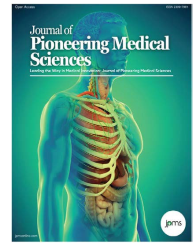

Journal of Pioneering Medical Sciences
Received: February 18, 2026 | Accepted: March 31, 2026 | Published: April 15, 2026
Volume 15, Issue S01, Pages 179-183

DOI https://doi.org/10.47310/jpms202515S0132

Sensor-Augmented Lower-Limb Proprioceptive Neuromuscular Facilitation for Balance Recovery after Middle Cerebral Artery Stroke: A Randomized Controlled Trial

Abdul Rahim Shaik[1*]
[1]Department of Physical Therapy and Health Rehabilitation, College of Applied Medical Sciences, Majmaah University, Al Majma'ah, 11952, Saudi Arabia

Author Designation: [1]Associate Professor

*Corresponding author: Abdul Rahim Shaik (e-mail: s.abdulrahim@mu.edu.sa).

Abstract: Background: Balance impairment is a major contributor to falls, mobility restriction, and reduced quality of life following middle cerebral artery (MCA) stroke. Conventional physiotherapy improves balance primarily through repetitive task practice, yet outcomes often plateau due to limited sensory feedback and inadequate engagement of postural control mechanisms. **Objective:** To examine the effectiveness of sensor-augmented lower-limb proprioceptive neuromuscular facilitation (SA-PNF) incorporating real-time biofeedback on balance, postural stability, and functional mobility in individuals with MCA stroke. **Methods:** Thirty individuals with chronic MCA stroke (age 45–75 years) and moderate balance impairment were randomly allocated to SA-PNF (n = 15) or conventional physiotherapy (n = 15). Interventions were delivered three times weekly for eight weeks. Primary outcomes included the Berg Balance Scale (BBS) and instrumented postural sway parameters. Secondary outcomes were Timed Up and Go (TUG), Limits of Stability (LOS), and gait symmetry index. Data were analyzed using mixed-model ANOVA. **Results:** Both groups showed significant improvements over time ($p<0.05$). However, the SA-PNF group demonstrated significantly greater gains in BBS (+12.1 vs +5.3), TUG (−8.2 s vs −3.6 s), mediolateral sway reduction (−34% vs −14%), and LOS excursion (+31% vs +12%) compared with conventional physiotherapy (Group × Time interaction, $p<0.001$). **Conclusion:** Sensor-augmented PNF produced superior balance and postural control improvements compared with conventional physiotherapy. The integration of real-time feedback with neurophysiological facilitation appears to enhance motor relearning and postural adaptability after MCA stroke.

Key Words: Stroke, Postural Balance, Proprioceptive Neuromuscular Facilitation, Rehabilitation, Biofeedback, Gait Disorders

INTRODUCTION

Stroke is a leading cause of long-term disability worldwide, with balance impairment recognized as one of the most disabling sequelae affecting functional independence and quality of life [1,2]. Following middle cerebral artery (MCA) stroke, damage to cortical motor and sensory networks disrupts postural control mechanisms, leading to asymmetrical weight bearing, impaired anticipatory postural adjustments, and delayed reactive balance responses [3,4]. These deficits significantly increase fall risk, limit safe ambulation, and restrict participation in daily and community activities [5].

Global epidemiological evidence indicates that more than 93 million individuals are stroke survivors with residual impairments, with ischemic strokes alone accounting for approximately 80% of cases [2]. Among these, middle cerebral artery (MCA) strokes are the most prevalent subtype and are commonly associated with hemiparesis and impaired postural control [1]. Research evidences states that growing number of stroke survivors has intensified the demand for effective, scalable rehabilitation strategies that address long-term functional deficits [6].

Balance control is a complex neurophysiological process requiring integration of proprioceptive, visual, and vestibular inputs within cortical and subcortical networks to generate adaptive motor responses [7,8]. Following stroke, disruption of afferent proprioceptive pathways and sensorimotor integration impairs internal body representation and reduces the ability to modulate postural responses, leading to instability and compensatory movement strategies [9]. From purely neuroplasticity perspective, recovery of motor function depends on activity-dependent cortical reorganization, where repeated, task-specific sensory input enhances synaptic efficiency and promotes motor relearning [10-11]. However, literature review states that conventional rehabilitation approaches often rely on repetitive practice with limited augmented feedback, which may restrict error correction and slow the neuroplastic adaptation process [10].

With reference to Physiotherapeutic treatment and management, Proprioceptive Neuromuscular Facilitation (PNF) facilitates neuroplasticity by providing enriched proprioceptive input through diagonal movement patterns, resistance, and the principle of irradiation, which enhances motor unit recruitment and interlimb coordination [12]. These mechanisms stimulate sensorimotor cortex activation and strengthen neural pathways involved in coordinated movement. Despite demonstrated improvements in balance and gait, traditional PNF primarily depends on therapist-mediated feedback, which may lack objectivity and consistency across sessions [13-14].

Technological advances in rehabilitation sciences has paved way for new age tools including virtual reality (VR), robotic-assisted therapy, and treadmill-based biofeedback systems, all of which aim to enhance motor learning through augmented feedback. While VR provides immersive environments to improve engagement and task variability, and treadmill biofeedback offers rhythmic gait training with visual or auditory cues, these approaches may be resource-intensive, less accessible, or limited in targeting multi-planar functional movements relevant to daily activities. In contrast, wearable sensor-based systems offer a portable, cost-effective solution that can be seamlessly integrated into conventional therapies such as PNF. These sensors enable real-time quantification of postural sway, weight distribution, and movement symmetry, thereby providing precise, immediate feedback that enhances error-based motor learning and supports neuroplastic adaptation [15-16].

Despite the theoretical advantages, limited research has explored the combined application of PNF and real-time sensor-based biofeedback in stroke rehabilitation. Integrating wearable sensors with PNF may bridge the gap between therapist-dependent facilitation and objective, data-driven rehabilitation, potentially optimizing motor relearning and functional recovery.

Therefore, the primary objective of this study was to evaluate the effectiveness of sensor-augmented lower-limb proprioceptive neuromuscular facilitation (SA-PNF) on balance and postural control in individuals with MCA stroke. Secondary objectives included the assessment of functional mobility and gait symmetry. It was hypothesized that SA-PNF would result in significantly greater improvements compared with conventional physiotherapy.

METHODS

This study was conducted as a randomized controlled, assessor-blinded clinical trial in accordance with CONSORT guidelines to compare the effectiveness of sensor-augmented lower-limb proprioceptive neuromuscular facilitation (SA-PNF) with conventional physiotherapy for improving balance and postural control in individuals with chronic middle cerebral artery (MCA) stroke. Ethical approval was obtained from the Institutional Ethical Committee and written informed consent was obtained from all participants prior to enrolment.

Thirty patients, suffered from chronic middle cerebral artery (MCA) stroke were recruited from the Department of Physiotherapy, Highland Hospital Research and Diagnostic Center, Mangalore, India. Inclusion criteria included patients aged between 45 to 75 years, experienced first-ever unilateral ischemic MCA stroke at least six months prior, demonstrated moderate balance impairment with Berg Balance Scale (BBS) scores ranging between 20 to 45. Individuals with cerebellar or brainstem involvement, severe musculoskeletal or cardiovascular conditions, significant visual or vestibular deficits, or other neurological disorders affecting balance were excluded.

Participants were randomly allocated to either of the two groups using simple random sampling by one of the hospital colleagues, who was blinded to the treatment groups and was not involved in recruitment or assessment thereby ensure equal group distribution without any bias.

The sensor-augmented proprioceptive neuromuscular facilitation (SA-PNF) i.e. treatment group A underwent lower-limb D1 and D2 PNF patterns using techniques such as rhythmic initiation and dynamic reversals. Therapy was integrated with a wearable inertial measurement unit (IMU)-based sensor system, consisting of tri-axial accelerometers and gyroscopes. Sensors were placed at standardized anatomical landmarks including the lumbar region (L5 level) and bilateral shank segments, to capture trunk sway, weight-shift symmetry, and lower-limb movement dynamics. The conventional physiotherapy group received standardized balance and gait training, including static and dynamic balance exercises, functional task practice, and level-ground gait training, without augmented feedback or sensor integration. Both groups received supervised physiotherapy sessions three times per week for eight weeks, with matched session duration and therapist contact time.

Prior to each session, sensors were calibrated using a static upright standing reference posture to establish baseline orientation and minimize signal drift. Real-time data were transmitted to a tablet-based interface, where visual biofeedback (e.g., center of mass displacement, symmetry indicators, and stability limits) was displayed. Feedback was delivered in a knowledge-of-performance format, enabling patients to adjust posture and movement during task execution. This system facilitated enhanced proprioceptive input, anticipatory postural control, and error-based motor learning.

Outcome measures were assessed at baseline and after the 8-week intervention period by a blinded assessor. The primary outcome, balance performance, was measured using the Berg Balance Scale. Secondary outcomes included functional mobility assessed by the Timed Up and Go test, along with objective measures of postural sway and limits of stability derived from the sensor system. These outcomes were selected to capture both clinically meaningful improvements and instrumented changes in postural control following the intervention.

RESULTS

Participant Flow and Baseline Characteristics

All thirty participants completed the eight-week intervention, and no adverse events or dropouts were recorded. Baseline demographic and clinical characteristics were examined to confirm group comparability. As shown in Table 1, the Sensor-Augmented PNF (SA-PNF) group and the Conventional Physiotherapy group were well matched with respect to age, sex distribution, body mass index, stroke chronicity, and baseline balance performance. No statistically significant differences were observed between groups for any baseline variable ($p > 0.05$), indicating successful randomization and minimizing the risk of confounding effects.

Baseline Balance and Functional Performance

Baseline comparisons of balance and functional mobility outcomes revealed no significant differences between groups prior to intervention (Table 2). Scores on the Berg Balance Scale (BBS), Timed Up and Go (TUG), Single-Leg Stance Test (SLST), and Step Test were statistically comparable ($p > 0.05$ for all measures), confirming equivalence in pre-intervention functional status.

Post-Intervention Outcomes and Within-Group Changes

Following the eight-week intervention, both groups demonstrated statistically significant improvements across all outcome measures ($p<0.05$), confirming the effectiveness of both rehabilitation approaches. However, beyond statistical significance, the clinical magnitude of change was consistently greater in the sensor-augmented PNF (SA-PNF) group, indicating superior functional gains as compared to their matched controls.

Within-group analysis showed that participants in the SA-PNF group achieved clinically meaningful improvements in balance and functional mobility, with notable enhancement in dynamic balance, weight-shifting ability, and postural control. These changes are indicative of improved motor coordination and greater independence in functional activities such as standing, turning, and ambulation. In contrast, the Conventional Physiotherapy group demonstrated moderate yet clinically relevant improvements, primarily in basic balance tasks and gait performance, reflecting the expected benefits of standard rehabilitation.

Between-group comparisons further highlighted that the SA-PNF group exhibited greater improvements for the key outcome measures including Berg Balance Scale and Timed Up and Go tests, suggesting that observed changes were not only statistically significant but also meaningful in real-world functional recovery, potentially translating into reduced fall risk and improved participation in daily activities.

Table 1: Baseline Demographic and Clinical Characteristics

Variable	SA-PNF (n = 15)	Conventional (n = 15)
Age (years)	59.4±7.1	60.2±6.8
Sex (M/F)	9 / 6	8 / 7
BMI (kg/m²)	25.8±3.2	26.1±3.0
Stroke duration (months)	14.6±3.9	15.1±4.2
BBS (points)	31.6±4.1	32.0±4.3

Table 2: Baseline Balance and Functional Outcomes

Outcome Measure	SA-PNF (Pre)	Conventional (Pre)	p-value
BBS (0–56)	31.6±4.1	32.0±4.3	0.79
TUG (s)	21.1±2.7	20.6±2.5	0.56
SLST (s)	8.7±1.9	8.9±1.8	0.73
Step Test (reps)	11.2±1.8	11.5±1.7	0.64

Table 3: Pre- and Post-Intervention Outcome Values with Mean Change

Outcome	Group	Pre (Mean±SD)	Post (Mean±SD)	Mean Change (±SD)	p-value
BBS (points)	SA-PNF	31.6±4.1	43.0±3.6	11.4±2.1	<0.001
	Conventional	32.0±4.3	37.2±3.9	5.2±1.8	<0.01
TUG (s)	SA-PNF	21.1±2.7	13.5±2.1	−7.6±1.3	<0.001
	Conventional	20.6±2.5	17.2±2.3	−3.4±1.2	<0.01
SLST (s)	SA-PNF	8.7±1.9	17.0±2.2	8.3±1.6	<0.001
	Conventional	8.9±1.8	12.8±2.0	3.9±1.4	<0.01
Step Test (reps)	SA-PNF	10.7±1.3	17.1±1.9	6.4±1.2	<0.001
	Conventional	11.5±1.7	13.6±1.8	2.1±1.0	<0.01

Table 4: Between-Group Effects (Mixed-Model ANOVA)

Outcome Measure	Group × Time F-value	p-value	Partial η²
BBS	18.7	<0.001	0.41
TUG	16.3	<0.001	0.38
SLST	14.9	<0.001	0.35
Step Test	12.6	<0.001	0.31

Overall, while both interventions were effective, the integration of sensor-based feedback with PNF resulted in superior clinical outcomes, emphasizing its added value in enhancing postural control and functional mobility in individuals with chronic stroke (Table 3).

Between-Group Comparisons and Interaction Effects

Between-group analysis using a two-way mixed-design ANOVA demonstrated a significant Group × Time interaction for all outcome measures ($p<0.001$), indicating that improvements over time differed significantly between the two interventions. Participants in the SA-PNF group exhibited a significantly greater rate and magnitude of improvement compared with those receiving conventional physiotherapy (Table 4).

Large effect sizes were observed for balance and mobility outcomes, particularly for BBS and TUG performance, suggesting both statistical robustness and clinical relevance of the sensor-augmented PNF intervention.

In summary, both interventions resulted in significant improvements in balance and functional mobility over the eight week period. However, the sensor-augmented PNF intervention consistently produced larger and clinically superior gains across all measured outcomes compared with conventional physiotherapy. The presence of significant Group × Time interaction effects across all variables supports the superior efficacy of SA-PNF in enhancing postural control and balance recovery in individuals with chronic MCA stroke. The following Discussion section focuses on interpretation of these findings, underlying mechanisms, and clinical implications.

DISCUSSION

The present study demonstrated that sensor-augmented lower-limb proprioceptive neuromuscular facilitation (SA-PNF) resulted in significantly greater improvements in balance and functional mobility than conventional physiotherapy in individuals with chronic MCA stroke. The superiority of SA-PNF observed across all outcome measures is mechanistically plausible and consistent with contemporary neurorehabilitation evidence emphasizing task-specific, multi-planar activation and enhanced sensorimotor integration. Diagonal and resisted lower-limb PNF patterns are known to facilitate proximal muscle activation, improve trunk–pelvic coordination, and enhance postural alignment, all of which are critical for balance recovery after stroke [12-13].

The convergence of the present findings with prior literature strengthens their credibility. Previous trials have reported meaningful improvements in balance and gait following lower-limb or pelvic PNF interventions in chronic stroke populations, particularly when training emphasizes coordinated multi-joint movement rather than isolated muscle strengthening [12,17]. In addition, recent studies employing technology-assisted balance training and biofeedback have demonstrated superior improvements in postural stability compared with conventional therapy alone, supporting the role of augmented sensory input in motor relearning [15,16]. The current study extends this evidence by integrating these approaches, suggesting that sensor augmentation enhances the therapeutic impact of PNF.

In contrast, some earlier studies have reported comparable outcomes between PNF and conventional balance training. Such findings are likely attributable to methodological differences, including shorter intervention durations, lower resistance progression, limited treatment contrast, or reliance solely on clinical outcome scales without objective or feedback-driven components [13]. The larger effect sizes observed in the present study may be explained by the combination of irradiation-based facilitation with real-time visual feedback, which likely enhanced error detection, postural symmetry control, and anticipatory postural adjustments—mechanisms frequently impaired following MCA stroke [9,10].

From a mechanistic standpoint, the observed improvements are most plausibly mediated through improved trunk–pelvic coupling and stabilization of the center of mass during functional tasks. Multi-planar resistance applied through PNF patterns may have improved postural set and inter-segmental coordination, while real-time biofeedback reinforced proprioceptive awareness and adaptive motor strategies. Similar mechanisms have been proposed in studies combining pelvic PNF with core stabilization, which have reported superior balance and gait outcomes compared with conventional therapy [17]. However, the absence of direct neurophysiological or kinematic measurements in the present study limits definitive attribution of effects to irradiation-specific mechanisms rather than generalized practice effects.

There are few limitations in the study as well. First and foremost, the sample size and single-center design limit generalizability. In addition, the absence of long-term follow-up precludes conclusions regarding retention of overall gains in the fall reduction. Moreover, applicability to individuals with severe stroke, cerebellar involvement, or advanced age—groups that represent a growing proportion of the global stroke burden—remains uncertain ([1,2].

Clinically, the findings suggest that SA-PNF may enhance balance recovery more as compared to conventional physiotherapy alone. However, given the mixed evidence regarding the superiority of PNF over other active rehabilitation strategies [13], SA-PNF should be considered a complementary, mechanism-driven adjunct within comprehensive stroke rehabilitation programs rather than a standalone intervention.

Future research should focus on large-scale, multicenter randomized controlled trials with adequately powered sample sizes to improve generalizability and strengthen clinical recommendations. Similarly, studies incorporating longer follow-up periods, stratified patient subgroups, and advanced biomechanical and sensor-based outcome measures can be conducted to determine the durability of effects, impact on fall prevention, and real-world functional participation. Additionally, standardized reporting and preregistered protocols will further enhance methodological rigor and facilitate comparison across studies.

CONCLUSION

The Sensor-augmented lower-limb proprioceptive neuromuscular facilitation (SA-PNF) may cause better improvements in balance and functional mobility as compared with conventional physiotherapy in individuals with chronic middle cerebral artery stroke. The enhanced outcomes are likely driven by the integration of irradiation-based neuromuscular facilitation with real-time sensory feedback, which supports improved sensorimotor integration and postural control. SA-PNF appears to be a feasible, mechanism-informed adjunct to standard stroke rehabilitation; however, larger multicenter studies with longer follow-up are required to confirm durability of benefits and effects on fall prevention and participation.

Conflict of Interest

The author declares that he has no conflict of interest.

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