm reaching using a multi-muscle FES strategy that specifically targets the elbow extensors and finger extensor musculature, working in coordination with the REACH device. The objective of this pilot study was to assess the preliminary efficacy of hybrid REACH+multi-muscle FES UE training compared to REACH training alone on UE function in individuals with chronic stroke. We hypothesized that individuals with stroke receiving the hybrid REACH+multi-muscle FES training, would demonstrate greater UE functional gains in comparison with those receiving REACH alone training.

## Methods

### Participants

This was a non-blinded, randomized, two-group comparison study. Eligible participants included adults aged 22–85 years with a single ischemic or hemorrhagic stroke that occurred greater than 6 months prior to enrollment and resulted in hemiparesis of the UE with ability to actively reach forward at > 2.5 cm (this reaching ability criteria is lower than most robotic/hybrid studies [7, 28]). Exclusion criteria were as follows: (1) musculoskeletal impairments, other than hemiparesis, including pain or arthritis of the arm or hand; (2) inability to tolerate electrical stimulation; (3) presence of pacemaker, spinal cord or deep brain stimulator; (4) fixed contracture of the arm or hand; (5) inability to follow 3 step commands; (6) botox injection to the UE within 3 months prior to study initiation.

## Study Design

A computerized random generator created the randomization sequence, allocating eligible participants to either the REACH + FES or REACH alone group. Group allocation was revealed after baseline testing. Participants were instructed to abstain from other rehabilitation during the study period. The Institutional Review Board approved the trial, and all participants provided written informed consent. All procedures were conducted in a laboratory setting. The study was registered with Clinical Trials.gov (NCT05854485).

## Hybrid REACH + FES system

The robotic interface used was the REACH robot (NextStep Robotics, MD, USA). The REACH device is a one degree-of-freedom (1-DOF) end-effector robot worn unilaterally on the affected limb, designed to provide active mechanical assistance for elbow flexion-extension (Fig. 1A). Its actuation mechanism is highly backdrivable (6.6 N stiction, 1.4 kg inertia) and capable of delivering continuous net torque up to 20 Nm. Actuation is achieved by a single brushless DC motor (Maxon EC-i 40), amplified (226 $m^{-1}$) and transmitted via a traction drive featuring a custom, threadless linear screw actuator (NextStep Robotics, MD). The threadless linear actuator converts rotary motion into linear motion with a nominal lead length of 25 mm/rev and peak rated thrust capacity of 133 N. Due to its threadless interface and large virtual screw lead, the linear actuator is exceptionally backdrivable, allowing the device to respond passively to the user's intentional movements when required.

For sensing, REACH employs a linear absolute magnetic encoder (LA11, RLS, Komenda, Slovenia) mounted on the traction drive with a resolution of 3.9 μm. Torque is estimated via an empirical linear model relating motor torque to pulse width modulation duty cycles. The device incorporates a simple impedance controller with programmable parameters: a reference position (defined by a minimum jerk trajectory), a proportional gain (approximating controllable linear stiffness), and a derivative gain (approximating controllable linear damping). Active, as-needed assistance is rendered by establishing time-varying, dynamic upper and lower boundaries around the reference trajectory to reflect "normative" hand positions. This control strategy ensures that no forces are generated within these dynamic boundaries ("zone

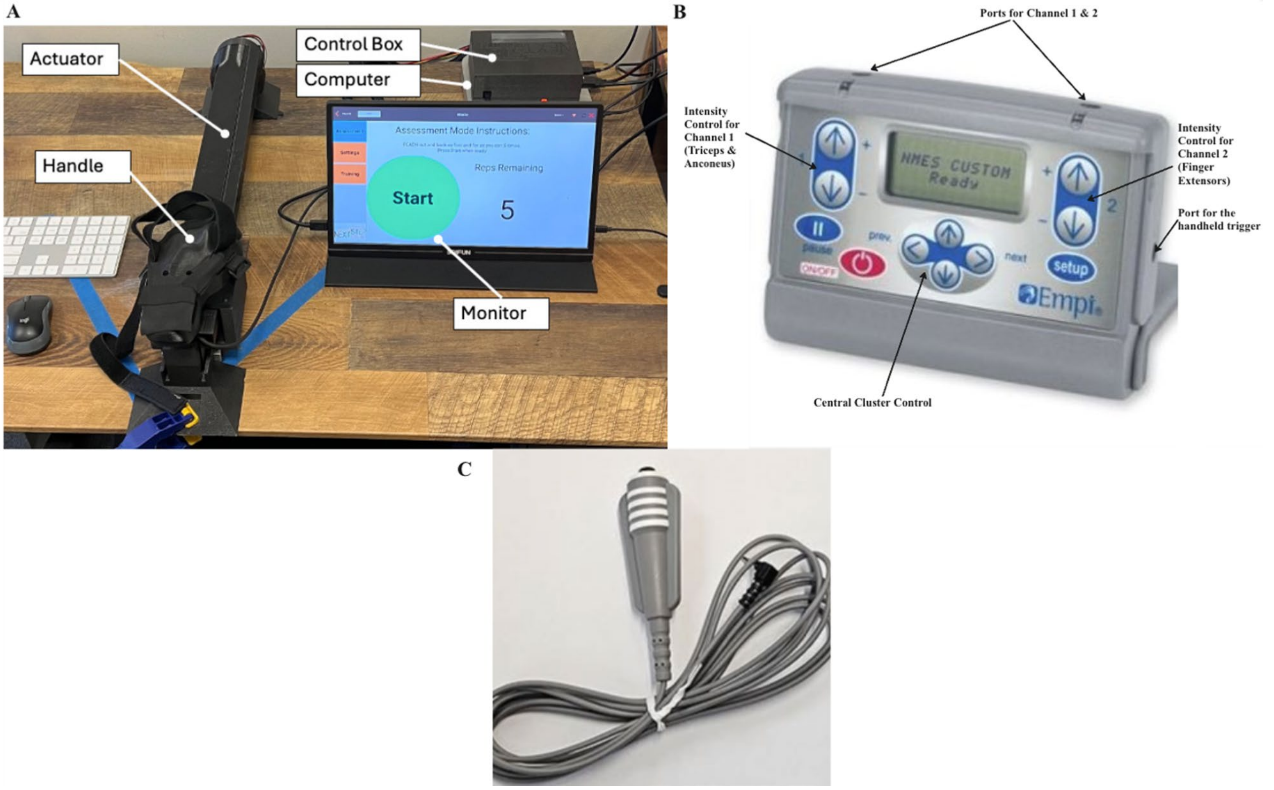

**Fig. 1** **A.** The REACH Device: Actuator: A back-drivable motor-actuator system providing assisted or unassisted training. Handle: The interface held by the participant during the intervention. Control Box: Contains the electronics and directs the actuator's operation. Computer: Runs the REACH application and stores assessment data. Monitor: Displays the REACH application interface. **B.** EMPI 300PV dual channel stimulator: Stimulation intensity for Channel 1 (triceps and anconeus) and Channel 2 (finger extensors) was controlled by the up/down arrow pairs on each side of the display. The red on/off button powered the device on and off. The pause button interrupted stimulation. The setup button was used to set stimulation parameters. The central control cluster navigated the setup menu that controlled device operation. **C** The handheld trigger switch

of autonomy"), thereby promoting user autonomy and intentional movement.

The system incorporates several layers of safety redundancy. The device can be rapidly removed in under 30 s in case of emergency. Software continuously monitors critical parameters such as torques, velocities, and displacements and disables the system if pre-established limits are exceeded or critical component malfunctions occur. The traction drive acts as a mechanical "fuse," inherently slipping above a preset thrust range (96–116 N). Overtorquing is further prevented by an electrical fuse (10 A) and a software-implemented threshold.

For multi-muscle stimulation, we used the commercially available EMPI 300PV (Empi, Inc., St. Paul, MN, USA), a portable, dual-channel stimulator. The system components are described in Fig. 1B. Channel 1 of the stimulator was designated to triceps and anconeus musculature and Channel 2 to the finger extensors. The stimulator was operated via a manual handheld trigger switch (Fig. 1C) controlled by the physical therapist.

## Intervention

Both groups participated in 18 training sessions over a six-week period (three 60-minute sessions per week), supervised by a physical therapist (6 years of stroke rehabilitation experience). This training schedule was selected to balance treatment exposure with practical constraints of participant recruitment and retention in this single-site pilot study. Previous literature examining dose-response relationships in stroke rehabilitation have demonstrated meaningful motor improvements within this session range, with the six-week duration allowing sufficient time for motor learning while remaining deliverable within standard outpatient clinical scheduling [29–31].

### *Training protocol*

Prior to each training session, a brief pre-training setup of the REACH device was performed. This involved three main steps. First, the actuator was positioned relative to the training table based on the participant's impaired side (e.g., left side for left-side impairment). Second, an appropriate handle was selected based on each participant's hand size from four available options (Small, Medium, or Large for either side) and affixed to the mounting plate atop the actuator. Finally, the setup was completed by powering on the control box, opening the dedicated REACH application on the computer, and selecting the participant's profile within the application. Once these steps were finalized, the device and software were ready for therapy.

Each session began with 10 min of manual stretching of the shoulder, elbow, wrist and fingers performed by the physical therapist. Participants were then seated in a chair with back support in front of a table with the REACH device. The paretic forearm was positioned in pronation with the wrist in 0° to 5° extension on the 3D-printed handle of the REACH device, designed to accommodate various hand sizes and allow finger-wrist extension during reaching movements. The hand was secured to the handle with flexible Velcro straps for stability and alignment.

The REACH robot was used for both groups following identical protocols except that the REACH + FES group received multi-muscle stimulation during the reaching task, while the REACH alone group did not. Each session consisted of a pre-training assessment, followed by training, and then a post-training assessment, all conducted using the REACH robot.

During assessments, participants performed five trials of reaching out (shoulder flexion, elbow extension) and reaching in (shoulder extension, elbow flexion) at self-selected speeds. The REACH system recorded kinematic parameters including movement smoothness ($1/s^2$), peak speed (cm/sec), and linear range (cm) for both extension and flexion phases. Participants were instructed to reach as far as possible at a self-selected speed. Based on the pre-training assessment outcomes conducted at the start of each training session, the software set each participant's reaching distance and speed for that training session. The post-training assessment was conducted to evaluate immediate training effects and establish whether performance changed during each session. By comparing performance to the pre-training baseline, participants received immediate feedback on their within-session improvements. This feedback served as motivation to continue their efforts in subsequent sessions. These within-session assessments were separate from the primary study assessments (conducted at baseline and post-intervention).

### *Active reaching training*

During training, participants performed targeted reaching movements using the REACH device, visualized in real-time as a cursor on a monitor. The task required moving the cursor toward a target by extending the arm, then returning to the starting position by flexing the arm. A feedback line moved between the starting point and target at the speed determined by pre-training assessment, providing a visual benchmark (Fig. 2A). Participants aimed to keep their hand movement, represented by the real-time cursor, ahead of the feedback line during each target-reaching attempt. The REACH device provided assistance as needed when participants' movement lagged behind the feedback line, ensuring continuous engagement and visual feedback throughout the training. Participants received standardized verbal cues (e.g., "reach as far as you can") to maximize voluntary

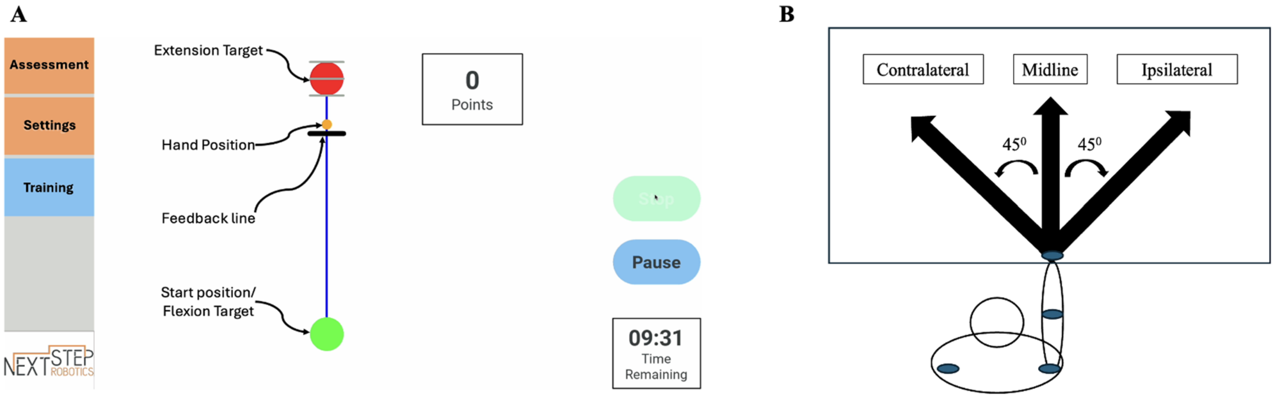

**Fig. 2** **A.** Interactive interface of the REACH software. The targets for the reaching task utilized during training are illustrated. The red circle indicates the extension target, and the green circle indicates the start position/flexion target. The black line indicates the feedback line providing visual benchmark for speed during the training. The orange circle represents the real time hand position during the training. **B.** The training directions for the participants with right hemiparesis is depicted. A reverse setup was presented to participants with left hemiparesis(i.e., ipsilateral is left, contralateral is right)

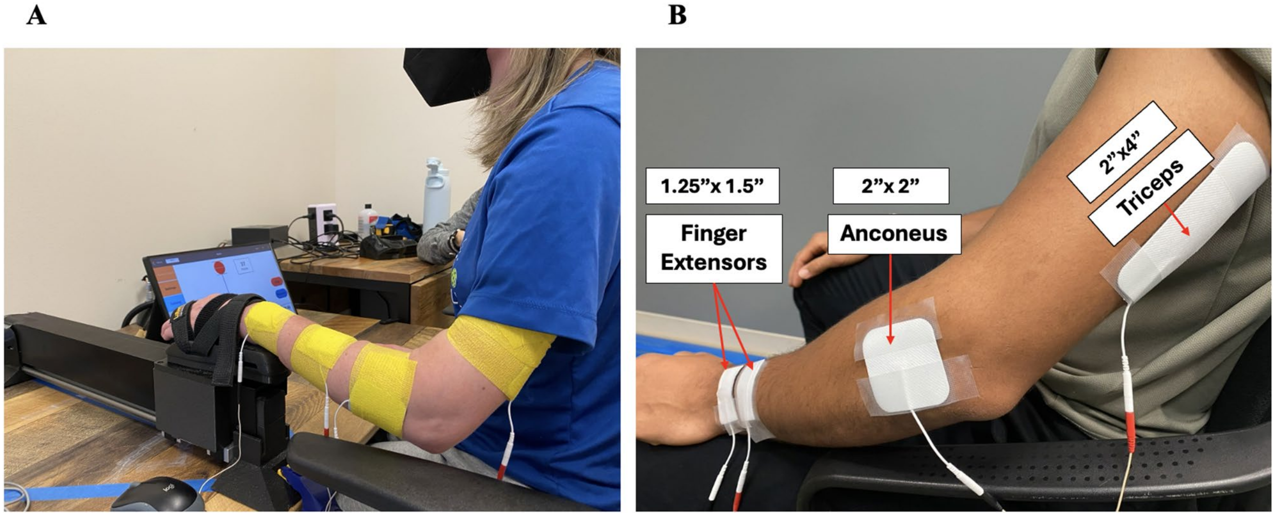

**Fig. 3** REACH + FES setup depicting **A.** secure placement of the paretic hand on the REACH device and the positioning of the FES electrodes during training, and **B.** multi-muscle FES electrode size and placement application for the triceps, anconeus, finger extensors

movement throughout the training and received scores based on their reach extent after each reaching movement to enhance motivatio..

### *Training directions*

Reaching training was conducted in three directions relative to the paretic arm. The midline direction was aligned with the paretic shoulder, requiring straight forward movement. The ipsilateral direction was set at a 45° toward the hemiparetic side, requiring outward reach away from the body/trunk. The contralateral direction was set at a 45° angle away from the hemiparetic side, requiring inward reach closer to the body/trunk (Fig. 2B). Training followed a structured format that included midline reach, contralateral, ipsilateral reach, and a second block of midline reach. This provided four movement blocks with 20 min dedicated to midline reaches and 10 min each to contralateral and ipsilateral reaches.

### *FES application (REACH + FES Group only)*

For the REACH + FES group, self-adhesive hydrogel electrodes were placed over the triceps brachii, anconeus, and extensor digitorumto target movement at the elbow, metacarpal, and proximal interphalangeal joints of the paretic UE (Fig. 3A & B). During reaching movements, the therapist manually triggered FES stimulation upon observing the participant actively moving the orange cursor. All muscles were stimulated simultaneously when the therapist clicked the trigger. To achieve desired muscle contraction strength without causing undue fatigue, stimulation parameters were set at a 0.1 msec pulse duration and a 50 Hz pulse rate, with intensity adjusted based on participant tolerance [9, 32, 33]. The daily stimulation dose across 18 training sessions ranged from 480 to 1152 microcoulombs for the triceps and the anconeus and 504–1288 microcoulombs for finger extensors musculature.

### Outcome measures

Participants underwent both clinical and kinematic evaluations at baseline and post-intervention.

#### *Primary outcomes: kinematic measures*

To assess the transfer of training effects from constrained to unconstrained reaching in a horizontal plane, we used the Kinereach® system (EZ Kinetics, State College, PA), a virtual reality motion tracking system. Figure 4A illustrates the Kinereach setup. During evaluation, participants sat with their arm placed on a glass tabletop. The task was displayed from an inverted 60 inch HD television on to a mirror positioned at chin level, creating the illusion of the task being on the same horizontal plane as the hands, while blocking direct hand view. Hand position was depicted by a cursor on the screen. The system tracked hand-forearm and upper arm segments using two 6-degree of freedom magnetic sensors (trakSTAR, Ascension Technology) attached to the dorsal hand surface and lateral deltoid. A third sensor was utilized to calibrate these sensors, ensuring the accurate mapping of the UE joints in relation to the x, y, z coordinate system. Data were recorded at 116 Hz, tracking motion of the shoulder, elbow, and wrist and low pass filtered at 8 Hz (3rd order, dual pass Butterworth). All kinematic data were processed and analyzed with a custom program written in IgorPro software (WaveMetrics, Inc.).

Participants performed a total of 28 trials consisting of 4 repetitions to each of the 7 targets, presented sequentially in pseudorandom order. Each trial included a start, and a target circle located 0.2 m away (Fig. 4B). The 7 targets were arranged radially 30° apart in a semi-circle (Fig. 4C). Visual feedback on the movement trajectory was provided at the end of each trial. After each trial concluded, there was a 2-second delay before the next target appeared, prompting participants to return the cursor to the start position before initiating the next reach.

Kinematic measures included reach distance (m), maximum velocity (peak movement speed, Vmax), end error (Euclidean distance between the final cursor position and the target center), and linearity (ratio of the minor to major axis of movement path). Lower values of linearity and end error indicate straighter trajectories and more accurate final positions. For the analysis, targets were categorized into three directional groups: contralateral (0°-60°), midline (90°) and ipsilateral (120°-180°).

#### *Secondary outcomes: clinical measures*

Clinical measures included assessments of UE impairment, function, reaching performance, and spasticity. Impairment was assessed using the Upper Extremity-Fugl Meyer Assessment (UE-FMA), a widely recognized quantitative tool with scores ranging from 0 to 66 [35]. The Action Research Arm Test (ARAT) was utilized to measure the UE function, with scores ranging from 0 to

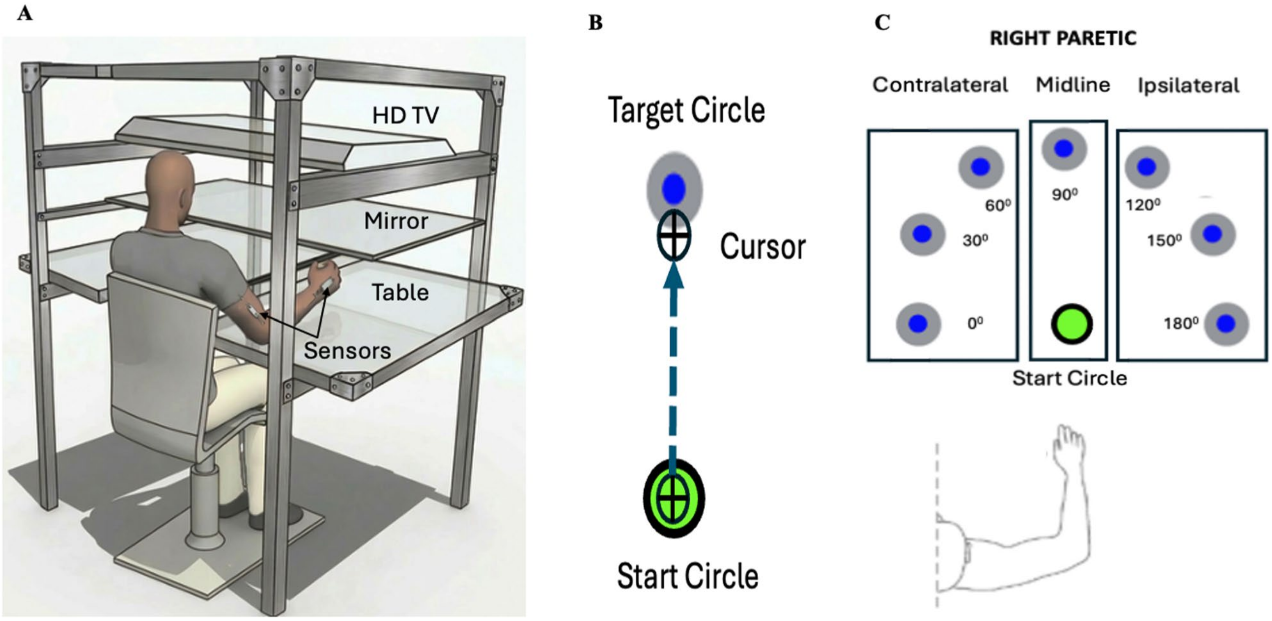

**Fig. 4** Illustration of the Kinereach experimental setup to assess reaching kinematic pre- and post-training. **A** Kinereach device (Adapted from Sainburg [34]). **B** Schematic of one of the targets for the reaching task showing start position (green circle,0.03m diameter), target circle (gray circle, 0.03m diameter) and movement of the cursor to the midline target; **C** Directional task targets and direction locations for the participants right hemiparesis. A reverse setup was presented to participants with left hemiparesis (i.e,ipsilateral targets to the left and contralateral to the right)

57 [36]. Reaching performance was evaluated using the Reaching Performance Scale for Stroke (RPSS), which assesses the quality and compensatory strategies during reach-to-grasp tasks for close and far objects, with each task scored from 0 to 18 [37]. Spasticity at the elbow, wrist, and finger musculature was assessed with Modified Ashworth Scale (MAS), with a scale from 0 to 4 (0, 1, 1+, 2, 3, 4) [38].

### Statistical analyses

Descriptive statistics were calculated for all measures baseline and post-intervention. The Shapiro-Wilk test assessed normality of the outcome measures. Due to the non-normal distribution of the data, non-parametric statistics were used for all outcome measures. The Wilcoxon Signed Rank test was used to analyze within-group differences, and the Mann-Whitney U test was used to assess between-group differences. To account for the baseline differences between the groups, we normalized the pre-post intervention change to the baseline values. The significance threshold was set at an alpha level of 0.05.

## Results

A total of 45 individuals with chronic stroke were screened for eligibility, of which 22 met the criteria. These participants were then randomly allocated, resulting in 11 participants per group. During the intervention, one participant from each group withdrew due to reasons not related to the intervention, leaving 10 participants in each group (Fig. 5). Table 1 presents the baseline demographic and clinical characteristics of the participants. Both groups demonstrated comparable profiles in terms of age, time since stroke onset, and baseline UE-FMA scores.

### Feasibility

Both training protocols demonstrated good feasibility. Adherence was high, with all 20 participants who completed the study attending all 18 scheduled training sessions (100% adherence). No adverse events related to the intervention were reported in either group. Participants tolerated the FES stimulation well, with stimulation parameters successfully adjusted based on individual tolerance throughout the training period.

### Clinical outcomes

#### *Primary outcomes: kinematic measures*

Consistent with the study's inclusion criteria, the Kinereach reaching task was deemed successful if the participant achieved a reach distance greater than 2.5 cm from the start circle toward the target. Any attempt falling short of this threshold was categorized as a failure and excluded from the analysis. Additionally, a minimum success rate of 67% per direction was required for inclusion (2/3 trials for midline; 6/9 trials for contralateral and ipsilateral directions), consistent with evidence that 2–3 trials per condition provide adequate within-session reliability for kinematic variables in post-stroke individuals [39, 40]. Overall, trial success rates were high: 100% of participants in both groups ($n$ = 10/group) successfully performed the midline trials. In the contralateral and ipsilateral directions, success rates were 90% for both groups. One participant from each group ($n$ = 2 total) failed to meet the threshold in these directions due to the severity of their impairments, recording reaches of < 2.5 cm (contralateral) and < 1 cm (ipsilateral). As a result, data from the contralateral and ipsilateral directions were excluded for these two participants, while their midline data were retained. Final statistical analyses utilized mean values derived exclusively from successful trials.

Table 2 presents the kinematic outcomes measured by the Kinereach device during 2-dimensional reaching tasks. The REACH + FES group demonstrated improvements in reaching distance across all three directions: midline ($\Delta = 0.06$, $p = 0.008$, d = 0.59), contralateral ($\Delta = 0.03$ m, $p = 0.008$, d = 0.59), and ipsilateral ($\Delta = 0.04$ m, $p = 0.01$, d = 0.56). Between-group comparisons revealed significantly greater improvements in the REACH + FES group for all directions (midline: $p = 0.02$, d = 0.50; contralateral: $p = 0.01$, d = 0.54; ipsilateral: $p = 0.01$, d = 0.58). The REACH alone group showed no significant changes in reaching distance in any direction.

Movement quality, as assessed by linearity, significantly improved in the REACH + FES group for contralateral direction ($p = 0.01$, d = 0.50) compared to the REACH alone group. The REACH + FES group also showed significant reductions in end error for the contralateral ($p = 0.01$, d = 0.54) and ipsilateral ($p = 0.02$, d = 0.49) directions, but no between group differences were identified. The REACH alone group showed no significant changes in linearity or end error in any direction. Movement velocity (Vmax) remained largely unchanged post-intervention in both groups across all reaching directions, with no significant within-group or between-group differences observed.

#### *Secondary outcomes: clinical measures*

Table 3 outlines the results from the clinical measures. Both intervention groups demonstrated significant improvements in UE impairment as demonstrated by the UE-FMA. The REACH + FES group improved by $\Delta = 15.6$ points ($p = 0.005$, d = 0.62), while the REACH alone group improved by $\Delta = 9.3$ points ($p = 0.008$, d = 0.59). The between group comparison revealed significantly greater improvement in the REACH + FES group ($p = 0.004$, d = 0.64). Similarly, for UE function measured by ARAT, both groups showed within-group improvements. The REACH + FES group improved by $\Delta = 5.1$

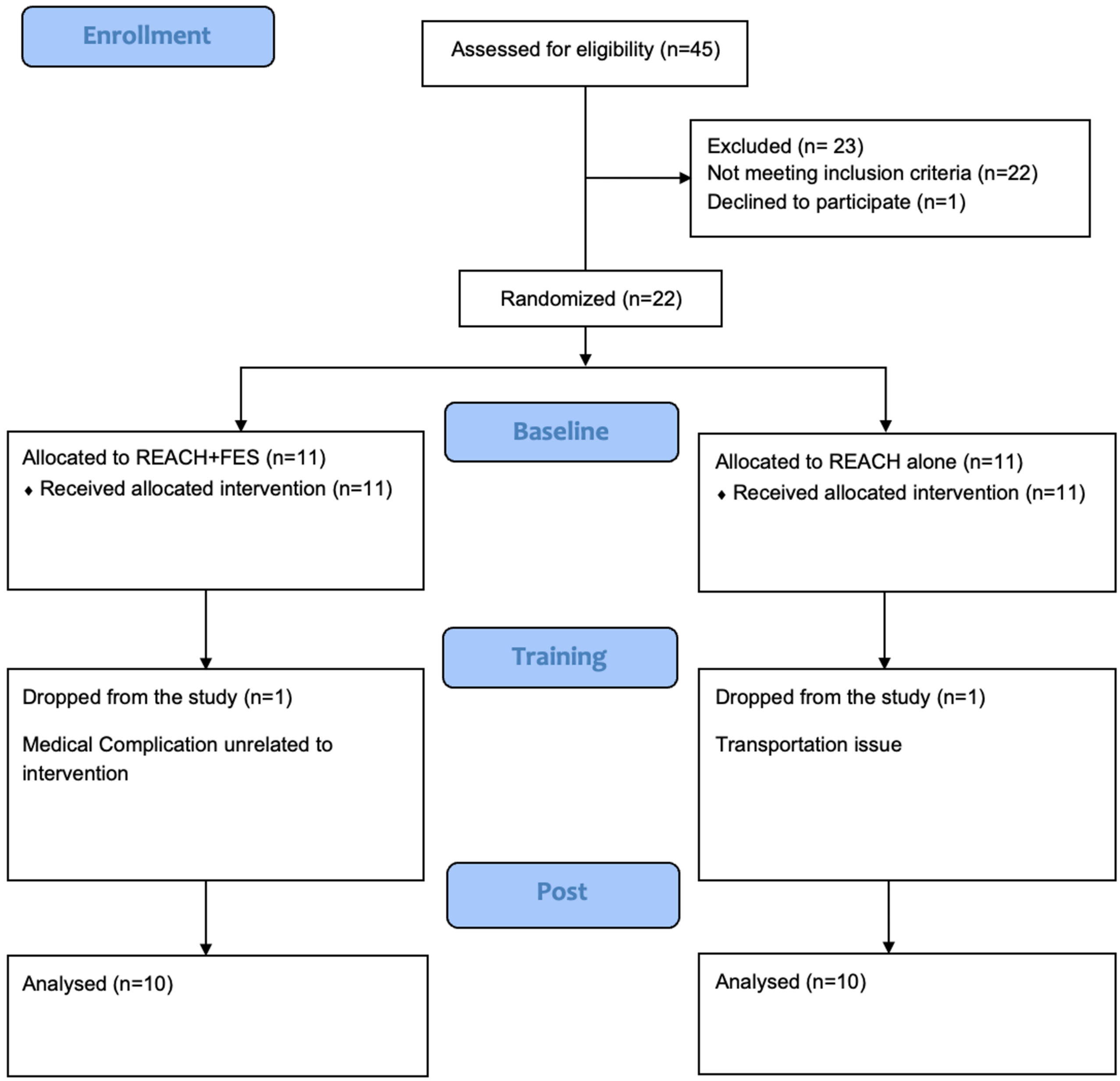

**Fig. 5** Participant CONSORT Flowchart

**Table 1** Demographic characteristics of participants at baseline

| | **REACH + FES (*n* = 10)** | **REACH Alone (*n* = 10)** | ***p*-value** |
|---|---|---|---|
| Age, years (Mean ± SD) | 60.20 ± 9.60 | 60.70 ± 12.60 | 0.91 |
| TSO, years (Mean ± SD) | 9.30 ± 6.70 | 7.60 ± 8.0 | 0.58 |
| Paretic arm (R: L) | 1:9 | 2:8 | - |
| Dominant arm (R: L) | 8:2 | 8:2 | - |
| Type of stroke (I: H) | 5:5 | 7:3 | - |
| UE-FMA Motor (Mean ± SD) | 16.90 ± 11.01 | 17.50 ± 11.82 | 0.89 |
| (Range) | 6–41 | 7–41 | |

TSO: Time Since Stroke Onset; R: Right; L: Left; I: Ischemic; H: Hemorrhagic; UE-FMA: Upper Extremity-Fugl Meyer Assessment

points ($p = 0.005$, $d = 0.62$), and the REACH alone group improved by $\Delta = 2$ points ($p = 0.02$, $d = 0.49$). The between group comparison demonstrated the superiority of the REACH + FES group ($p = 0.001$, $d = 0.71$).

For reaching performance assessed by RPSS, both groups showed significant improvements in both close and far target reaching. For close targets, the REACH + FES group improved by $\Delta = 7.33$ points ($p = 0.008$, $d = 0.59$) and the REACH alone group by $\Delta = 4.42$ points ($p = 0.01$, $d = 0.53$), with no significant difference between groups ($p = 0.12$, $d = 0.34$). For far targets, while both groups improved significantly (REACH + FES: $\Delta = 5.11$ points, $p = 0.01$, $d = 0.56$; REACH alone: $\Delta = 3.11$

**Table 2** Within and between group changes for the Kinereach kinematic measures

| Outcome (Mean ± SD) | Direction | Group | Time | | Within (p-value) | Group (p-value) |
|---|---|---|---|---|---|---|
| | | | Pre | Post | | |
| **Distance (m)** | Midline | REACH + FES | 0.09 ± 0.07 | 0.15 ± 0.06 | **0.008** | **0.02** |
| | | REACH Alone | 0.11 ± 0.06 | 0.12 ± 0.07 | 0.59 | |
| | Contralateral | REACH + FES | 0.12 ± 0.07 | 0.15 ± 0.06 | **0.008** | **0.01** |
| | | REACH Alone | 0.15 ± 0.04 | 0.14 ± 0.05 | 0.76 | |
| | Ipsilateral | REACH + FES | 0.12 ± 0.06 | 0.16 ± 0.06 | **0.01** | **0.01** |
| | | REACH Alone | 0.14 ± 0.05 | 0.13 ± 0.05 | 0.76 | |
| **End error (m)** | Midline | REACH + FES | 0.09 ± 0.08 | 0.04 ± 0.05 | 0.06 | 0.40 |
| | | REACH Alone | 0.10 ± 0.06 | 0.09 ± 0.08 | 0.67 | |
| | Contralateral | REACH + FES | 0.06 ± 0.06 | 0.03 ± 0.03 | **0.01** | 0.27 |
| | | REACH Alone | 0.07 ± 0.04 | 0.06 ± 0.06 | 0.67 | |
| | Ipsilateral | REACH + FES | 0.06 ± 0.02 | 0.02 ± 0.03 | **0.02** | 0.17 |
| | | REACH Alone | 0.07 ± 0.05 | 0.07 ± 0.06 | 0.85 | |
| **Linearity** | Midline | REACH + FES | 0.21 ± 0.13 | 0.14 ± 0.10 | 0.05 | 0.56 |
| | | REACH Alone | 0.18 ± 0.08 | 0.15 ± 0.05 | 0.26 | |
| | Contralateral | REACH + FES | 0.17 ± 0.12 | -0.19 ± 0.21 | **0.01** | **0.01** |
| | | REACH Alone | 0.17 ± 0.07 | 0.18 ± 0.06 | 0.21 | |
| | Ipsilateral | REACH + FES | 0.13 ± 0.10 | 0.08 ± 0.04 | **0.02** | 0.25 |
| | | REACH Alone | 0.15 ± 0.08 | 0.15 ± 0.08 | 0.85 | |
| **Vmax (m/s)** | Midline | REACH + FES | 0.18 ± 0.17 | 0.21 ± 0.19 | 0.13 | 0.25 |
| | | REACH Alone | 0.16 ± 0.05 | 0.18 ± 0.08 | 0.51 | |
| | Contralateral | REACH + FES | 0.25 ± 0.21 | 0.24 ± 0.21 | 0.85 | 0.62 |
| | | REACH alone | 0.22 ± 0.10 | 0.22 ± 0.12 | 0.76 | |
| | Ipsilateral | REACH + FES | 0.28 ± 0.23 | 0.25 ± 0.18 | 0.51 | 0.82 |
| | | REACH Alone | 0.20 ± 0.06 | 0.23 ± 0.11 | 0.31 | |

m: meter; s: second; Vmax: Maximum Velocity. Significant differences ($p < 0.05$) are reported in bold

points, $p = 0.02$, d = 0.49), the REACH + FES group demonstrated significantly greater improvement ($p = 0.02$, d = 0.36).

Regarding muscle tone assessed by MAS, the REACH + FES group showed significant reductions in spasticity across elbow flexors ($p = 0.01$, d = 0.55), elbow extensors ($p = 0.04$, d = 0.36), wrist flexors ($p = 0.006$, d = 0.61), wrist extensors ($p = 0.01$, d = 0.53), finger flexors ($p = 0.01$, d = 0.55), and finger extensors ($p = 0.01$, d = 0.56). In contrast, the REACH alone group showed significant reduction only in finger extensor spasticity ($p = 0.03$, d = 0.46). Between-group comparisons revealed significantly greater reductions in spasticity for the REACH + FES group in elbow flexors ($p = 0.04$, d = 0.45) and wrist flexors ($p = 0.03$, d = 0.46). The individual participant data for the elbow, wrist and finger flexors for the REACH + FES and REACH alone groups are presented in Supplementary Tables 1 & 2 respectively.

## Discussion

This pilot RCT investigated the preliminary efficacy of a novel hybrid rehabilitation approach combining an assist-as-needed REACH robotic device with tailored dosage of multi-muscle FES in individuals with moderate to severe impairments after stroke. The REACH + FES achieved superior outcomes compared to equally intensive REACH alone training, specifically in unconstrained reaching distance across all directions and contralateral movement linearity. Secondarily, the clinical measures exhibited significant gains in impairment (UE-FMA, RPSS, MAS) and function (ARAT) for the hybrid group. Notably, both groups likely benefitted from the core components of the REACH such as the provision of multi-directional reach training and individualized intervention protocols via task inputs adapted to each participant's level of impairment.

### Feasibility of the hybrid approach

The hybrid REACH + FES intervention demonstrated strong feasibility, with 91% retention (10/11 participants completing the protocol in each group). The FES parameters were successfully individualized based on participant tolerance, and no adverse events were reported. The compact design of the REACH device, combined with the portable FES unit, supports potential translation into clinical settings where space and equipment constraints are common considerations. These feasibility findings are particularly relevant given the moderate to severe impairment levels of our participants, a population often excluded from robotic rehabilitation studies due to stringent motor inclusion criteria [6, 7, 28].

**Table 3** Within and between group comparison for secondary clinical outcomes

| **Outcome/Groups (Mean ± SD)** | **Time** | | **Within (p-value)** | **Between (p-value)** |
|---|---|---|---|---|
| | **Pre** | **Post** | | |
| **UE-FMA** | | | | **0.004** |
| REACH + FES | 16.90 ± 11.01 | 32.50 ± 11.99 | **0.005** | |
| REACH Alone | 17.50.±11.82 | 26.80 ± 16.49 | **0.008** | |
| **ARAT** | | | | **0.001** |
| REACH + FES | 8 ± 8.06 | 13.1 ± 8.90 | **0.005** | |
| REACH Alone | 8.40 ± 8.85 | 10.40 ± 10.53 | **0.02** | |
| **RPSS close target** | | | | 0.12 |
| REACH + FES | 4.22 ± 4.73 | 11.55 ± 9.22 | **0.008** | |
| REACH Alone | 4.80 ± 4.75 | 9.22 ± 5.78 | **0.01** | |
| **RPSS far target** | | | | **0.02** |
| REACH + FES | 1.66 ± 2.59 | 6.77 ± 5.42 | **0.01** | |
| REACH Alone | 2.33 ± 2.78 | 5.44 ± 6.08 | **0.02** | |
| **MAS ELB FLX** | | | | **0.04** |
| REACH + FES | 1.50 ± 0.40 | 1.05 ± 0.43 | **0.01** | |
| REACH Alone | 1.60 ± 0.65 | 1.40 ± 0.39 | 0.10 | |
| **MAS ELB EXT** | | | | 0.13 |
| REACH + FES | 0.95 ± 0.68 | 0.30 ± 0.48 | **0.04** | |
| REACH Alone | 0.75 ± 1.06 | 0.40 ± 0.69 | 0.06 | |
| **MAS WRS FLX** | | | | **0.03** |
| REACH + FES | 1.65 ± 0.41 | 1.10 ± 0.45 | **0.006** | |
| REACH Alone | 1.45 ± 0.43 | 1.3 ± 0.58 | 0.41 | |
| **MAS WRS EXT** | | | | 0.34 |
| REACH + FES | 1.15 ± 0.52 | 0.40 ± 0.51 | **0.01** | |
| REACH Alone | 0.85 ± 0.78 | 0.50 ± 0.81 | 0.14 | |
| **MAS FING FLX** | | | | 0.13 |
| REACH + FES | 1.45 ± 0.55 | 1.05 ± 0.64 | **0.01** | |
| REACH Alone | 1.80 ± 0.71 | 1.35 ± 0.57 | 0.08 | |
| **MAS FING EXT** | | | | 0.20 |
| REACH + FES | 1.00 ± 0.47 | 0.40 ± 0.51 | **0.01** | |
| REACH Alone | 1.20 ± 0.85 | 9.22 ± 5.78 | **0.03** | |

UE-FMA: Upper Extremity Fugl Meyer; ARAT: Action Research Arm Test; RPSS: Reaching Performance Scale for Stroke; MAS: Modified Ashworth Scale; ELB: Elbow; WRS: Wrist; FING: Fingers; FLX: Flexors; EXT: Extensors. Significant differences ($p < 0.05$) are reported in bold

### Improvements in reaching kinematics

Unlike previous hybrid studies, our study evaluated the transfer of multi-directional reach training to a similar task performed in a kinematically distinct environment (Kinereach/trakSTAR). The REACH + FES group exhibited significant increases in reaching distance across all three directions, whereas the REACH alone group showed minimal changes. This highlights the potential for hybrid interventions such as REACH + FES in alleviating fixed stereotypical synergy patterns by promoting joint individuation and facilitating greater reach, particularly in the challenging ipsilateral direction [41]. Additionally, reduced end errors were observed in contralateral and ipsilateral directions in the REACH + FES group. While promising, this finding should be interpreted cautiously, as decreased end error might reflect increased reach distances rather than true accuracy improvements. Since end error measures the distance from the final cursor position to the target center, reaching farther could inherently reduce error even without enhanced precision. Moreover, our training emphasized reaching the target rather than precisely hitting its center.

Movement quality, as measured by linearity, improved significantly in the REACH + FES group, but only in the contralateral direction. This directional specificity may reflect that contralateral reaching is generally easier [41, 42], an observation supported by unsolicited participant feedback during the study. Participants likely used their UE more frequently in the contralateral workspace during daily activities, and the repetitive reaching training with coordinated muscle stimulation reinforced and enhanced movement quality specifically in this direction. Despite improvements in reaching distance in midline and ipsilateral directions, movement quality did not similarly improve. This suggests that extended training beyond 18 sessions may further improve movement quality [43, 44].

We observed no significant changes in movement velocity post-training in either group. Improvements in peak velocity typically emerge later in motor learning, reflecting greater movement automaticity [45]. Given that most participants had moderate to severe UE impairments, the 18 training sessions may have been insufficient to induce significant adaptations toward movement automaticity, suggesting that longer interventions might be beneficial for achieving performance proficiency.

### Improvements in clinical measures

Secondary clinical measures provided corroborative evidence supporting the primary kinematic findings. Arm motor impairment measured by UE-FMA showed clinically significant gains in the REACH + FES group. The REACH robot assisted with the constrained movement training in a normal trajectory that is controlled and repeatable, while the multi-muscle FES selectively activated the key muscles (triceps and finger extensors to counteract an overly active biceps and finger flexors). Previous studies have shown that robotic training alone can reduce flexor synergy and improve joint range of motion [46–48]; and the addition of targeted FES may have further amplified this effect [49]. This synergistic use of an assist-as-needed robot combined with multi-muscle FES activation, likely enhanced inter-joint stability and coordination and may have facilitated more integrated motor recovery across the entire UE.

The ARAT improvements observed in the REACH + FES group likely result from multiple mechanisms, including targeted FES stimulation of elbow and finger extensors intensive task-specific training, and improved motor control from coordinated reaching practice [50–52]. Reduced spasticity, as evidenced by reductions in MAS scores for elbow and wrist flexors, may have also contributed to better motor output. While the hybrid intervention targets multiple potential mechanisms for improvement, the specific contribution of proximal-distal FES versus the robotic training component alone cannot be definitively determined from this non-blinded pilot study. Although our hybrid intervention targeted both proximal and distal musculature, studies using distal-only FES have also demonstrated substantial ARAT improvements, suggesting that distal stimulation alone may be sufficient to enhance UE function [9]. Ambrosini et al. [53] also reported considerably larger ARAT gains (11.5 points) in their hybrid robot+multi-muscle FES approach; however, direct comparison is difficult given the differences in participant population (predominantly sub-acute vs. our chronic cohort), intervention type (passive RETRAINER device vs. our assist-as-needed REACH robot), and study design.

The REACH + FES group also demonstrated significantly greater gains on the RPSS far target task (5.11 points vs. 3.11 points), though no between-group difference was observed for close-target reaching. This improvement is clinically meaningful, as far reaching represents a more challenging functional task requiring greater joint excursion and motor control [54, 55]. The multi-muscle FES targeting elbow and finger extensors may have been effective in enhancing the range and power needed for extended reaches. Importantly, these secondary clinical gains align with our primary kinematic findings, where the REACH + FES group demonstrated significant increases in reaching distance across all directions. Together, these RPSS and kinematic improvements indicate that the enhanced reaching capacity translated to improved movement quality and reduced compensatory patterns during functional reach tasks. While these clinical findings are encouraging, the potential for observer bias inherent in non-blinded assessment limits the conclusions that can be drawn.

### Neurophysiological underpinnings of the hybrid intervention

Integrating FES with robotic assistance likely enhanced sensory input critical for motor recovery. FES has been shown to augment tactile and proprioceptive feedback, potentially facilitating cortical reorganization [56, 57], while the assist-as-needed function and an individualized visuo-motor task of the REACH device promoted active participation and task completion. We posit that the combination of active volitional effort with simultaneous FES and robotic assistance linked central motor commands to peripheral feedback, strengthening synaptic connections and inducing experience-dependent cortical plasticity [58]. Additionally, the training enabled participants to practice reaching movements along natural, straight-line paths in each training direction, aligning with the preferred operation of the human motor system [59, 60]. This multidirectional practice may have created a realistic training environment that supports the transfer of skills to daily activities in the home environment. Such aspects provide insights into the efficacy of hybrid systems for rehabilitation of individuals with significant motor impairments.

### Study limitations

Several limitations warrant acknowledgement. The primary limitation of this study is the use of a non-blinded evaluator for the clinical outcome measures (UEFMA, ARAT, RPSS, MAS). We acknowledge that these measures are susceptible to observer expectancy bias. While we included objective kinematic measures to address this limitation, the clinical findings should be considered exploratory and require replication in blinded trials. Second, this pilot study was designed to test the preliminary efficacy of our hybrid approach with a small sample size ($N = 20$) and lower session count (typical stroke rehabilitation studies often employ 24–36 + sessions), potentially limiting generalizability. The application of this training program during sub-acute rehabilitation remains unexplored but represents an attractive direction for future research. Additionally, the pre-post design without follow-up leaves questions about long-term retention of the improvements observed. Third, we did not stratify participants based on their level of functioning (low vs. high), which could have enabled a clearer identification of responders versus non-responders to the intervention. Fourth, the manual rather than automated triggering of the FES limited the ability to dynamically adjust stimulation amplitude in response to real-time physiological demands, which can reduce targeted muscle recruitment efficiency.

## Conclusion

This pilot RCT demonstrated that combining multi-muscle FES with assist-as-needed robotic reaching training produced superior gains in reaching distance and movement quality compared to robotic training alone. Secondary clinical outcomes suggest these kinematic improvements may translate into reduced impairment and improved function, though the non-blinded assessment warrants cautious interpretation. The study also demonstrated the feasibility of this hybrid approach, with 100% adherence and no adverse events. These preliminary findings emphasize the need to develop rehabilitation systems that incorporate task-oriented, individualized interventions, enabling even those with minimal movement control to actively engage in therapy and achieve clinically meaningful improvements. Integrating hybrid systems, which combine UE robotic devices and FES, into clinical settings holds potential for advancing stroke rehabilitation outcomes. Future research should include a larger, single-blinded RCT with a conventional care comparator arm to validate these preliminary findings. Additionally, we plan to assess the benefits of this approach during the early sub-acute phase of stroke recovery.

### Abbreviations

| | |
|---|---|
| ARAT | Action Research Arm Test |
| Cm | Centimeters |
| FES | Functional Electrical Stimulation |
| MAS | Modified Ashworth Scale |
| MCID | Minimal Clinically Important Difference |
| RCTs | Randomized Controlled Trials |
| RPSS | Reaching Performance Scale for Stroke |
| SD | Standard Deviation |
| UE | Upper Extremity |
| UE-FMA | Upper Extremity Fugl Meyer Assessment |
| Vmax | Maximum Velocity |

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-026-01942-7.

Supplementary Material 1

### Author contributions

SR, GA, JW, AR, and KW contributed to the conceptualization and methodology. SR, BB, BH, AR and KW helped in participant recruitment and grant application. SR and BB took part in data collection and project management. SR conducted the data analysis and wrote the manuscript. GA, JW, AR, BH and KW critically revised the manuscript. All the authors read and approved the final manuscript.

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### Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

### Ethics approval and consent to participate

This study was approved by the Institutional Review Board of the University of Maryland, Baltimore and was registered at Clinicaltrials.gov, unique identifier NCT05854485. All participants provided written informed consent before participating in this study.

### Competing interests

AR and BH hold equity position in NextStep Robotics, Inc., the company that manufactures this type of technology under license to the University of Maryland, Baltimore.

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