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EFFECTIVENESS OF PERSONALIZED REHABILITATION, FUNCTIONAL ELECTRICAL STIMULATION, AND COGNITIVE-MOTOR TRAINING ON MOTOR FUNCTION AND COGNITIVE RECOVERY IN STROKE PATIENTS: A RANDOMIZED CONTROLLED TRIAL

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ABSTRACT

Background: Stroke frequently produces combined motor and cognitive impairment that limits functional independence. Functional Electrical Stimulation (FES) and Cognitive-Motor Training (CMT) each have supportive evidence, but head-to-head comparison against personalized, patient-tailored rehabilitation is lacking.

Objective: To compare the effectiveness of FES, CMT, and personalized rehabilitation on motor function, cognitive recovery, and functional independence after stroke.

Methods: In this randomized, single-blind, three-arm controlled trial, 120 patients with ischemic or hemorrhagic stroke (mean age 60.4 ± 8.8 years) were randomized to Group A (FES + conventional rehabilitation, n = 40), Group B (CMT + conventional rehabilitation, n = 40), or Group C (personalized rehabilitation, n = 40) for eight weeks. Outcomes were the Fugl-Meyer Assessment (FMA), Mini-Mental State Examination (MMSE), Functional Independence Measure (FIM), and 6-Minute Walk Test (6MWT), assessed pre- and post-intervention. Paired t-tests evaluated within-group change; one-way ANOVA with Tukey's HSD evaluated between-group differences.

Results: All groups improved significantly on every measure ($p < .001$). Group C achieved the largest gains in FMA (+30.0), FIM (+35.5), and 6MWT (+166.3 m), significantly exceeding Groups A and B (all $p < .001$; $\eta^2 = .87–.94$). Group B achieved the largest MMSE gain (+5.28), statistically equivalent to Group C (+5.43, $p = .75$) and significantly greater than Group A (+0.93, $p < .001$). Group A showed intermediate motor/functional gains, significantly greater than Group B but smaller than Group C on FMA, FIM, and 6MWT (all $p < .001$).

Conclusion: Personalized rehabilitation produced the broadest gains across motor and functional domains, while cognitive-motor training was most effective for cognitive recovery. Individually tailored rehabilitation strategies that match intervention to a patient's impairment profile may outperform uniformly applied single-modality protocols.

Keywords: Stroke Rehabilitation; Functional Electrical Stimulation; Cognitive-Motor Training; Personalized Rehabilitation; Fugl-Meyer Assessment; Randomized Controlled Trial

1 INTRODUCTION

Stroke is a leading global cause of death and long-term disability, with an estimated 12.2 million incident cases and over 100 million prevalent survivors worldwide, and more than 87% of survivors requiring some form of rehabilitation (Feigin et al., 2021; Cieza et al., 2020). Motor impairment — hemiparesis, spasticity, and loss of selective motor control — is the most disabling consequence of stroke and is strongly associated with reduced quality of life (Franceschini et al., 2010). The historical view that the mature central nervous system has limited capacity for reorganization has given way to an experience-dependent plasticity model, in which the specificity, repetition, and intensity of practice delivered during rehabilitation directly shape the extent of functional recovery (Kleim & Jones, 2008; Nudo, 2013).

Functional Electrical Stimulation (FES) delivers controlled electrical stimulation to paretic musculature to elicit a functional contraction (Peckham & Knutson, 2005), enabling task-specific practice that would otherwise be impossible, and systematic reviews report significant gains in activities of daily living and motor impairment following FES relative to usual care (Eraifej et al., 2017; Howlett et al., 2015). Broader evidence on physical rehabilitation approaches after stroke, including Cochrane and AHA/ASA-endorsed reviews, supports active, task-oriented, repetitive practice as the common ingredient underlying effective motor recovery, regardless of the specific named technique used to deliver it (Pollock et al., 2014; Veerbeek et al., 2014; Winstein et al., 2016; Langhorne et al., 2009). Independently, cognitive impairment — affecting attention, memory, and executive function — is now recognized as a near-universal companion of stroke that directly interferes with motor relearning (Cirstea et al., 2006; Levin et al., 2009). Cognitive-Motor Training (CMT), which trains cognitive and motor tasks concurrently, has shown benefit for both cognitive and dual-task gait outcomes (Choi et al., 2015; Kim & Kim, 2018).

A third paradigm, personalized rehabilitation, adapts intervention type, dosage, and progression to each patient's specific impairment profile rather than applying a fixed protocol uniformly. Individualized programs have produced rapid, multi-domain gains in balance, functional capacity, and markers of neuroplasticity (Rahayu et al., 2021), consistent with dose-response evidence showing that higher, better-titrated therapeutic intensity yields superior motor outcomes (Kwakkel et al., 1999; Lohse et al., 2014). Despite separate evidence bases for FES, CMT, and personalized rehabilitation, direct randomized comparison of all three approaches within a single cohort, using a common battery of validated outcome measures, is lacking. This trial was designed to close that gap by comparing the independent effectiveness of FES, CMT, and personalized rehabilitation on motor function, cognitive recovery, and functional independence in stroke survivors.

2 METHODS

2.1 Design and Setting

This was a prospective, randomized, single-blind, parallel-group controlled trial reported in accordance with CONSORT guidelines. Ethical approval and Clinical Trials Registry–India (CTRI) registration were obtained prior to recruitment. Participants were recruited from Jaipur Physiotherapy College, Neuro Spine Solution, and Bone and Brain Physiotherapy Clinic, Jaipur, Rajasthan, India.

2.2 Participants

A total of 120 patients with ischemic or hemorrhagic stroke, at least three months post-onset, aged 18–80 years, with mild-to-moderate motor impairment and cognitive impairment on standardized screening, were enrolled. Exclusion criteria included severe cognitive impairment (MMSE < 18), severe motor impairment precluding participation, confounding neurological disease, unstable cardiovascular/respiratory disease, seizure risk with electrical stimulation, pregnancy, and concurrent enrollment in another trial. The cohort (n = 120) comprised 62 men and 58 women, mean age 60.4 ± 8.8 years, 81 ischemic and 39 hemorrhagic strokes, with a mean of 8.1 ± 4.4 months since stroke onset.

2.3 Randomization and Interventions

Participants were allocated by computer-generated simple randomization to three parallel arms of 40 each. All groups received a common base of conventional physiotherapy (range-of-motion, strengthening, gait and balance training) five days per week for eight weeks. Group A additionally received FES (30 min/day, 5 days/week) targeting the primary muscle groups limiting function. Group B additionally received CMT (30–45 min/day, 5 days/week), pairing a graded cognitive task with a concurrent motor task such as treadmill walking. Group C received an individualized combination and progression of therapeutic elements selected according to each participant's baseline profile, formally reviewed and adjusted every two weeks.

2.4 Outcome Measures

Primary outcomes were motor function (Fugl-Meyer Assessment, FMA; Fugl-Meyer et al., 1975), a validated measure of post-stroke motor impairment with established reliability (Gladstone et al., 2002), and cognitive recovery (Mini-Mental State Examination, MMSE; Folstein et al., 1975). Secondary outcomes were functional independence (Functional Independence Measure, FIM; Keith et al., 1987) and walking capacity (6-Minute Walk Test, 6MWT; Butland et al., 1982). All assessments were performed by a blinded assessor at baseline and at eight weeks.

2.5 Statistical Analysis

Analyses were performed in Python (SciPy, statsmodels). Baseline homogeneity was assessed using one-way ANOVA (continuous variables) and chi-square tests (categorical variables). Within-group change was analyzed with paired-sample t-tests. Between-group differences in change scores were analyzed using one-way ANOVA with Tukey's HSD post-hoc tests. Effect sizes are reported as eta-squared (η^2) and Cohen's d. Significance was set at $p < .05$.

3 RESULTS

All 120 participants completed the eight-week intervention with no losses to follow-up. The three groups did not differ significantly at baseline on any demographic, clinical, or outcome variable (all $p > .40$), confirming successful randomization (Table 1).

Table 1: Baseline Characteristics and Outcome Scores by Group (Mean ± SD)

Variable	Group A (FES) n=40	Group B (CMT) n=40	Group C (Personalized) n=40	p
Age, years	60.48 ± 9.16	60.30 ± 8.60	60.43 ± 8.56	0.996
Sex, M/F	22/18	20/20	20/20	0.875
Stroke type, Isch./Hem.	28/12	26/14	27/13	0.892
Baseline FMA (0–100)	40.03 ± 7.81	41.28 ± 7.78	42.45 ± 9.10	0.425
Baseline MMSE (0–30)	22.35 ± 2.82	21.80 ± 2.80	22.60 ± 2.99	0.446
Baseline FIM (18–126)	62.70 ± 7.42	63.83 ± 8.64	64.35 ± 10.19	0.695
Baseline 6MWT, m	139.53 ± 34.12	142.33 ± 34.39	144.98 ± 39.68	0.797

3.1 Within- and Between-Group Change

All three groups improved significantly from baseline to eight weeks on every outcome measure (paired t-test, all $p < .001$; Table 2), with large within-group effect sizes (Cohen's d = 3.5–20.5). Between-group ANOVA on change scores was significant for all four outcomes (FMA $F(2,117) = 986.0$; MMSE $F(2,117) = 298.2$; FIM $F(2,117) = 777.5$; 6MWT $F(2,117) = 402.3$; all $p < .001$, $\eta^2 = .84$–$.94$).

Table 2: Mean Change (Post – Pre) by Group with Between-Group Comparison

Outcome	Group A Δ	Group B Δ	Group C Δ	ANOVA p	Post-hoc (Tukey)
FMA (0–100)	+24.85	+15.60	+30.00	< .001	C > A > B (all p < .001)
MMSE (0–30)	+0.93	+5.28	+5.43	< .001	B ≈ C > A (p < .001); B vs C ns
FIM (18–126)	+25.38	+20.63	+35.53	< .001	C > A > B (all p < .001)
6MWT (m)	+121.03	+74.00	+166.28	< .001	C > A > B (all p < .001)

Note. A = FES; B = CMT; C = Personalized rehabilitation. ns = not significant.

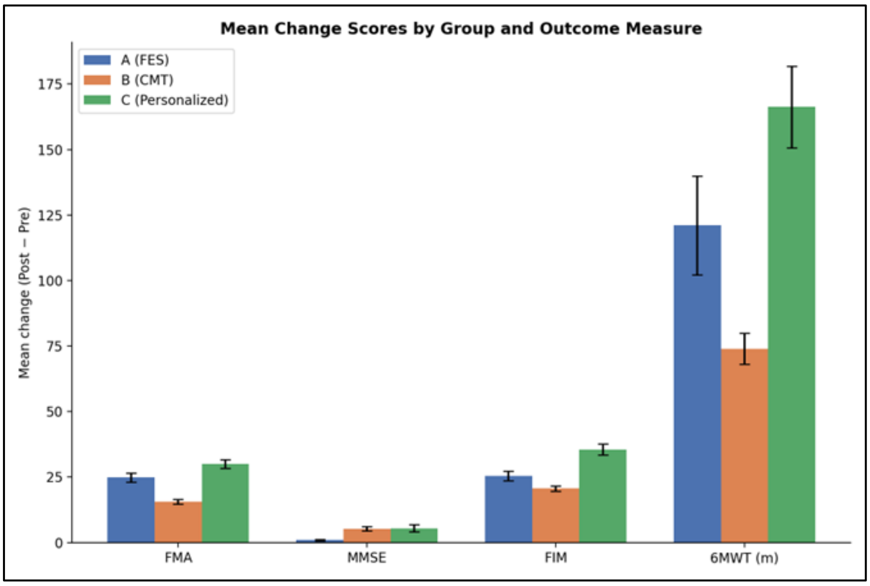

Figure 1: Mean Change Scores (Post – Pre, ± SD) by Group and Outcome Measure

In summary, personalized rehabilitation produced the largest gains on three of four outcomes (FMA, FIM, 6MWT), CMT produced the largest cognitive gain (statistically equivalent to personalized rehabilitation), and FES produced intermediate motor/functional gains but the smallest cognitive gain. No adverse events were recorded.

4 DISCUSSION

This trial found that all three interventions produced statistically significant within-group improvement across motor, cognitive, and functional domains, but that relative effectiveness diverged sharply by domain. Personalized rehabilitation produced the largest gains in motor function, functional independence, and walking capacity, while cognitive-motor training produced the largest cognitive gain, essentially matching personalized rehabilitation on that single domain. FES occupied an intermediate position on motor and functional outcomes but produced the smallest cognitive gain.

4.1 Motor and Functional Recovery

The FMA gain observed with FES (+24.85 points) is consistent with prior FES trials and meta-analyses reporting significant motor and activity gains relative to usual care (Eraifej et al., 2017; Howlett et al., 2015; Demir et al., 2018; Marquez-Chin et al., 2017; Hara et al., 2006; Meilink et al., 2008), and with device-assisted reaching trials such as Barker et al. (2008), which similarly found significant motor gains from targeted stimulation-based training relative to conventional care. The present trial extends this literature by benchmarking FES against two active comparators rather than usual care alone, and FES was significantly outperformed by personalized rehabilitation while significantly outperforming CMT on motor and functional measures. The superior outcomes of personalized rehabilitation are consistent with, and considerably strengthen, prior evidence for individualized protocols (Rahayu et al., 2021) and align with dose-response principles showing that better-titrated therapeutic intensity yields superior motor recovery (Kwakkel et al., 1999; Lohse et al., 2014). A plausible mechanism is that personalized rehabilitation's capacity to adjust specificity, salience, and intensity of practice to the individual — core determinants of experience-dependent plasticity (Kleim & Jones, 2008; Nudo, 2013) — allowed participants to train closer to their individual capacity threshold than a uniformly applied fixed protocol permits, consistent with cautions that translating plasticity principles into clinical benefit requires careful calibration of dose and specificity (Krakauer et al., 2012). The comparatively smaller motor gain in the CMT group may reflect divided attentional resources within a fixed session duration, consistent with evidence that cognitive engagement interacts directly with motor-skill reacquisition after stroke (Cirstea et al., 2006).

4.2 Cognitive Recovery

CMT's MMSE gain (+5.28) was statistically indistinguishable from personalized rehabilitation (+5.43, $p = .75$) and significantly larger than FES (+0.93, $p < .001$), consistent with dual-task and cognitive-motor training literature showing that concurrent cognitive-motor practice drives cognitive as well as motor adaptation (Choi et al., 2015; Kim & Kim, 2018), with virtual-reality cognitive-motor rehabilitation trials showing comparable dual-domain benefit (Faria et al., 2016), and with Cochrane evidence that structured cognitive rehabilitation produces measurable benefit for executive dysfunction (Chung et al., 2013). FES, as a peripherally targeted motor intervention, provides limited direct engagement of attention and working-memory networks, consistent with its modest cognitive gain. That personalized rehabilitation matched CMT's cognitive gain while producing superior motor gains suggests that an individually tailored protocol can avoid the apparent motor–cognitive trade-off observed when a single fixed-protocol modality is applied uniformly across a heterogeneous population.

4.3 Clinical Implications and Limitations

These findings support investment in genuinely individualized rehabilitation planning — structured reassessment, flexible dosing, and tailored intervention selection — while affirming that FES and CMT remain valuable, evidence-based tools for targeting motor and cognitive recovery respectively, particularly where full personalization is not resource-feasible. Limitations include the single-blind design (participants and therapists could not be blinded to allocation), the eight-week follow-up period (longer-term durability of gains is unknown), single-region sampling limiting generalizability, and reliance on the MMSE as a screening-level cognitive measure rather than domain-specific neuropsychological testing. As all groups received a common conventional-therapy base, reported effects reflect added value relative to an active baseline rather than versus no treatment. Longer-term, multi-center trials incorporating neurophysiological outcome measures and cost-effectiveness analysis are warranted to confirm and extend these findings.

5 CONCLUSION

Functional Electrical Stimulation, Cognitive-Motor Training, and personalized rehabilitation each produced significant improvement in motor function, cognitive recovery, and functional independence after stroke. Personalized rehabilitation produced the most comprehensive gains, significantly outperforming FES and CMT on motor function, functional independence, and walking capacity while matching CMT's cognitive gains. These findings support individually tailored, iteratively adjusted rehabilitation strategies matched to each patient's motor and cognitive impairment profile, while confirming FES and CMT as valuable domain-targeted interventions.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

Statement of ethical approval

This study was approved by the Institutional Ethics Committee and registered with the Clinical Trials Registry–India (CTRI).

Statement of informed consent

Written informed consent was obtained from all participants prior to enrollment.

Data availability

The dataset analyzed during the current study is available from the corresponding author on reasonable request.

Author contributions

J.A. contributed to study design, data collection, statistical analysis, and manuscript drafting. M.R.S. contributed to study conception, supervision, critical revision of the manuscript, and final approval of the version submitted for publication.

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