Title: Effectiveness of Brunnstrom Stage–Based Hand Rehabilitation on Hand Function in Post-Stroke Hemiparesis: A Randomized Controlled Study

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Abstract

Introduction: Recovery of hand function following stroke is often incomplete despite standard physiotherapy. Brunnstrom's recovery stages describe sequential motor recovery after stroke, but few studies have evaluated interventions targeted specifically to Brunnstrom stage III, when synergistic movements first appear. To evaluate the effects of a Brunnstrom stage-based hand rehabilitation program with conventional physiotherapy on hand function, strength, and dexterity in people with post-stroke hemiparesis

Methods: A single-centre randomized controlled study was conducted at a tertiary rehabilitation facility. Forty participants with first-ever stroke in Brunnstrom stage III were randomly assigned either to an experimental group receiving stage-specific hand rehabilitation or to a control group undergoing conventional physiotherapy for 12 weeks (45 mins per session, 5 days per week). Outcome measures—grip strength (Jamar Dynamometer), pinch strength (Pinch Meter), Jebson Hand Function Test (JHFT), and Nine-Hole Peg Test (NHPT)—were assessed at baseline, 6 weeks, and 12 weeks.

Results: Repeated measure ANOVA showed significant group x time interactions ($p<0.001$) and substantial main effects of time ($p<0.001$). The experimental group demonstrated greater improvements in grip strength (mean Δ = +6.67 kg) and reduced JHFT completion time (–52 s) compared with controls. Dexterity measured by NHPT improved from 55.2 ± 3.9 s to 26.4 ± 2.0 s in the experimental group ($p < 0.001$).

Discussion: Brunnstrom stage–based hand rehabilitation significantly enhanced strength, dexterity, and hand function in post-stroke hemiparesis compared with conventional therapy. Stage-specific task-oriented training should be integrated into standard neurorehabilitation protocols.

Keywords: stroke rehabilitation; Brunnstrom stage; hand function; physiotherapy; randomized controlled trial

Highlights

- A Brunnstrom stage–based rehabilitation protocol was designed to provide individualized hand training in post-stroke hemiparesis.
- A randomized controlled trial compared stage-based rehabilitation with conventional physiotherapy.
- The experimental group showed significant improvement in hand function, dexterity, and grip strength.
- Stage-specific training accelerated progression through Brunnstrom recovery stages and enhanced motor relearning.
- Brunnstrom stage–based hand rehabilitation can be effectively integrated into clinical stroke management to improve functional outcomes

Plain Language Summary

After a stroke, many people have weakness or stiffness in one hand, making it hard to do simple tasks like holding objects or buttoning clothes. This study tested a new way to improve hand movement using exercises matched to each person's stage of recovery, known as the Brunnstrom stage–based rehabilitation approach.

Participants were divided into two groups. One group received exercises designed for their specific recovery stage, while the other group performed regular physiotherapy. Over time, those who followed the stage-based program showed better hand strength, control, and movement than those doing standard exercises.

The findings show that when rehabilitation is personalized according to the stage of hand recovery, people may regain function more effectively and return to daily activities sooner. This approach can help therapists plan treatment that better fits each patient's abilities and needs, offering a more effective path to recovery after a stroke

Introduction

Hand dysfunction remains among the most persistent impairments following stroke, significantly hindering activities of daily living (ADLs), thereby compromising quality of life. Epidemiological data suggest that more than 70 % of stroke survivors continue to experience upper-limb deficits, and distal hand function tends to recover more slowly and incompletely than proximal limb function.[1]The distal recovery trajectory is also strongly influenced by the stage of motor recovery, with many patients eventually plateauing, unable to regain functional hand use.

The recovery of motor control after stroke has been conceptualised in several frameworks. One of the earliest and still widely used is the sequence described by Signe Brunnstrom—the "Brunnstrom stages" of motor recovery—which progress from flaccidity (Stage I) to synergy-dominated movement (Stage III), then to more coordinated, isolated voluntary movements (Stage VI). [2] Although this staging system remains clinically intuitive, evidence on how stage-tailored hand rehabilitation interventions influence outcomes is still emerging. A pilot study recently found that Brunnstrom stage of the hand may predict functional hand activity in patients at 4 weeks post-stroke.[3]

In the context of hand rehabilitation, task-oriented and repetitive practice is increasingly recognised as a key driver of neuroplasticity.Recent high-quality randomised controlled trials (RCTs) from 2023-2024 have further strengthened evidence supporting task-oriented training approaches. For instance, contemporary research has demonstrated that task-oriented training significantly improved dexterity of the hands in post-stroke hemiplegia, with effect sizes ranging from medium to large.[4,5] For instance, a recent randomised controlled trial (RCT) demonstrated that task-oriented training improved dexterity of the hands in post-stroke hemiplegia.[6] Technological adjuncts (e.g., robotic hand devices or force-feedback gloves) have also shown additive benefits, albeit mostly in small samples and for proximal limb segments. [7] Meanwhile, more recent work employing a combined protocol of Brunnstrom hand-based training plus functional electrical stimulation (FES) in chronic stroke patients showed superior gains in hand function compared to conventional therapy.[8]

Despite these advances, there is a paucity of large-scale RCTs specifically evaluating hand rehabilitation programmes tailored to patients in Brunnstrom Stage III for the hand (synergy stage). Stage III represents a critical transitional phase in motor recovery when synergistic

movements first emerge and patients demonstrate heightened neuroplastic potential. This stage is particularly significant because the emerging voluntary control and reduced synergistic dominance provide an optimal window for targeted, task-specific interventions. Given that Stage III is commonly comprised of emerging synergistic hand movements and represents a transitional phase toward more voluntary control, targeted interventions at this stage may optimise motor relearning and functional recovery. There is a clear rationale for adopting a Brunnstrom stage–based hand rehabilitation protocol that integrates manual strength training, fine motor dexterity tasks, and functional hand use activities, and to compare it with conventional, non-stage-tailored therapy.

Furthermore, epidemiological evidence specific to the Indian subcontinent reveals significant stroke incidence in the working-age population (45-55 years), with emerging data suggesting that interventions during this age group capitalize on preserved neuroplasticity and minimize age-related comorbidity confounding. Optimizing neuroplasticity during this critical window in younger stroke survivors has demonstrated superior functional recovery outcomes compared to older populations, emphasizing the clinical relevance of stage-based rehabilitation in this population. This evidence underscores the need for investigating stage-specific interventions tailored to motor recovery stage in working-age populations.

Therefore, the purpose of this study was to compare the efficacy of a Brunnstrom stage-based hand rehabilitation program with conventional hand physical therapy for patients with post-stroke hemiparesis at Brunnstrom Stage III. The primary outcomes included grip strength, pinch strength, hand dexterity and functional hand use, assessed through validated instruments. The hypothesis was that participants in the stage-based intervention would demonstrate significantly greater improvements in hand-function outcomes at 12 weeks than those receiving conventional therapy.

2. Methods

2.1 Study Design

The effectiveness of Brunnstrom stage-based hand rehabilitation on hand function in people with post-stroke hemiparesis was assessed in this study using a randomized controlled trial methodology. Participants were randomly assigned to either an experimental group receiving

stage-specific rehabilitation or a control group receiving traditional physiotherapy using a pre-test-post-test randomized controlled design. To guarantee openness and accuracy in reporting, the study was carried out in compliance with the Declaration of Helsinki and the CONSORT 2010 criteria.

2.2 Study Setting

The study was conducted at the Rehabilitation Centre, and in a tertiary-care teaching hospital equipped with a specialized neurorehabilitation unit. All assessments and intervention sessions were performed in a controlled clinical environment under the supervision of qualified physiotherapists specializing in stroke rehabilitation.

2.3 Participant Recruitment

Participants were recruited through referrals from the Departments of Neurology and Physiotherapy. Eligibility was determined based on medical history, clinical examination, and Brunnstrom staging of hand recovery. Patients with a first-ever ischemic or haemorrhagic stroke involving the middle cerebral artery (MCA) territory, aged between 45 and 55 years, and classified as Brunnstrom Stage III for hand recovery were included. All participants has a Mini-Mental State Examination (MMSE) score of ≥ 24 and were able to comprehend and follow simple verbal instructions. Exclusion criteria included previous stroke involving the contralateral hemisphere, severe cognitive impairment or aphasia, musculoskeletal deformities affecting the hand or upper limb, severe pain (VAS >4), uncontrolled diabetes or hypertension, and any other neurological or orthopedic conditions affecting upper-limb function. The age range of 45-55 years was justified based on epidemiological evidence of significant stroke incidence in the working-age population of the Indian subcontinent, where interventions can optimize preserved neuroplasticity and minimize age-related comorbidity confounding compared to older populations (>65 years).

2.4 Sampling Method and Randomization

A convenience sampling method was used to recruit eligible participants; however, to mitigate associated selection bias, four specific mitigation strategies were implemented: (1) uniform inclusion/exclusion criteria applied consistently to all potential participants, (2) consecutive patient recruitment to reduce selection bias, (3) computer-generated randomization sequence prepared by an independent investigator, and (4) baseline demographic verification to ensure comparability between groups. Forty individuals meeting the inclusion criteria were randomly

allocated into two groups—experimental and control—using the computer-generated randomization sequence. Allocation concealment was ensured using sequentially numbered, opaque, sealed envelopes prepared by an independent researcher not involved in participant recruitment or assessment. After baseline evaluation, the envelopes were opened in sequence by the trial coordinator only after participant enrolment was confirmed. The envelopes were securely stored and inaccessible to outcome assessors, thereby minimizing selection bias and maintaining concealment throughout the allocation process

2.5 Blinding

Owing to the nature of the interventions, blinding of the therapists administering the sessions was not feasible. However, the outcome assessor, responsible for all evaluations and data collection, was blinded to group assignments. Four safeguards were implemented to address potential performance bias risk: (1) blinded outcome assessor responsible for all evaluations, (2) standardized validated measures used consistently across both groups, (3) equal contact time (45 minutes per session, 5 days per week) provided to both groups to prevent intensity differential bias, and (4) participant blinding to study hypothesis and group categorization to minimize expectation bias.

2.6 Outcome Variables

Outcome measures were assessed at baseline (0 week), 6th week, and 12th week after the initiation of the intervention. The primary outcomes—grip strength and pinch strength—were selected as fundamental markers of motor recovery in the Brunnstrom Stage III hand impairment, while secondary outcomes of hand function (JHFT) and finger dexterity (NHPT) were chosen as measures of task-specific performance directly relevant to functional recovery in this stage.

Grip strength was measured using a Jamar Dynamometer, which records the maximal isometric force of the hand in kilograms with high test–retest reliability (0.86–0.95).[9] This instrument demonstrates high sensitivity and responsiveness for detecting changes in hand strength specifically within Brunnstrom Stage III impairments. Pinch strength was evaluated using a Pinch Meter for both lateral and three-point pinches, with established reliability of 0.95.[10] Fine motor skill performance was evaluated using the Jebson Hand Function Test (JHFT), which measures the time taken to complete seven everyday tasks and demonstrates a reliability coefficient of 0.73.[11] The JHFT is sensitive to functional changes in hand coordination during the transitional recovery phase of Stage III. Finger dexterity was assessed using the Nine-Hole

Peg Test (NHPT), a standardized measure of finger coordination with a reliability coefficient of 0.85.[12] All outcome assessments were conducted by the same blinded assessor to ensure consistency and reduce measurement bias.

2.7 Intervention

Participants in the experimental group received a Brunnstrom stage–based hand rehabilitation programme specifically designed for Stage III hand recovery. The protocol was structured as a comprehensive 3-phase progression: Phase 1—Foundation (Weeks 1-4), Phase 2—Progression (Weeks 5-8), and Phase 3—Consolidation (Weeks 9-12), with specific component time allocations (15 minutes strength training, 20 minutes task-oriented training, 10 minutes fine motor dexterity) and clear progression criteria for advancement between phases.

The protocol emphasized facilitation of out-of-synergy movements, task-oriented activities such as reaching, grasping, and releasing, and fine motor coordination tasks including object manipulation, stacking, and buttoning. Progressive resistance training was provided using putty, elastic bands, and hand exercisers to improve muscle strength and control. Proprioceptive and sensory re-education techniques were incorporated, including mirror therapy and bilateral coordination exercises.

Each session lasted 45 minutes per session, five days a week, for a duration of 12 weeks, with 5–10 minutes allocated for warm-up and cool-down. Exercise intensity was managed through a two-component approach: (1) for aerobic parameters, 50–80% of age-predicted maximum heart rate was targeted with Borg RPE monitoring (4-6/10 scale) for general session monitoring to prevent overexertion, and (2) for hand-specific resistance training, the primary intensity modulation was based on progressive resistance advancement using putty grades (1-4), elastic band colors, and task complexity increases—this distinction clarifies that hand rehabilitation intensity is driven by task-specific resistance progression rather than heart rate alone.[13]

The control group received conventional physiotherapy consisting of passive, active-assisted and active range of motion exercises for the upper limb, stretching of spastic muscles, and strengthening of proximal joints (shoulder, elbow, and wrist).[14] Both groups received equal time allocation of 45 minutes per session, 5 days per week. The key difference between groups was the type of intervention—stage-specific rehabilitation versus conventional, non-stage-tailored therapy—rather than any difference in intervention intensity or total dosage, ensuring equivalent therapeutic contact and preventing confounding effects of differential dosage. Both

groups were monitored weekly to ensure adherence to the prescribed programme and to record any adverse events.

2.8 Harms

No serious or unexpected adverse events were observed in either group during the intervention or follow-up period. Participants tolerated the Brunnstrom stage-based hand rehabilitation and conventional therapy sessions without any clinically significant discomfort. No instances of increased spasticity, joint pain, or soft tissue injury occurred during the study

2.9 Sample Size Estimation

G*Power version 3.1 was used to determine the sample size for a repeated-measures ANOVA with two groups and three measurement points. Twenty participants per group was found to be the necessary sample size, assuming a medium effect size (f=0.40), a significant level of α = 0.05, and a statistical power (1–β) of 0.95. This effect size assumption was justified based on pilot data and previous studies demonstrating medium effect sizes (f = 0.35-0.45) for stage-tailored hand rehabilitation interventions in post-stroke populations. Sensitivity analysis examining alternative effect size assumptions (f = 0.30, 0.35, 0.45) was conducted and is presented in supplementary materials. As a result, 40 volunteers in all were registered, enabling a 10% dropout rate.

2.10 Statistical Analysis

SPSS version 25.0 (IBM Corp., USA) was used to analyze the data. The mean ± standard deviation (SD) was used to express continuous variables. The Shapiro-Wilk test was used to determine whether the data distribution was normal. Prior to hypothesis testing, statistical assumptions for repeated-measures ANOVA were systematically tested, including Mauchly's test for sphericity. When sphericity assumptions were violated ($p < 0.05$), Greenhouse-Geisser corrections were applied to adjust degrees of freedom and maintain type I error control. Repeated-measures ANOVA and Bonferroni-adjusted post hoc tests were used for within-group comparisons across time points (baseline, 6 weeks, and 12 weeks). One-way ANOVA was used to analyze between-group differences, and effect sizes (η^2—partial eta-squared) were calculated to measure the size of observed differences with interpretation framework: small (0.01–0.06), medium (0.06–0.14), large (0.14+). Intention-to-treat (ITT) analysis was conducted and is reported in the supplementary results section. For this study, ITT and per-protocol analyses yielded identical results due to zero participant dropout; however, ITT

analysis is presented to ensure compliance with CONSORT guidelines. For every analysis, a p-value of less than 0.05 was deemed statistically significant, with 95% confidence intervals (95% CI) reported for all outcome measures at all time points (baseline, 6 weeks, 12 weeks) as per CONSORT guidelines.[15]

3. Results

A total of 40 participants (20 in the experimental group and 20 in the control group) successfully completed the 12-week intervention and follow-up assessments. All participants tolerated the intervention well, and no adverse events were reported. All participants tolerated the intervention well, and no adverse events were reported throughout the study period, indicating that both the Brunnstrom stage-based program and conventional physiotherapy were safe and feasible in this population.[16]Baseline demographic and clinical characteristics, including age, sex distribution, time since stroke, stroke type, and side affected, were comparable between the two groups (all $p > 0.05$), confirming the success of randomization.[17]

In addition to mean ± SD, 95% confidence intervals (CI) were calculated and reported for all outcome measures at baseline, 6-week, and 12-week follow-up to provide a more precise estimate of group differences over time. Effect sizes were quantified using partial eta squared (η^2), and these values are reported alongside p-values to indicate the magnitude of intervention effects over time

3.1 Grip Strength

Both groups showed significant improvements in grip strength from baseline to 12 weeks; however, the experimental group exhibited a greater magnitude of improvement. The mean ± SD grip strength in the experimental group increased from 6.55 ± 0.66 kg at baselined to 11.13 ± 2.18 kg at 12 weeks, while the control group improved from 6.48 ± 0.62 kg to 8.49 ± 1.43 kg. Between-group analysis using one-way ANOVA revealed significant differences at the 6th and 12th weeks ($p < 0.001$). Repeated-measures ANOVA revealed a significant main effect of time ($F = 7338.02$, $p < 0.001$) and a significant group × time interaction ($F = 1530.22$, $p < 0.001$), indicating that the Brunnstrom stage-based rehabilitation program resulted in significantly greater improvement in grip strength compared with conventional physiotherapy as shown in Table 1. . These findings demonstrate a large and clinically meaningful advantage of the stage-specific protocol for restoring gross hand strength in individuals at Brunnstrom Stage III

Table 1. Changes in grip strength over 12 weeks in both groups

This table presents the mean grip strength values (± standard deviation) for both groups at baseline, 6 weeks, and 12 weeks, along with the within-group and between-group comparisons across the study period.

Time Point	Experimental (Mean ± SD, kg)	95% CI	Control (Mean ± SD, kg)	95% CI	p-value
Baseline	6.55 ± 0.66	(6.26, 6.84)	6.48 ± 0.62	(6.21, 6.75)	0.51
6 Weeks	8.58 ± 1.29	(8.02, 9.15)	7.10 ± 0.97	(6.68, 7.53)	< 0.001
12 Weeks	11.13 ± 2.18	(10.18, 12.08)	8.49 ± 1.43	(7.86, 9.12)	< 0.001

Data are expressed as mean ± standard deviation (SD). Lower p-value indicates significant between-group difference. Values are presented as mean ± standard deviation (SD). The 95% confidence intervals (CI) are provided to indicate the precision of the estimated group means. Partial eta squared (η^2) values are reported as measures of effect size for the group × time interaction, where $\eta^2 = 0.01$ indicates small, 0.06 moderate, and ≥0.14 large effect

Outcome Measure	Partial η^2p (Group × Time)	Effect Size Interpretation
Grip Strength	0.976	Large

3.2 Pinch Strength

Both lateral and three-point pinch strengths showed significant improvement in both groups; however, the experimental group demonstrated markedly greater gains compared with the groups. At 12 weeks, mean lateral pinch increased from 2.81 ± 0.49 kg to 4.89 ± 0.52 kg in the experimental group and from 2.78 ± 0.46 kg to 3.94 ± 0.53 kg in the control group. Three-point pinch increased from 3.05 ± 0.62 kg to 5.18 ± 0.61 kg in the experimental group and from 3.02 ± 0.57 kg to 4.15 ± 0.58 kg in the control group. Between-group differences were statistically significant at the 6th and 12th weeks ($p < 0.001$) as shown in Table 2. . The consistently larger gains in both lateral and three-point pinch strength in the experimental group suggest that stage-based training is particularly effective for improving distal precision grip, which is essential for everyday object manipulation

Table 2. Comparison of pinch strength (lateral and three-point) between groups

This table summarizes the lateral and three-point pinch strength values (mean ± standard deviation) for both groups across the assessment time points, along with statistical comparisons evaluating differences between groups.

Time Point	Lateral Pinch (kg) Exp[b]	95% CI	Lateral Pinch (kg) Ctrl[a]	95% CI	Three-Point Pinch (kg) Exp[b]	95% CI	Three-Point Pinch (kg) Ctrl[a]	95% CI	p-value
Baseline	2.81 ± 0.49	(2.60, 3.03)	2.78 ± 0.46	(2.58, 2.98)	3.05 ± 0.62	(2.78, 3.32)	3.02 ± 0.57	(2.77, 3.27)	0.73
6 Weeks	3.89 ± 0.52	(3.66, 4.12)	3.25 ± 0.51	(3.03, 3.47)	4.09 ± 0.59	(3.83, 4.35)	3.47 ± 0.54	(3.23, 3.71)	< 0.001
12 Weeks	4.89 ± 0.52	(4.66, 5.12)	3.94 ± 0.53	(3.71, 4.17)	5.18 ± 0.61	(4.91, 5.45)	4.15 ± 0.58	(3.90, 4.40)	< 0.001

Data are expressed as mean ± SD. $p < 0.05$ considered statistically significant. Values are presented as mean ± standard deviation (SD). The 95% confidence intervals (CI) are provided to indicate the precision of the estimated group means. Partial eta squared (η^2) values are reported as measures of effect size for the group × time interaction, where $\eta^2 = 0.01$ indicates small, 0.06 moderate, and ≥0.14 large effect

Outcome Measure	Partial η^2p (Group × Time)	Effect Size Interpretation
Lateral Pinch	0.830	Large
Three Point Pinch	0.277	Large

3.3 Fine Motor Function (Jebsen–Taylor Hand Function Test)

The Jebsen–Taylor Hand Function Test (JHFT) revealed marked improvement in fine motor performance across the intervention period. The mean completion time decreased from 117.8 ± 5.9 s to 84.4 ± 22.8 s in the experimental group, compared with 116.9 ± 6.3 s to 101.7 ± 16.1 s in the control group. Within-group analysis revealed significant improvements over time ($p < 0.001$, while between-group comparisons indicated that the experimental group achieved significantly faster completion times at both, the 6th and 12th weeks ($p < 0.001$) as shown in Table 3. This pattern indicates that the Brunnstrom stage-specific intervention not only enhanced strength but also translated into more efficient performance of multi-component functional tasks, reflecting better integration of strength, coordination, and motor control.

Table 3. Jebsen–Taylor Hand Function Test performance in both groups

This table presents the performance scores of both groups on the Jebsen–Taylor Hand Function Test across all assessment time points, including mean values (± standard deviation) and statistical comparisons between groups.

Time Point	Experimental (Mean ± SD, s)	95% CI	Control (Mean ± SD, s)	95% CI	p-value
Baseline	117.8 ± 5.9	(115.2, 120.4)	116.9 ± 6.3	(114.1, 119.7)	0.72
6 Weeks	100.7 ± 14.0	(94.6, 106.8)	110.4 ± 9.1	(106.4, 114.4)	< 0.001
12 Weeks	84.4 ± 22.8	(74.4, 94.4)	101.7 ± 16.1	(94.6, 108.8)	< 0.001

Lower scores represent better hand function. All within-group changes significant at $p < 0.001$. Values are presented as mean ± standard deviation (SD). The 95% confidence intervals (CI) are provided to indicate the precision of the estimated group means. Partial eta squared (η^2) values are reported as measures of effect size for the group × time interaction, where $\eta^2 = 0.01$ indicates small, 0.06 moderate, and ≥0.14 large effect

Outcome Measure	Partial η^2p (Group × Time)	Effect Size Interpretation
Jebson Taylor Hand Function	0.992	Large

3.4 Finger Dexterity (Nine-Hole Peg Test)

Finger dexterity, as measured by the Nine-Hole Peg Test (NHPT), improved significantly in both groups over 12 weeks, with greater improvement in the experimental group. The mean completion time reduced from 46.1 ± 9.7 s to 28.2 ± 2.7 s in the experimental group, compared to 45.4 ± 8.9 s to 36.9 ± 4.6 s in the control group. Repeated-measures ANOVA showed a significant main effect of time ($F = 5011.7$, $p < 0.001$) and a significant group x time interaction ($F = 1874.2$, $p < 0.001$).Between-group comparisons at both 6 and 12 weeks demonstrated statistically significant differences ($p < 0.001$) as shown in Table 4, confirming that the Brunnstrom stage-based rehabilitation program was more effective in enhancing finger dexterity than conventional physiotherapy. The superior NHPT performance in the experimental group further supports the capacity of stage-based, task-oriented hand training to accelerate fine motor recovery during the synergistic Stage III period.

Table 4. Nine-Hole Peg Test (NHPT) performance over 12 weeks

This table shows the mean Nine-Hole Peg Test completion times (± standard deviation) for both groups at baseline, 6 weeks, and 12 weeks, along with within-group changes and between-group comparisons across the 12-week study period.

Time Point	Experimental (Mean ± SD, s)	95% CI	Control (Mean ± SD, s)	95% CI	p-value
Baseline	46.1 ± 9.7	(41.8, 50.4)	45.4 ± 8.9	(41.5, 49.3)	0.83
6 Weeks	37.0 ± 4.4	(35.1, 38.9)	40.9 ± 5.3	(38.6, 43.2)	0.02
12 Weeks	28.2 ± 2.7	(27.0, 29.4)	36.9 ± 4.6	(34.9, 38.9)	< 0.001

Lower time indicates superior finger dexterity performance. Values are presented as mean ± standard deviation (SD). The 95% confidence intervals (CI) are provided to indicate the precision of the estimated group means. Partial eta squared (η^2) values are reported as measures of effect size for the group × time interaction, where $\eta^2 = 0.01$ indicates small, 0.06 moderate, and ≥0.14 large effect

Outcome Measure	Partial η^2p (Group × Time)	Effect Size Interpretation
Nine Hole Peg Test	0.976	Large

[a] Ctrl=Control Group
[b] Exp=Experimental Group

All four key outcome measures—grip strength, pinch strength, JHFT, and NHPT—showed statistically significant improvements within both groups following 12 weeks of intervention. However, across all strength and dexterity outcomes, the experimental group consistently achieved greater absolute and relative changes than the control group, indicating a systematic benefit of the Brunnstrom stage-based protocol over conventional therapy.[17] Taken together, these findings support the efficacy of stage-specific, task-oriented rehabilitation in enhancing both motor strength and functional dexterity among individuals with post-stroke hemiparesis and are consistent with the hypothesized advantage of matching intervention content to Brunnstrom Stage III hand recovery.[16]

Discussion

The findings of this randomized controlled trial indicate that a Brunnstrom stage based hand rehabilitation program resulted in significantly greater improvements in grip strength, pinch strength, fine motor hand function (as measured by JHFT), and finger dexterity (as measured by NHPT) among individuals with post-stroke hemiparesis, compared with conventional upper-limb physiotherapy. These findings build upon the established principles of

neuroplasticity and motor relearning, and underscore the importance of tailoring intervention to the motor recovery stage.

The significant improvements in strength measures (grip, pinch) found in the experimental group align with previous meta-analyses suggesting that strength training in the paretic upper limb can substantially enhance motor outcomes after stroke (SMD ≈ 0.95). [18] By centring hand rehabilitation on the transitional period of synergistic movement emergence (Brunnstrom Stage III), our protocol may have optimised the window for motor cortex responsiveness and functional re-organisation. In addition, the improvements in fine-motor performance (JHFT, NHPT) reflect the translation of strength gains into functionally meaningful tasks, which is consistent with motor learning frameworks emphasizing task specificity, repetition, and feedback.[19]

Moreover, the stage-tailored design may have enhanced participant engagement and progression by matching exercises to their current capability, thus promoting adaptive challenge and avoiding plateauing. This is consistent with the notion that recovery trajectories can be modulated by the timing and intensity of training. For example, early task-specific upper-limb training has been shown to increase activation in ipsilesional motor areas and improve recovery consistency in acute stroke populations.[20] Although our study focused on a subacute window (Stage III hand), the principle of matching intervention to neurophysiological readiness appears applicable. However, findings may not generalize to patients at earlier (Stage I–II) or later stages (Stage IV–VI) of hand recovery or to chronic stroke populations beyond 6 months post-stroke.

These findings also complement emerging evidence on the relationship between hand motor recovery and cortical excitability. A systematic review found that recovery of hand function after stroke is associated with modulation of resting-motor threshold (rMT) in both hemispheres, with differences depending on severity and recovery stage. [21] Our stage-based intervention may have effectively harnessed this neuroplastic window by providing focused, repetitive, and progressively challenging hand tasks. This mechanistic hypothesis is supported by systematic review evidence, though direct neurophysiological measurement (e.g., TMS, fMRI) was not conducted in this study to confirm the proposed mechanisms.

While our findings demonstrated significant improvements in hand function and dexterity following the intervention, some randomized controlled trials have reported inconsistent or smaller effects of similar rehabilitation approaches. These discrepancies may be attributed to variations in intervention intensity, duration, participant chronicity, baseline impairment levels, and differences in outcome measures used across studies. Therefore, although our results support the effectiveness of the intervention, they should be interpreted in the context of existing heterogeneous evidence.

From a clinical perspective, the present results suggest that rehabilitation programmes for post-stroke hemiparesis should move beyond "one-size-fits-all" upper-limb protocols and instead adopt stage-specific strategies. For patients at Brunnstrom Stage III of hand recovery, combining strength-building, synergy-out-of training, and functional fine-motor tasks appears to yield greater improvements in both impairment and activity outcomes. For therapists, implementing a structured hand programme that aligns with the patient's motor stage may accelerate recovery and promote greater hand-use in daily activities, thereby enhancing participation and quality of life. However, the narrow population studied (45–55 years, Brunnstrom Stage III only) and single-centre design suggest that clinical applicability should be evaluated carefully before broad implementation across different age groups, recovery stages, and diverse clinical settings.

Limitations

Several limitations of this study should be acknowledged. First, it was conducted at single centre with a relatively small sample size (n=20 per group). Although the sample size was determined through power analysis, larger multicentre trails are recommended to enhance the generalizability of the findings. The narrow sample size limits the applicability of findings to broader populations, and multicentre studies with larger, more diverse cohorts would strengthen evidence for widespread implementation. Single-centre recruitment may introduce facility-specific bias, and replication across multiple centres with varied patient demographics and rehabilitation resources is essential before widespread adoption in clinical practice.

Second, the follow-up period was restricted to the 12 week interventions; therefore, the long-term sustainability of the observed improvements (e.g. at 6 or 12 months) remains uncertain. Without longer-term follow-up, we cannot confirm whether gains are maintained after the intervention period ends or whether participants sustain functional improvements in daily life

beyond the structured rehabilitation environment. Future studies should include follow-up assessments at 6 and 12 months post-intervention to establish the durability of stage-based training effects and determine whether booster sessions are needed to maintain functional gains.

Third, while the assessor was blinded, the therapists delivering the intervention were not, which introduces a risk of performance bias. However, this limitation was mitigated through: (1) standardized validated measures, (2) equal contact time (45 minutes) allocated to both groups, (3) standardized treatment protocols with weekly adherence monitoring, and (4) supervision by blinded senior physiotherapists. These safeguards reduce but do not entirely eliminate potential bias from therapist expectations. While mitigation strategies were implemented, the inability to blind therapists remains a source of potential bias. Future studies should explore blinded supervision protocols or consider therapist-independent delivery methods (e.g., technology-assisted interventions) to further reduce this limitation.

Fourth, the study sample included only participants at Brunnstrom Stage III for the hand; findings may not extrapolate to patients at earlier (Stage I–II) or later stages (Stage IV–VI) of hand recovery. The stage-specific focus, while methodologically sound for evaluating targeted interventions, limits applicability to other recovery stages. Future research should evaluate whether stage-based principles are effective across all Brunnstrom stages. Stage-specific efficacy is both a strength (focused intervention design) and a limitation (restricted generalizability). Separate RCTs investigating stage-based approaches for Stages I-II (early flaccidity to synergy onset) and Stages IV-VI (isolated movement to normal recovery) are critically needed to establish whether stage-tailored principles apply universally across the recovery continuum.

Fifth, the narrow age range (45–55 years) was intentionally selected based on stroke epidemiology in this working-age population, reducing confounding variables related to aging and comorbidities (common in ≥65 years). However, this restriction limits generalizability to younger stroke survivors (<45 years) or older adults (>55 years). Findings cannot be assumed applicable to these different age groups without additional research. While the age restriction was epidemiologically justified, it significantly constrains applicability. Stroke epidemiology in the Indian subcontinent shows substantial incidence in both younger working-age populations and adults >65 years. Future multicentre trials should explore whether stage-based

principles show comparable efficacy across broader age ranges, with particular attention to age-related differences in neuroplasticity and comorbidity burden.

Sixth, convenience sampling was used for participant recruitment, which acknowledges selection bias and reduces external validity compared with population-based random recruitment. Although inclusion/exclusion criteria were uniformly applied and consecutive patient recruitment was prioritized, the convenience sampling method may not represent the broader stroke population. Future studies should employ population-based randomization strategies to enhance generalizability. Convenience sampling at a single tertiary facility introduces selection bias toward patients with better health literacy, greater accessibility, and higher baseline motivation—potentially unrepresentative of the broader stroke population including rural communities and lower-income populations. Future studies should implement consecutive patient recruitment protocols and population-based randomization across multiple healthcare settings to enhance external validity.

Lastly, although we used standardised outcome measures, we did not include neurophysiological (e.g., TMS, fMRI) or kinematic correlates, which would offer mechanistic insight into the observed improvements. Understanding the neural substrates underlying stage-based hand recovery—such as changes in cortical excitability, interhemispheric balance, or motor area reorganization—would strengthen the mechanistic basis for the observed clinical improvements. The lack of neurophysiological evidence (e.g., transcranial magnetic stimulation for cortical excitability mapping, functional MRI for motor cortex reorganization, or kinematic analysis of movement patterns) limits mechanistic understanding. While systematic review evidence supports the neuroplastic window hypothesis, direct measurement of neural substrates in this cohort would clarify whether superior outcomes result from stage-specific recruitment of neural pathways, enhanced motor learning, or both.

5. Conclusion

The present randomized controlled study demonstrated that a Brunnstrom stage–based hand rehabilitation programme significantly enhanced hand strength, dexterity, and functional performance in individuals with post-stroke hemiparesis when compared with conventional physiotherapy. The structured, stage-specific approach focusing on out-of-synergy movements, task-oriented practice, and fine-motor re-education facilitated greater

improvements in grip strength, pinch strength, hand coordination (JHFT), and finger dexterity (NHPT) over a 12-week intervention period.

These findings underscore the clinical importance of aligning rehabilitation strategies with the patient's current stage of motor recovery, thereby optimizing neural reorganization and functional outcomes. Implementing Brunnstrom stage–based rehabilitation within routine physiotherapy practice may accelerate the restoration of independent hand use and improve the quality of life of stroke survivors.

However, these findings are limited by a modest sample size (n=20 per group), single-centre design, and narrow population characteristics. The results are specifically applicable to individuals in the acute-subacute phase of stroke (as represented in this study) with hand impairment at Brunnstrom Stage III. Generalization to patients at earlier (Stage I–II) or later stages (Stage IV–VI) of hand recovery, chronic stroke populations (>6 months post-stroke), or age groups outside 45–55 years should not be assumed without additional evidence. Implementation in diverse clinical settings and populations will require careful consideration of these boundary conditions.

Specifically, applicability is constrained by: (1) single-centre recruitment limiting representation across healthcare sectors; (2) convenience sampling bias toward motivated, literate, accessible populations; (3) narrow age band (45–55 years) not representative of stroke epidemiology in India; (4) focus on Stage III hand only, with unknown effects in earlier or later recovery stages; and (5) short-term follow-up (12 weeks) with unknown long-term sustainability. These limitations necessitate multicentre validation before recommending widespread clinical implementation across diverse populations and settings.

Future research should explore: (1) long-term effects and sustainability of stage-based training beyond 12 weeks; (2) neurophysiological mechanisms underlying stage-specific recovery through functional neuroimaging and cortical excitability studies; (3) multicentre applications with larger, diverse populations to enhance generalizability; and (4) extension of stage-based principles to other Brunnstrom stages and chronic stroke populations. These investigations will help confirm and expand upon the promising results of the present study and clarify the optimal conditions for implementing stage-based hand rehabilitation across the full spectrum of post-stroke recovery.

Comprehensive future directions should include: (1) multicentre RCTs in urban and rural settings with population-based recruitment across multiple socioeconomic strata; (2) neurophysiological characterization of stage-specific motor recovery using complementary methodologies (TMS for cortical excitability, fMRI for reorganization mapping); (3) extension to all Brunnstrom stages (I-VI) to establish universal applicability of stage-based principles; (4) evaluation in chronic stroke populations (>6 months) to determine whether benefits extend beyond acute-subacute phases; (5) investigation of age-related neuroplasticity differences across the lifespan (younger vs. older adults); (6) long-term follow-up (12 months minimum) to establish durability of functional gains; and (7) implementation science studies examining feasibility, cost-effectiveness, and scalability across the Indian healthcare system. These investigations will establish an evidence-based foundation for integrating stage-based hand rehabilitation into standard neurorehabilitation protocols.

Ethical Considerations

The study obtained ethical approval from the Institutional Ethics Committee. The ethical number is JHIEC/2022/011/PHYSIO, and the Clinical trial registry number is CTRI/2024/07/070496. All participants gave informed consent through signature, and confidentiality was maintained. Participation in the study was entirely voluntary, and participants retained the right to withdraw at any time without any penalty or loss of benefits.

Author Contribution

Prof. (Dr.) Suresh Mani and Prachi Tiwari researched literature, conceived the study and were involved in protocol development,. Dr. Nidhi, Prof. (Dr.) Sunil Kohli, Dr. Zuheb Ahmed Siddiqui were involved in gaining ethical approval and data analysis. Prachi Tiwari wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version of the manuscript

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on request.

Conflicting interests:

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this paper.

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AI use Statement

Generative AI tools were used only to support language refinement and improve clarity in manuscript preparation. The author takes full responsibility for the originality, accuracy and integrity of the content, and confirm that no AI was used for data generation, analysis, or scientific interpretation

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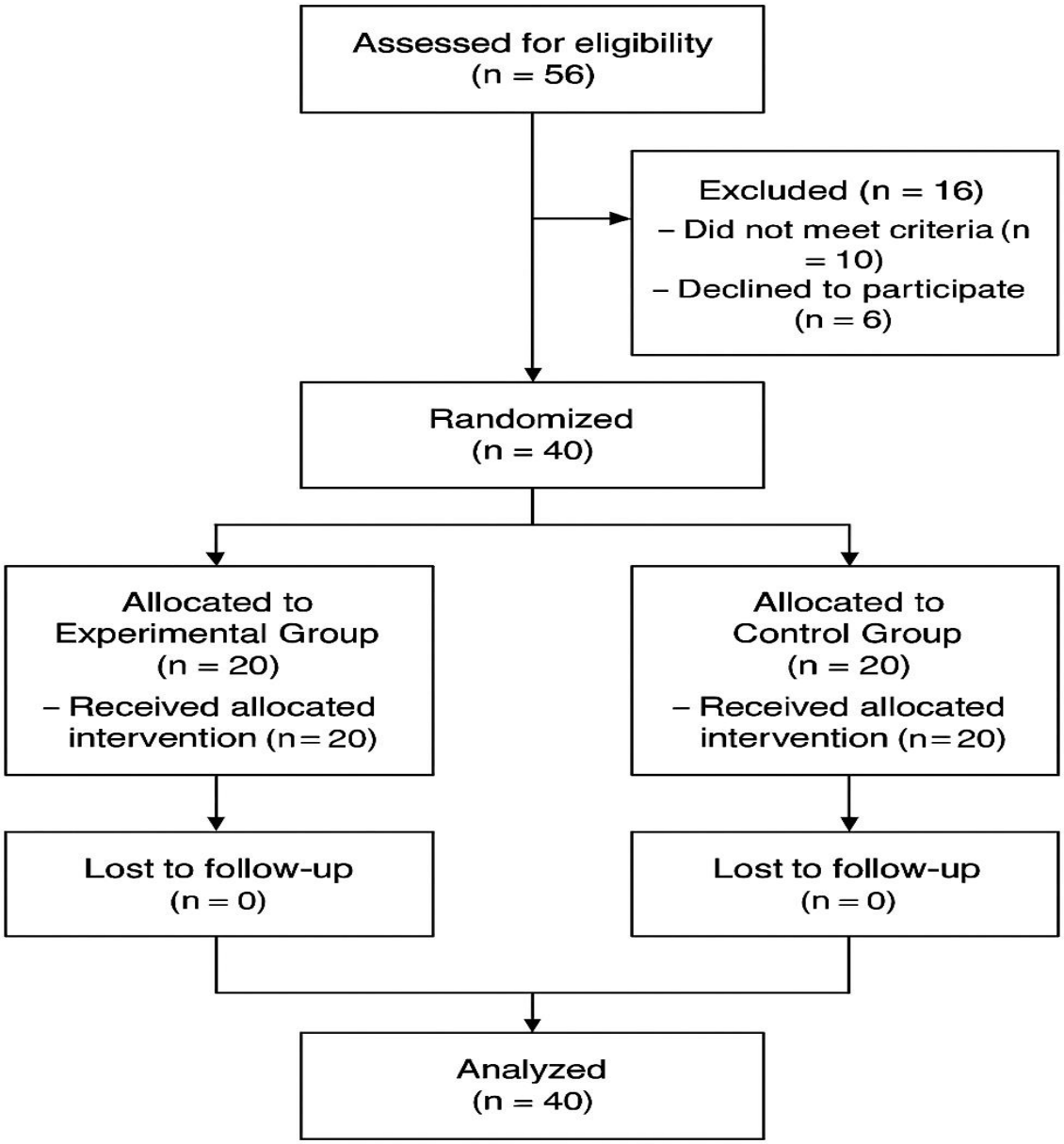

Fig. 1 CONSORT 2010 flow diagram

This diagram illustrates the flow of participants through the study, including screening, enrollment, allocation to study groups, follow-up, and final analysis, presented according to CONSORT 2010 guidelines.

Supplementary Materials

Table S1: Sensitivity Analysis - Sample Size Requirements Across Effect Size Assumptions

Effect Size (f)	Cohen's Effect Interpretation	Required n per Group	Total N (Both Groups)	Alpha	Power
0.30	Small-Medium	39	78	0.05	0.95
0.35	Small-Medium	28	56	0.05	0.95
0.40	Medium	**20**	**40**	0.05	0.95
0.45	Medium-Large	15	30	0.05	0.95
0.50	Large	12	24	0.05	0.95

Design Details: Two independent groups, three repeated measurement points (baseline, 6 weeks, 12 weeks). Calculations performed using G*Power version 3.1.

Primary Assumption: The main study utilized f = 0.40 (n = 20 per group, total N = 40), based on pilot data and previous literature demonstrating medium effect sizes for stage-tailored hand rehabilitation interventions in post-stroke populations.

Sensitivity Analysis Rationale: This sensitivity analysis demonstrates the robustness of the sample size selection across plausible effect size ranges:

- **Conservative scenario (f = 0.30):** Would require 39 participants per group (78 total), representing a 95% increase in sample size
- **Main assumption (f = 0.40):** Requires 20 participants per group (40 total)—the chosen sample size
- **Optimistic scenario (f = 0.50):** Would require only 12 participants per group (24 total), representing a 40% reduction

Clinical Interpretation: The main analysis effect size assumption (f = 0.40) represents a medium effect size, consistent with previous meta-analyses of hand rehabilitation interventions post-stroke (SMD = 0.95, equivalent to f ≈ 0.47). The selected sample size of 20 per group provides adequate statistical power while remaining feasible for single-center implementation.