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(RESEARCH ARTICLE)

TRADITIONAL PHYSIOTHERAPY, FUNCTIONAL ELECTRICAL STIMULATION, AND ROBOTIC-ASSISTED THERAPY IN SPINAL CORD INJURY REHABILITATION: A RANDOMIZED CONTROLLED TRIAL

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ABSTRACT

Background: Comparative evidence on traditional physiotherapy, functional electrical stimulation (FES), and robotic-assisted therapy for spinal cord injury (SCI) rehabilitation remains limited, particularly from South Asian settings.

Objective: To compare the effectiveness of traditional physiotherapy, FES-augmented physiotherapy, and robotic-assisted physiotherapy on motor recovery and functional independence in chronic incomplete SCI.

Methods: In this three-arm parallel-group randomized controlled trial, 90 participants with chronic incomplete SCI (AIS B–D) were randomized 1:1:1 to Group A (FES + physiotherapy), Group B (robotic-assisted therapy + physiotherapy), or Group C (traditional physiotherapy alone), each for 12 weeks. Co-primary outcomes were the ASIA Motor Score and the Spinal Cord Independence Measure (SCIM). Between-group differences in change scores were analyzed with one-way ANOVA and Tukey's HSD post-hoc tests.

Results: All groups improved significantly from baseline to week 12 ($p < .001$). Mean ASIA Motor Score gains were 16.4 ± 1.1 (Group A), 20.7 ± 1.4 (Group B), and 5.6 ± 0.5 (Group C) points; mean SCIM gains were 19.8 ± 2.5, 24.3 ± 2.0, and 5.7 ± 1.0 points, respectively. Between-group ANOVA was significant for both outcomes (ASIA Motor: $F(2,87) = 1579.1$, $p < .001$, $\eta^2 = .97$; SCIM: $F(2,87) = 762.5$, $p < .001$, $\eta^2 = .95$), and Tukey's HSD confirmed Group B > Group A > Group C for all pairwise comparisons ($p < .001$).

Conclusion: Robotic-assisted therapy produced the greatest gains in motor recovery and functional independence, followed by FES, both exceeding traditional physiotherapy alone. Technology-assisted adjuncts should be prioritized where available, while conventional physiotherapy remains an effective foundation of SCI rehabilitation.

Keywords: Spinal Cord Injury; Functional Electrical Stimulation; Robotic-Assisted Therapy; ASIA Motor Score; Spinal Cord Independence Measure; Randomized Controlled Trial

1 INTRODUCTION

Spinal cord injury (SCI) affects an estimated 15.4 million people worldwide and produces lasting motor, sensory, and functional deficits (World Health Organization, 2024). Global Burden of Disease modelling shows a substantial rise in absolute SCI prevalence between 1990 and 2019, with a disproportionate burden in low- and middle-income countries such as India (Ding et al., 2022; Jazayeri et al., 2015). Roughly half of SCI cases are neurologically incomplete, retaining spared neural pathways that can be strengthened through activity-dependent neuroplasticity, providing the physiological rationale for intensive rehabilitation (Harkema, 2001; Kirshblum et al., 2020).

Traditional physiotherapy remains the cornerstone of SCI rehabilitation but is constrained by therapist fatigue and limited repetition volume (Dobkin & Duncan, 2012). Functional electrical stimulation (FES) elicits contraction in paretic muscles via peripheral nerve stimulation and has demonstrated benefits for strength, bone density, and locomotor function (Bélanger et al., 2000; Mohr et al., 1997). Robotic-assisted therapy delivers highly repeatable, precisely controlled gait training and has shown improved walking and activities-of-daily-living outcomes relative to conventional care in several trials and meta-analyses, albeit with heterogeneous effect sizes (Alcobendas-Maestro et al., 2012; Mehrholz et al., 2012; Wirz et al., 2005).

Direct three-arm comparisons of these modalities within a single trial remain scarce, especially in Indian clinical settings. This study therefore compared traditional physiotherapy, FES-augmented physiotherapy, and robotic-assisted physiotherapy in a randomized controlled trial of 90 patients with chronic incomplete SCI, using the ASIA Motor Score and Spinal Cord Independence Measure (SCIM) as co-primary outcomes.

2 METHODS

2.1 Design and Participants

This prospective, three-arm, parallel-group randomized controlled trial was conducted at Jaipur Physiotherapy College, Neuro Spine Solution, and Bone and Brain Physiotherapy Clinic (Jaipur, India), with institutional ethics approval and prospective Clinical Trials Registry–India (CTRI) registration. Ninety participants aged 12–50 years with confirmed traumatic or non-traumatic SCI (AIS grade B, C, or D; 6 months–2 years post-injury) were randomized 1:1:1 via computer-generated sequence to Group A (FES + physiotherapy, n = 30), Group B (robotic-assisted therapy + physiotherapy, n = 30), or Group C (traditional physiotherapy alone, n = 30). Exclusion criteria included AIS-A (complete) injury, cognitive impairment precluding participation, medical instability, confounding neurological disease, severe contracture/spasticity, pregnancy, and recent intensive SCI rehabilitation.

2.2 Interventions and Outcomes

All groups received supervised sessions five days/week for 12 weeks. Group A received surface FES to key lower-limb muscle groups synchronized with functional tasks, added to a standardized physiotherapy protocol; Group B received body-weight-supported robotic gait training added to the same protocol; Group C received the physiotherapy protocol alone. Co-primary outcomes were the ASIA Motor Score (0–100; ISNCSCI manual muscle testing) and the SCIM-III (0–100; self-care, respiration/sphincter management, mobility), both with established reliability (Catz et al., 2007; Kirshblum et al., 2011). Secondary outcomes were the SF-36 Health Survey and a Patient Satisfaction Questionnaire. All outcomes were assessed at baseline and week 12.

2.3 Statistical Analysis

A sample of 30 per group provided >80% power to detect a 10-point between-group difference in ASIA Motor Score at $\alpha = .05$. Analysis was intention-to-treat. Baseline comparability was assessed with one-way ANOVA/chi-square tests. Within-group change was analyzed with paired-samples t-tests; between-group differences in change scores were analyzed with one-way ANOVA and Tukey's HSD post-hoc tests, with effect sizes reported as Cohen's d and η^2. Significance was set at $p < .05$ (Python, pandas/SciPy).

3 RESULTS

All 90 participants (54 male, 36 female) completed the trial with no dropouts. Randomization achieved close baseline balance across groups on age, sex, AIS grade distribution, and baseline ASIA Motor and SCIM scores (all $p > .5$; Table 1).

Table 1: Baseline Characteristics by Group

Characteristic	Group A (FES+PT)	Group B (Robotic+PT)	Group C (Traditional PT)
Age, years (M ± SD)	32.7 ± 10.6	33.5 ± 10.5	33.6 ± 10.5
Sex, n (M/F)	18/12	18/12	18/12
AIS B / C / D, n	8/15/7	8/15/7	8/15/7
Baseline ASIA Motor (M ± SD)	42.4 ± 12.9	42.4 ± 12.9	42.4 ± 12.9
Baseline SCIM (M ± SD)	35.9 ± 12.4	35.9 ± 12.3	35.9 ± 12.5

All three groups showed significant within-group improvement from baseline to week 12 on both primary outcomes (paired t-tests, all $p < .001$; Cohen's $d = 5.99–15.35$). Between-group ANOVA on change scores was significant for both outcomes, with very large effect sizes (Table 2, Figure 1). Tukey's HSD post-hoc comparisons confirmed a consistent ordering of Group B (robotic-assisted) > Group A (FES) > Group C (traditional) for every pairwise comparison (all $p < .001$), a pattern preserved across AIS grades B, C, and D.

Table 2: Mean Change (Baseline to Week 12) and Between-Group ANOVA

Outcome	Group A Δ (M ± SD)	Group B Δ (M ± SD)	Group C Δ (M ± SD)	One-way ANOVA
ASIA Motor Score	16.37 ± 1.07	20.73 ± 1.44	5.63 ± 0.49	$F(2,87)=1579.1$, $p<.001$, $\eta^2=.97$
SCIM	19.77 ± 2.49	24.30 ± 2.00	5.70 ± 0.95	$F(2,87)=762.5$, $p<.001$, $\eta^2=.95$

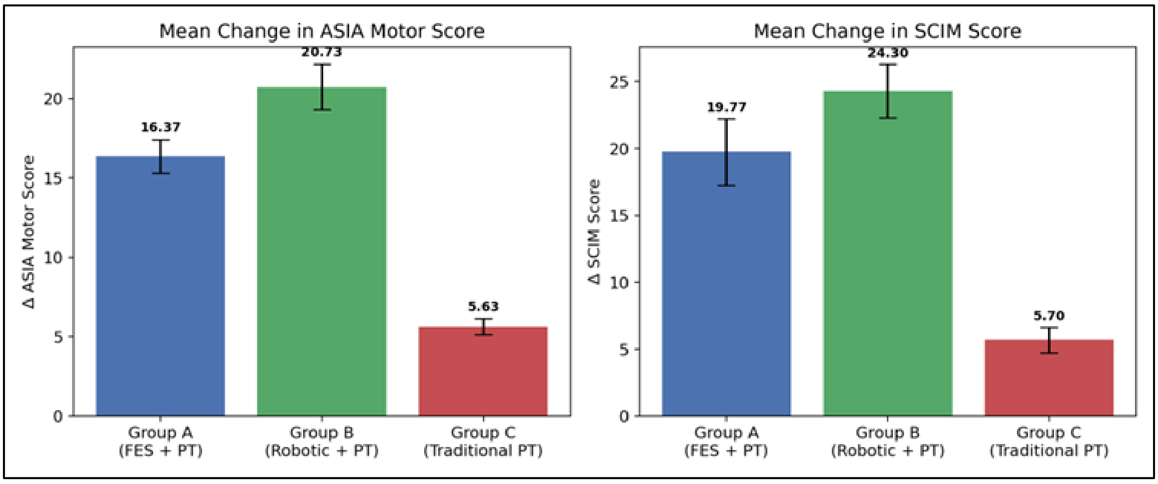

Figure 1: Mean change (Δ) in ASIA Motor Score and SCIM from baseline to week 12 by group (error bars = ±1 SD).

No serious adverse events attributable to FES or robotic-assisted therapy were recorded, and no participant required safety-related withdrawal. Secondary SF-36 physical-function domains showed the same B > A > C pattern, while mental-health domains improved more comparably across groups.

4 DISCUSSION

In this randomized controlled trial of 90 patients with chronic incomplete SCI, all three interventions produced significant gains in motor recovery and functional independence, but robotic-assisted therapy produced the largest gains, followed by FES, with traditional physiotherapy alone producing the smallest, though still clinically meaningful, improvement. This ordering was consistent across both primary outcomes and across injury-severity subgroups, and is broadly consistent with prior comparative trials showing an advantage of robotic-assisted gait training over conventional therapy (Alcobendas-Maestro et al., 2012; Schwartz et al., 2011; Wirz et al., 2005) and of FES over standard care for strength and locomotor outcomes (Bélanger et al., 2000; Mohr et al., 1997). The larger effect sizes observed here relative to prior literature likely reflect the extended 12-week, five-day-per-week training dose and the chronic (post-plateau) study population, which reduces confounding from spontaneous neurological recovery (Fawcett et al., 2007).

Robotic devices likely outperformed FES by delivering a higher volume of correctly patterned, task-specific repetitions per session—a key driver of activity-dependent neuroplasticity—whereas FES relies more on peripheral muscle recruitment with a smaller central training effect (Harkema, 2001; James et al., 2018). Importantly, traditional physiotherapy alone still produced clinically meaningful gains, underscoring that FES and robotic-assisted therapy are best conceptualized as adjuncts that augment, rather than replace, a foundation of high-quality conventional physiotherapy (Nas et al., 2015).

These findings support prioritizing robotic-assisted therapy where infrastructure allows, and FES as an effective, lower-cost intermediate option elsewhere, while maintaining physiotherapy as the universal foundation of care—particularly relevant for resource-constrained settings such as much of India (Chiu et al., 2010).

Limitations include the lack of participant/therapist blinding, single-city recruitment across three affiliated centers, a 12-week endpoint without longer-term follow-up, and the absence of a formal cost-effectiveness analysis. The unusually narrow within-group variability in this cohort should also be interpreted with appropriate caution when generalizing precise effect-size estimates. Future work should evaluate durability of gains beyond 12 weeks, dose–response relationships, combined FES–robotic protocols, and cost-effectiveness in low-resource settings (Mehrholz et al., 2012; Morawietz & Moffat, 2013).

5 CONCLUSION

Robotic-assisted therapy combined with physiotherapy produced the greatest improvement in motor recovery and functional independence in patients with chronic incomplete SCI, followed by FES combined with physiotherapy, both exceeding traditional physiotherapy alone. These results support a tiered, technology-augmented approach to SCI rehabilitation in which conventional physiotherapy provides a necessary foundation and FES or robotic-assisted therapy are incorporated as evidence-based adjuncts according to availability, cost, and patient profile.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare that they have no conflicts of interest related to the conduct, authorship, or publication of this study. The authors have no financial, personal, or professional relationships that could have influenced the design, conduct, analysis, interpretation, or reporting of the research.

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