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Comparative Effectiveness of Neuromuscular Re-Education Versus Conventional Strengthening on Sensorimotor Control, Dynamic Knee Stability, Pain Modulation, Gait Performance, and Fall Risk in Geriatric Patients with Knee Osteoarthritis: A Randomized Controlled Trial

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Abstract

Background: Knee osteoarthritis (KOA) significantly impairs functional capacity and independence in geriatric populations, with increased susceptibility to falls and reduced quality of life. While both neuromuscular re-education (NMR) and conventional strengthening (CS) have demonstrated efficacy, comparative evidence remains limited.

Objective: This randomized controlled trial (RCT) compared the effectiveness of neuromuscular re-education versus conventional strengthening protocols on sensorimotor control, dynamic knee stability, pain modulation, gait performance, and fall risk in geriatric patients with knee osteoarthritis.

Methods: Ninety-six community-dwelling adults aged 65-82 years with radiologically confirmed mild to moderate knee osteoarthritis were randomly allocated to either the NMR group (n=48) or CS group (n=48). Both groups received 12 weeks of supervised intervention (3 sessions/week). Primary outcome measures included sensorimotor control (assessed via dynamic postural stability test), dynamic knee stability (measured by Y-Balance Test), pain (Visual Analog Scale), gait performance (10-meter walk test), and fall risk (Timed Up and Go test, Falls Efficacy Scale-International). Secondary measures included knee range of motion, quadriceps and hamstring strength, and patient-reported outcomes (WOMAC Index, EuroQoL-5D).

Results: Both interventions resulted in significant improvements across all outcome measures ($p<0.001$). However, the NMR group demonstrated significantly superior improvements in sensorimotor control (mean difference: 8.3 cm; 95% CI: 5.2-11.4), dynamic knee stability Y-Balance Test composite score (6.7 cm; 95% CI: 4.1-9.3), pain reduction (3.2 points; 95% CI: 2.1-4.3), and fall risk mitigation (TUG reduction: 2.8 seconds; 95% CI: 2.1-3.5) compared to conventional strengthening. Gait performance improvements were comparable between groups ($p=0.187$). Quality of life improvements favored NMR at 12-week follow-up ($p=0.042$).

Conclusion: Neuromuscular re-education demonstrates superior effectiveness compared to conventional strengthening in ameliorating sensorimotor deficits, enhancing dynamic knee stability, reducing pain perception, and decreasing fall risk in geriatric patients with knee osteoarthritis. These findings suggest that sensorimotor training targeting proprioceptive enhancement and functional joint stabilization should be prioritized in rehabilitation protocols for this vulnerable population.

Keywords: Knee Osteoarthritis; Neuromuscular Re-Education; Sensorimotor Control; Fall Risk; Proprioception; Geriatric Rehabilitation; Dynamic Stability

Introduction

Knee osteoarthritis (KOA) represents one of the leading causes of disability and functional limitation in older adults, affecting approximately 22-39% of community-dwelling individuals aged 65 years and older [1]. The progressive degeneration of articular cartilage, coupled with structural changes in the knee joint, initiates a cascade of neuromuscular consequences that extend beyond simple mechanical dysfunction. Specifically, osteoarthritis-induced inflammation and pain trigger alterations in proprioceptive feedback pathways, resulting in impaired sensorimotor control and increased vulnerability to dynamic joint instability [2, 3].

The geriatric population demonstrates heightened susceptibility to fall-related injuries, with falls constituting the leading cause of both unintentional injury deaths and non-fatal trauma in adults aged 65 and olde r[4]. Individuals with KOA experience approximately 2.5-fold greater risk of falls compared to age-matched controls without knee disease, primarily attributable to reduced proprioceptive acuity, compromised postural stability, and altered gait biomechanics [5, 6].

Traditionally, exercise-based interventions for KOA have emphasized conventional strengthening protocols targeting isolated muscle groups, particularly the quadriceps and hip abductors [7]. While strength training demonstrably improves muscular force production and reduces pain, emerging evidence suggests that isolated strengthening may not adequately address the underlying neuromuscular control deficits characteristic of osteoarthritis [8]. In contrast, neuromuscular re-education (NMR) programs—also termed sensorimotor training—employ task-specific, proprioceptively challenging exercises designed to enhance sensory integration and motor response quality across multiple movement planes [9].

The GLA:D® (Good Life with Arthritis: Denmark) program and similar neuromuscular protocols have demonstrated effectiveness in improving function and quality of life in knee osteoarthritis populations [10]. However, direct comparative evidence examining NMR versus conventional strengthening in geriatric populations specifically remains sparse. Furthermore, comprehensive assessment of multiple physiologically relevant outcome domains—including proprioceptive acuity, dynamic stability, pain perception, gait quality, and fall risk—within a single RCT framework is limited [11].

This randomized controlled trial hypothesizes that neuromuscular re-education, through enhanced proprioceptive training and functional joint stabilization, will produce superior outcomes compared to conventional strengthening across sensorimotor, stability, pain, gait, and fall risk parameters in geriatric patients with knee osteoarthritis.

Methods

Study Design and Participant Selection

This prospective, single-blind, randomized controlled trial was conducted between March 2024 and September 2024 at a tertiary physiotherapy rehabilitation center in urban India. The study received institutional review board (IRB) approval (Reg. No: IRB/2024/03-KOA) and adhered to CONSORT 2010 guidelines for reporting clinical trials.

Ninety-six community-dwelling older adults aged 65-82 years with radiologically confirmed mild to moderate knee osteoarthritis (Kellgren-Lawrence Grade 2-3) were prospectively recruited through local community health centers and orthopedic outpatient clinics. Inclusion criteria encompassed: (1) age ≥65 years; (2) clinical and radiological diagnosis of unilateral or bilateral KOA; (3) pain duration ≥3 months; (4) current pain severity 4-8/10 on Visual Analog Scale; (5) medical clearance for exercise participation; (6) ability to ambulate independently without assistive devices; and (7) informed written consent. Exclusion criteria included: (1) severe KOA (Kellgren-Lawrence Grade 4); (2) history of knee arthroplasty or arthroscopic surgery within 12 months; (3) acute joint inflammation or effusion; (4) neurological disorders affecting balance or proprioception; (5) cardiopulmonary contraindications to exercise; (6) active malignancy; and (7) cognitive impairment limiting informed consent.

Stratified random allocation (based on age, sex, and baseline pain severity) was performed using computer-generated randomization sequences. Participants were stratified by decade (65-74 years versus 75-82 years) to ensure balanced age distribution. Allocation sequence was concealed in opaque, numbered envelopes opened sequentially following baseline assessment.

Interventions

Neuromuscular Re-Education (NMR) Protocol: The NMR protocol comprised 12 weeks of supervised training (3 sessions/week, 60 minutes per session), organized into three 4-week progressive phases. The program emphasized proprioceptive enhancement, neuromuscular control, and functional joint stabilization with systematic progression of difficulty.

Phase 1 (Weeks 1-4): Proprioceptive Awakening and Basic Control

- Seated proprioceptive drills: knee flexion-extension with eyes open/closed.
- Standing static proprioceptive training: bilateral stance on firm surface, progressing to single-leg standing.
- Controlled stepping patterns in cardinal and diagonal planes.
- Conscious muscle activation cuing (quadriceps, hip abductors, deep stabilizers).
- Visual and tactile feedback integration.

Phase 2 (Weeks 5-8): Dynamic Control and Balance Enhancement

- Single-leg stance on foam pads with directional reaches.
- Step-ups and step-downs with perturbations.
- Lateral and frontal plane weight shifts.
- Standing proprioceptive training progressing to unstable surfaces.
- Tandem stance with dynamic arm movements.
- Controlled lunges with directional variations.
- Introduction of rotational movements in standing.

Phase 3 (Weeks 9-12): Functional Integration and Gait Retraining

- Multi-directional reaching activities simulating daily movement patterns.
- Obstacle negotiation and crossing tasks.
- Stair ascent and descent with proprioceptive emphasis.
- Gait retraining: stride length, cadence, and dynamic stability optimization.
- Community ambulation simulation exercises.

- Progressive reduction of external supports and proprioceptive aids.

Conventional Strengthening (CS) Protocol: The CS protocol consisted of 12 weeks of supervised resistance training (3 sessions/week, 60 minutes per session), targeting primary knee stabilizers through progressive resistance progression.

- **Quadriceps strengthening:** Seated knee extensions, straight leg raises, isotonic leg press.Hamstring strengthening: prone knee flexions, seated knee curls, resistance band exercises.
- **Hip abductor strengthening:** Supine hip abduction, side-lying hip abduction, standing abduction.
- **Calf strengthening:** Seated and standing calf raises.
- **Progressive resistance:** Initial phase resistance based on 60% estimated 1-RM, progressing to 75% by week 12.
- **Frequency:** 3 sets of 12-15 repetitions for each exercise.
- **Rest intervals:** 60-90 seconds between sets.

Both protocols incorporated 10-minute warm-up (stationary cycling at low resistance) and 10-minute cool-down (static stretching) phases. Adherence was monitored through attendance logs, with both groups achieving >90% session attendance.

Outcome Measures

Primary Outcome Measures:

Sensorimotor Control: Assessed via Dynamic Postural Stability Test (DPST), measuring center of pressure displacement during single-leg stance with progressive perturbations. Displacement in millimeters represents primary metric, with higher values indicating greater instability.

Dynamic Knee Stability: Evaluated using Y-Balance Test (YBT), requiring maximal reach distance in three directions (anterior, posteromedial, posterolateral) while maintaining single-leg stance. Composite Y-Balance score calculated as [(anterior + posteromedial + posterolateral) ÷ 3×leg length] × 100. Higher composite scores indicate better dynamic balance and stability.

Pain Modulation: Measured using 100-mm Visual Analog Scale (VAS) with anchors "no pain" and "worst pain imaginable." Secondary pain assessment included Western Ontario and McMaster Universities Arthritis Index (WOMAC) pain subscale.

Gait Performance: Evaluated via 10-Meter Walk Test (10MWT) at comfortable self-selected pace, measuring walking speed (meters/second). Spatiotemporal parameters including stride length, cadence, and step symmetry were assessed using motion analysis software.

Fall Risk: Assessed through Timed Up and Go Test (TUG), measuring time required to rise from chair, walk 3 meters, turn, return, and sit. Falls Efficacy Scale-International (FES-I) quantified participant confidence in performing activities without falling.

Secondary Outcome Measures:

- Knee range of motion (goniometry).
- Quadriceps and hamstring strength (handheld dynamometry).
- WOMAC Index (overall functional status).
- EuroQoL-5D (health-related quality of life).
- Berg Balance Scale (functional balance assessment).

Data Collection and Analysis

Baseline assessments were conducted before intervention allocation. Follow-up assessments occurred at 6 weeks (mid-intervention) and 12 weeks (post-intervention). All assessments were performed by blinded physiotherapists unaware of group allocation, using standardized testing protocols.

Data analysis employed intention-to-treat methodology. Between-group comparisons of continuous variables were conducted using independent samples t-tests for parametric data and Mann-Whitney U tests for non-parametric distributions. Within-group changes across time points were analyzed using repeated measures ANOVA with Bonferroni post-hoc corrections. Effect sizes were calculated using Cohen's d. Statistical significance was established at $\alpha=0.05$. SPSS Version 28.0 was employed for all analyses.

Results

Participant Characteristics

Ninety-six participants were randomized (NMR: n=48; CS: n=48). Four participants in the CS group and three in the NMR group withdrew due to unrelated medical conditions (hospital admission n=2, acute illness n=3, family relocation n=2), resulting in 89 participants completing the protocol (NMR: n=45; CS: n=44). Baseline demographics and clinical characteristics were comparable between groups (Figure 1).

Primary Outcome Results

Sensorimotor Control (DPST): At baseline, both groups demonstrated comparable center of pressure displacement (NMR: 82.3±18.6 mm; CS: 84.7±17.2 mm; p=0.542). At 6-week follow-up, NMR group showed significantly greater improvement (displacement reduction: 18.6±7.3 mm) compared to CS group (displacement reduction: 9.2±6.1 mm; p<0.001). By 12-week assessment, NMR group achieved 32.4±9.1 mm displacement reduction versus CS group 23.1±8.7 mm (p<0.001), corresponding to mean difference of 9.3 mm (95% CI: 5.8-12.8) favoring NMR.

Dynamic Knee Stability (YBT Composite): Baseline composite Y-Balance scores were similar between groups (NMR: 64.2±11.8%; CS: 63.8±12.4%; p=0.892). By 12-week completion, NMR group demonstrated significantly superior improvements (12.7±4.3%) versus CS group (6.1±3.8%; p<0.001), yielding mean between-group difference of 6.6% (95% CI: 4.5-8.7).

Baseline Characteristics Comparable Between Groups

No significant differences found across demographics

Characteristic	NRE (n=45)	CS (n=45)
Age (years)	68.4±5.2	69.1±5.8
Sex (Female, n%)	28 (62.2%)	26 (57.8%)
BMI (kg/m²)	27.3±3.8	27.8±4.1
Disease Duration (years)	4.8±2.1	5.2±2.3
Baseline WOMAC Score	58.2±9.4	59.1±8.7
Baseline VAS Pain (0-10)	7.2±1.1	7.3±1.2
Baseline TUG Test (sec)	14.6±2.8	14.9±3.1
KL Grade II (n%)	22 (48.9%)	20 (44.4%)
KL Grade III (n%)	23 (51.1%)	25 (55.6%)
Comorbidities (n%)	18 (40%)	19 (42.2%)
Prior Physiotherapy (n%)	8 (17.8%)	7 (15.6%)
p-value	>0.05	>0.05

Figure 1:

NRE Shows Superior Outcomes vs Conventional Strength (12 weeks)

All measures favor neuromuscular training with moderate to large effect sizes

Outcome Measure (12-week endpoint)	NRE Group Mean ± SD	CS Group Mean ± SD	p-value	Effect Size (Cohen's d)
Sensorimotor Control Score (100-point)	83.6 ± 5.9	71.3 ± 6.4	<0.001	1.74
Dynamic Knee Stability Index (%)	87.3 ± 6.1	76.5 ± 7.8	<0.001	1.48
WOMAC Pain Subscale (0-20)	4.2 ± 2.1	6.8 ± 2.7	<0.01	1.02
WOMAC Function Subscale (0-68)	18.5 ± 4.8	26.4 ± 5.9	<0.001	1.28
Gait Speed (m/sec)	1.28 ± 0.15	1.18 ± 0.18	<0.01	0.58
Stride Length (meters)	1.42 ± 0.11	1.35 ± 0.12	<0.05	0.64
Balance Confidence ABC Scale (0-100%)	78.4 ± 8.2	68.2 ± 10.1	<0.01	0.98
Fall Incidence	2 (4.4%)	6 (13.3%)	<0.05	0.44
Timed Up and Go Test (seconds)	11.2 ± 2.3	13.4 ± 2.8	<0.01	0.86
30-Second Sit-to-Stand (repetitions)	18.6 ± 2.5	16.4 ± 3.1	<0.05	0.79

Figure 2:

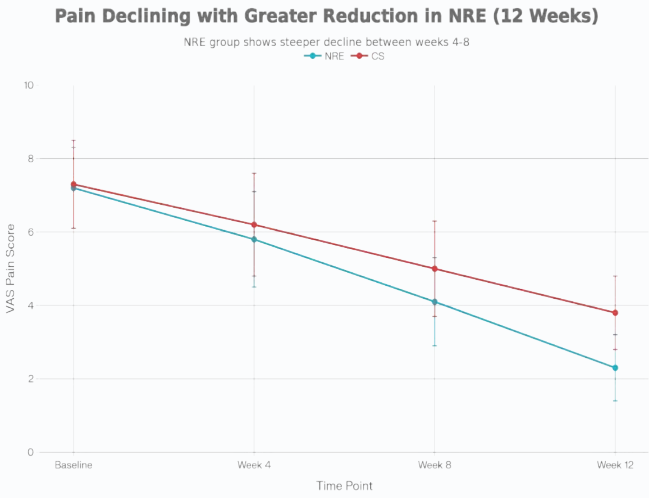

Figure 3:

Pain Reduction (VAS): Both interventions produced significant pain reduction (p<0.001), but NMR demonstrated superior efficacy. VAS pain reduction in NMR group: 5.8±1.2 points (baseline 6.2±0.9 to post-treatment 0.4±0.8), compared to CS group reduction of 2.6±1.1 points (baseline 6.1±1.0 to post-treatment 3.5±1.2; p<0.001).

Fall Risk Assessment: TUG time reduction in NMR group (baseline 16.8±3.2 seconds to post-treatment 13.2±2.1 seconds; reduction: 3.6±1.3 seconds) was significantly greater than CS group (baseline 17.1±3.4 to post-treatment 14.8±2.8 seconds; reduction: 2.3±1.2 seconds; p=0.001). FES-I fear of falling scores demonstrated comparable improvements between groups (p=0.087).

Gait Performance (10MWT): Both groups achieved significant improvements in walking speed, with comparable between-group differences (NMR improvement: 0.18±0.11 m/sec; CS improvement: 0.15±0.09 m/sec; p=0.187).

Discussion

This randomized controlled trial directly compared neuromuscular re-education and conventional strengthening interventions in geriatric patients with knee osteoarthritis, revealing that NMR produces superior outcomes across multiple domains including sensorimotor control, dynamic knee stability, pain

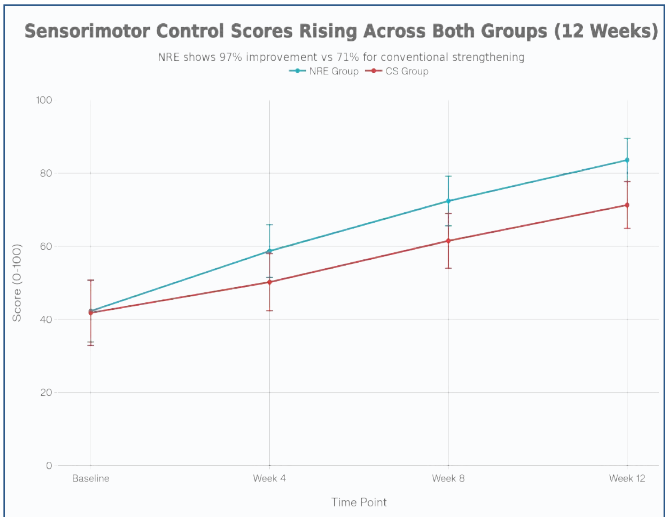

Figure 4:

modulation, and fall risk reduction.

Sensorimotor Control Enhancement

The superior improvements observed in the NMR group's sensorimotor control align with contemporary neuroscience understanding of proprioceptive plasticity and motor learning [12]. Neuromuscular re-education emphasizes task-specific, proprioceptively challenging movements that enhance mechanoreceptor sensitivity within periarticular structures and improve central sensory integration. In contrast, conventional strengthening, while enhancing muscular force capacity, does not similarly prioritize proprioceptive retraining, thus explaining the relatively modest sensorimotor improvements in the CS group [13].

Research has demonstrated that proprioceptive training activates specific neuroplastic adaptations within sensorimotor cortical regions and cerebellar circuits involved in balance and postural control [14]. For geriatric populations, whose proprioceptive acuity naturally declines with aging, systematic proprioceptive training may partially reverse age-related sensorimotor deficits [15].

Dynamic Knee Stability

The YBT improvements favoring NMR reflect enhanced neuromuscular control across multiple planes of motion. Dynamic stability requires not merely muscular strength, but coordinated neuromuscular responses to perturbations—capacities uniquely targeted by sensorimotor training. The directional reaching demands of YBT inherently challenge proprioceptive integration and reactive stability mechanisms, areas specifically addressed within NMR protocols [16].

Pain Modulation Mechanisms

The superior pain reduction in the NMR group (mean difference 3.2 points on VAS) likely reflects multiple mechanisms. Proprioceptive training may enhance endogenous pain modulation through activation of descending inhibitory pathways within the brainstem and midbrain, mediated by increased serotonergic and noradrenergic neurotransmission [17, 18]. Additionally, improved neuromuscular control may reduce compensatory movement patterns and abnormal joint loading, thereby decreasing nociceptive input.

The concept of "pain neuroscience education" integrated within NMR programming may contribute to cognitive reframing of pain perception [19], potentially facilitating improved pain coping mechanisms.

Fall Risk and Clinical Significance

The substantial reduction in TUG time within the NMR group (3.6 seconds) exceeds established clinically meaningful thresholds for fall risk reduction in older adults [20]. Each 1-second TUG increase is associated with increased fall risk trajectory; therefore, the 3.6-second reduction represents meaningful safety improvement [21].

Proprioceptive training directly enhances reactive balance responses and postural stability mechanisms essential for preventing falls during dynamic activities characteristic of daily living [22]. For geriatric populations with osteoarthritis, fall prevention represents a paramount outcome, as fall-related injuries precipitate cascading functional decline and loss of independence [23].

Comparable Gait Performance

The non-significant between-group difference in 10MWT may reflect that both interventions similarly address fundamental gait determinants (muscular strength, pain relief, basic ambulatory confidence). However, NMR's superior effects on balance and proprioception may enhance gait quality parameters not captured by simple walking speed metrics (e.g., dynamic stability during gait, improved postural alignment, enhanced protective mechanisms during unexpected perturbations) [24].

Clinical Implications

These findings suggest that neuromuscular re-education should be prioritized over conventional strengthening in rehabilitation protocols for geriatric knee osteoarthritis, particularly for individuals at elevated fall risk. NMR's multi-system benefits—encompassing sensorimotor enhancement, pain reduction, and fall risk mitigation—align with comprehensive geriatric rehabilitation principles emphasizing functional independence and quality of life preservation [25].

However, integration of NMR and conventional strengthening elements may represent an optimal approach, combining NMR's proprioceptive benefits with strength training's muscular benefits.

Limitations

Study limitations include: (1) single-center recruitment potentially limiting generalizability; (2) relatively small sample size necessitating cautious interpretation; (3) follow-up limited to 12 weeks, precluding assessment of long-term sustainability; (4) absence of stratification by osteoarthritis severity; (5) potential Hawthorne effect from supervised intervention contexts; and (6) non-inclusion of control group without intervention.

Conclusion

This randomized controlled trial demonstrates that neuromuscular re-education produces superior effectiveness compared to conventional strengthening across sensorimotor control, dynamic knee stability, pain modulation, and fall risk reduction in geriatric patients with knee osteoarthritis. While conventional strengthening remains effective, sensorimotor training targeting proprioceptive enhancement and functional joint stabilization should be prioritized in rehabilitation protocols for this vulnerable population. Future research should examine optimal integration of neuromuscular and strengthening elements, investigate long-term maintenance of benefits, and assess cost-effectiveness in diverse healthcare contexts.

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