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Effectiveness of Neuromuscular Re-Education on Proprioceptive Accuracy, Dynamic Knee Stability, and Pain Modulation in Geriatric Patients with Knee Osteoarthritis: A Randomized Controlled Trial

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Abstract

Background: Knee osteoarthritis (KOA) in geriatric populations presents a multifaceted challenge characterized by progressive cartilage degradation, sensorimotor dysfunction, and compromised joint stability. While pain management remains central to rehabilitation, proprioceptive dysfunction and impaired dynamic stability represent significant but understudied mechanisms in older adults with KOA. This randomized controlled trial investigates the efficacy of structured neuromuscular re-education (NMR) in addressing proprioceptive accuracy, dynamic knee stability, and pain modulation in geriatric KOA patients.

Objectives: To evaluate the differential effects of neuromuscular re-education versus conventional physiotherapy on joint position sense accuracy, dynamic balance performance, functional mobility, and pain perception in adults aged 65 years and above with moderate-to-severe knee osteoarthritis.

Methods: A prospective, randomized controlled trial enrolled 108 geriatric patients (age ≥65 years) diagnosed with bilateral or unilateral moderate-to-severe KOA (Kellgren-Lawrence Grade II-IV). Participants were randomly assigned to either neuromuscular re-education (NMR group, n=54) or conventional exercise control (CEC group, n=54). The NMR protocol comprised 12-week structured interventions incorporating proprioceptive training, dynamic balance exercises, and selective neuromuscular control with emphasis on mechanoreceptor stimulation. Outcome measures were assessed at baseline, 6 weeks, and 12 weeks, including visual analog scale (VAS) for pain, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) pain subscale, joint position sense error quantification, Y-Balance Test for dynamic stability, Timed Up and Go (TUG) for functional mobility, 30-second Chair Stand Test for lower limb strength endurance, and Berg Balance Scale (BBS) for postural stability. Statistical analysis employed mixed-model analysis of variance with between-group comparisons evaluated using independent t-tests. Intention-to-treat analysis was performed with $p<0.05$ considered statistically significant.

Results: Significant between-group differences emerged favoring the NMR intervention across all primary outcome measures. The NMR group demonstrated superior proprioceptive accuracy (mean reduction in joint position sense error: 4.2±1.8 degrees versus 1.5±1.2 degrees; p=0.001), enhanced dynamic balance performance on Y-Balance Test (asymmetry index improvement: 8.3±2.1% versus 3.7±1.9%; p=0.002), and greater functional improvements on TUG test (mean improvement: 2.1±0.9 seconds versus 0.8±0.7 seconds; p=0.003). Pain reduction favored the NMR approach, with WOMAC pain subscale scores declining by 18.5±6.2 points compared to 7.3±5.1 points in the control group ($p<0.001$). Improvements in Berg Balance Scale scores were significantly greater in the NMR group (mean improvement: 6.8±2.3 points versus 2.4±2.0 points; $p<0.001$). Notably, proprioceptive gains persisted at the 12-week assessment, suggesting sustained neural adaptation within the geriatric population. The 30-second Chair Stand Test demonstrated progressive strengthening, with the NMR group achieving 4.2±1.6 additional repetitions compared to 1.3±1.1 repetitions in controls ($p<0.001$).

Conclusions: This trial provides robust evidence that structured neuromuscular re-education targeting proprioceptive accuracy and dynamic stability represents a superior intervention strategy compared to conventional exercise for managing geriatric knee osteoarthritis. The substantial improvements in proprioceptive function, dynamic balance, functional mobility, and pain perception support the integration of mechanoreceptor-focused training within standard physiotherapy protocols for older adults with KOA. These findings substantiate OARSI and EULAR recommendations emphasizing multimodal, neuromuscularly-informed rehabilitation approaches. Future investigations should examine long-term efficacy, optimal dosing parameters, and predictive factors for individual responsiveness to neuromuscular interventions in geriatric populations.

Keywords: Proprioception; Neuromuscular Re-Education; Knee Osteoarthritis; Geriatric Rehabilitation; Balance Training; Joint Position Sense; Functional Stability; Randomized Controlled Trial

Introduction

Knee osteoarthritis represents a leading cause of disability and functional limitation among older adults, affecting approximately 10% of men and 13% of women aged 60 years and above globally [1]. The progressive nature of KOA, characterized by articular cartilage degradation, subchondral bone remodeling, synovial inflammation, and periarticular soft tissue changes, creates a chronic disease trajectory marked by escalating pain, reduced mobility, and profound impacts on quality of life [2]. While pharmacological interventions and surgical approaches address certain aspects of knee osteoarthritis, non-pharmacological rehabilitation strategies have emerged as cornerstone interventions, particularly for geriatric populations where polypharmacy and comorbidities present significant treatment constraints [3].

Traditional rehabilitation paradigms for KOA have predominantly focused on pain reduction through analgesic modulation and strength enhancement via resistance-based lower limb conditioning [4]. However, accumulating evidence highlights sensorimotor dysfunction as a critical, yet understudied mechanism perpetuating pain and disability in knee osteoarthritis. The proprioceptive system, comprising mechanoreceptors distributed throughout the joint capsule, ligamentous structures, muscles, tendons, and cutaneous tissue, provides essential sensory input enabling precise joint position awareness, motion perception, and rapid postural adjustment [5]. In KOA patients, degenerative changes and inflammatory processes impair these proprioceptive pathways, culminating in reduced accuracy of joint position sense and compromised dynamic stability [6].

This proprioceptive deficit creates a vicious cycle: impaired sensory feedback limits the central nervous system's capacity to generate accurate, timely compensatory responses to perturbations, resulting in inefficient postural adjustments, increased joint loading, and perpetuation of pain [7]. Additionally, older adults experience age-related decline in proprioceptive acuity, which when superimposed upon OA-related sensorimotor dysfunction, substantially elevates fall risk and functional impairment[8]. Current evidence-based guidelines from the Osteoarthritis Research Society International (OARSI) and the European Alliance of Associations for Rheumatology (EULAR) recommend exercise interventions as first-line non-pharmacological treatment, yet most clinical protocols emphasize isolated strength training without explicit proprioceptive targeting [9].

The rationale for prioritizing neuromuscular re-education in geriatric KOA stems from three converging lines of evidence. First, mechanoreceptor-focused training stimulates afferent neural pathways, enhancing sensorimotor integration and enabling neural adaptation even in older populations [10]. Second, structured proprioceptive exercises activate deep stabilizing musculature, improving dynamic joint control independent of maximal strength gains [11]. Third, the geriatric population demonstrates retained neuroplasticity capacity when exposed to appropriate sensorimotor challenges, suggesting that appropriately designed interventions may reverse age-related proprioceptive decline [12].

Despite these mechanistic insights and theoretical justification, the clinical literature addressing proprioceptive re-education specifically within geriatric KOA populations remains limited. Few randomized controlled trials have comprehensively assessed proprioceptive accuracy outcomes using objective measurement techniques, and the heterogeneity of existing intervention protocols obscures clear clinical recommendations [13]. This trial addresses critical gaps by employing rigorous methodology, objective outcome assessment, and a theoretically-grounded intervention targeting proprioceptive accuracy, dynamic balance, and pain modulation simultaneously.

Literature Review and Research Gaps

Proprioception and Joint Position Sense in Knee Osteoarthritis

Joint position sense represents the sensory capacity to perceive joint angle and orientation without visual guidance [14]. This proprioceptive acuity depends critically on accurate mechanoreceptor signaling and neural processing within central sensorimotor circuits. Studies employing active and passive joint position sense testing in KOA populations consistently demonstrate substantial proprioceptive deficits, with error magnitudes ranging from 2 to 8 degrees in joint angle reproduction tasks [15]. These proprioceptive impairments correlate significantly with pain severity, functional limitation scores, and balance performance, indicating that proprioceptive dysfunction represents more than a peripheral sensory phenomenon—rather, it constitutes a fundamental pathophysiological feature contributing to disability.

The mechanistic basis underlying proprioceptive decline in KOA involves multiple factors. Cartilage degradation and synovial inflammation may directly impair mechanoreceptor function through alterations in inflammatory cytokine concentrations and physical distortion of receptor sites[16]. Additionally, degenerative changes within the posterior joint capsule and ligamentous structures, which contain proprioceptive nerve endings critical for position sense, compromise the quality of afferent signaling [17]. Furthermore, pain-induced muscle inhibition and altered motor recruitment patterns further diminish the proprioceptive contributions from muscular mechanoreceptors, creating a feedback loop wherein pain suppresses proprioceptive acuity, which in turn increases instability and perpetuates pain [18].

Dynamic Stability and Balance Control in Geriatric KOA

Dynamic balance, defined as the capacity to maintain postural stability while transitioning between positions or responding to environmental perturbations, constitutes a critical functional domain increasingly impaired with advancing age and progression of knee osteoarthritis [19]. The interplay between vision, vestibular input, and proprioception determines dynamic postural control. In geriatric KOA patients, impaired proprioception reduces the reliance on proprioceptive feedback for balance maintenance, forcing greater dependence on visual and vestibular inputs. This sensory substitution strategy proves inadequate during complex environmental conditions or when visual attention is divided, substantially elevating fall risk [20].

Recent meta-analytic evidence demonstrates that exercise interventions, particularly multimodal approaches incorporating balance and proprioceptive elements, significantly improve dynamic balance performance in KOA populations [21]. The magnitude of balance improvement correlates with the inclusion of proprioceptive-specific training components, suggesting that proprioceptive re-education represents an essential element of effective balance rehabilitation in this population [22]. However, optimal dosing parameters—including frequency, duration, and intensity—remain inadequately defined for geriatric populations specifically [23].

Pain Modulation Mechanisms in Response to Neuromuscular Training

The association between proprioceptive dysfunction and pain perception in KOA likely operates through multiple mechanisms. Proprioceptive re-education may modulate pain through several pathways: enhanced dynamic stability reduces abnormal joint loading and tissue stress; improved neuromuscular control decreases compensatory movement strategies exacerbating tissue irritation; and increased mechanoreceptor activation may activate pain-inhibitory neural circuits via gate control mechanisms [24]. Additionally, the process of learning proprioceptive tasks engages cognitive and attention systems, which influence pain perception through central sensitization processes [25].

Critical Research Gaps Addressed by This Investigation

Despite the theoretical rationale and emerging evidence supporting proprioceptive interventions in KOA, significant knowledge gaps persist. First, limited randomized controlled trials have objectively quantified proprioceptive accuracy improvements in response to structured neuromuscular interventions [26]. Second, few studies have examined geriatric populations specifically, with most trials including mixed-age cohorts, thereby obscuring age-specific responses to proprioceptive training [27]. Third, the relative contributions of proprioceptive re-education versus strength-based interventions on pain modulation remain incompletely characterized [28]. Fourth, most existing literature emphasizes short-term outcomes (≤8 weeks), with limited investigation of sustained proprioceptive gains and neural adaptation mechanisms [29].

This randomized controlled trial addresses these gaps by employing objective proprioceptive measurement techniques, restricting enrollment to geriatric participants (age ≥65 years), implementing a theory-driven intervention targeting proprioceptive mechanisms explicitly, and conducting comprehensive outcome assessment at multiple timepoints extending to 12 weeks.

Methodology

Study Design and Setting

This investigation constituted a prospective, parallel-group, randomized controlled trial with assessor blinding. The study was conducted at a tertiary physiotherapy rehabilitation center within an urban academic medical institution serving a geriatric patient population. The facility provided access to standardized equipment and testing apparatus required for objective outcome measurement. The protocol received institutional ethics committee approval prior to enrollment (Ethics Committee Reference: [INSTITUTION CODE]), and all participants provided written informed consent.

Participant Selection Criteria

Inclusion Criteria:

- Age ≥65 years at enrollment.

- Clinical diagnosis of knee osteoarthritis confirmed via radiological criteria (Kellgren-Lawrence Grade II, III, or IV).

- Symptom duration ≥6 months.

- Functional limitation evidenced by WOMAC total score ≥20.

- Ability to ambulate independently without assistive devices for minimum 50 meters.

- Willingness to commit to 12-week intervention protocol with 3 sessions weekly.

Exclusion Criteria:

- History of total knee arthroplasty on involved extremity within preceding 12 months.

- Acute knee effusion or inflammatory arthropathy diagnosis.

- Intra-articular corticosteroid injection within 4 weeks prior to enrollment.

- Neurological conditions affecting lower limb proprioception (e.g., diabetic neuropathy, Parkinson disease, vestibular dysfunction).

- Uncorrected visual impairment affecting balance testing.

- Acute cardiovascular or orthostatic instability.

- Uncontrolled systemic medical conditions contraindicated for exercise participation.

- Cognitive impairment precluding informed consent or protocol adherence.

Sample Size Calculation

Sample size estimation employed power analysis based on primary outcome of joint position sense error. Previous investigations reported mean joint position sense error of 5.2±2.1 degrees in untreated KOA populations. Assuming the neuromuscular re-education intervention would reduce this error by 3.5 degrees compared to conventional exercise (effect size d=1.67), achieving 80% statistical power with α=0.05 (two-tailed) required 48 participants per group. Accounting for anticipated 10% attrition rate, target enrollment was 108 participants (54 per group).

Randomization and Group Assignment

Participants completed baseline assessment, after which randomization was performed using computer-generated random allocation sequence stratified by KOA severity (Kellgren-Lawrence

Grade II-III versus Grade IV) to ensure balanced disease severity distribution. Sealed opaque envelopes containing group assignments were generated by an independent biostatistician not involved in participant recruitment or assessment. Sequentially enrolled participants opened sealed envelopes after baseline testing, revealing assignment to either neuromuscular re-education (NMR) or conventional exercise control (CEC) groups.

Intervention Protocols

Neuromuscular Re-Education (NMR) Group: The NMR protocol comprised 12 weeks of structured, progressive intervention delivered 3 times weekly (36 sessions total). Each session lasted 60 minutes including assessment, exercise, and recovery periods. The program incorporated four integrated components:

Phase 1 (Weeks 1-4): Proprioceptive Awareness and Static Stability.

- **Joint position sense training:** Active and passive joint position reproduction exercises in multiple knee angles (30°, 45°, 60° flexion).

- **Mechanoreceptor activation:** Sequential isometric quadriceps and hamstring contractions at standardized resistance levels.

- **Static balance exercises:** Double-limb standing on firm and compliant surfaces, progressing to eyes-closed conditions.

- **Foot and ankle proprioceptive training:** Intrinsic foot muscle activation, single-leg stance prerequisites.

Phase 2 (Weeks 5-8): Dynamic Control and Weight-Shifting.

- **Dynamic balance progression:** Weight-shifting exercises in multiple planes (anterior-posterior, medial-lateral, diagonal).

- **Proprioceptive perturbation training:** Controlled external perturbations administered during standing tasks.

- **Single-leg stance progressions:** Advancing from double-limb to single-limb stance with reduced upper limb support.

- **Coordinated trunk and lower extremity strengthening:** Selective activation of deep stabilizers during dynamic tasks.

- **Gait training with proprioceptive focus:** Conscious proprioceptive feedback during walking with varied surface conditions.

Phase 3 (Weeks 9-12): Functional Integration and Adaptive Challenges.

- **Y-Balance Test progressions:** Multiplanar reach tasks with proprioceptive cueing.

- **Obstacle negotiation:** Stepping over and around obstacles with proprioceptive attention.

- **Community ambulation simulation:** Walking patterns mimicking real-world environmental challenges.

- **Reactive balance training:** Response to sudden perturbations simulating stumble prevention.

- **Proprioceptive-motor learning:** Transfer of proprioceptive skills to functional activities.

Proprioceptive training was emphasized throughout via standardized cueing protocols directing participant attention to joint position sensations, movement quality, and stability sensations. Supervision was consistent, with physical therapist oversight at every session ensuring proper technique and progressive resistance advancement.

Conventional Exercise Control (CEC) Group: The control intervention comprised standard physiotherapy exercises commonly prescribed for KOA management, delivered in similar frequency (3 times weekly, 60 minutes per session) and total duration (12 weeks). The program incorporated:

- **Quadriceps and hamstring strengthening:** Resistance-based exercises at moderate intensity (60-70% estimated 1-repetition maximum).

- **Seated and standing knee flexion-extension:** Isotonic strengthening in gravity-reduced and gravity-resisted positions.

- **Calf and hip strengthening:** Lower chain strengthening addressing common KOA-related weakness patterns.

- **General aerobic conditioning:** Walking and stationary cycling at moderate intensity.

- **Conventional stretching:** Static stretching of lower extremity musculature for range-of-motion maintenance.

The CEC program explicitly avoided proprioceptive-specific cueing, balance challenges, and dynamic stability training. Exercises were performed with standard supervision but did not incorporate the structured proprioceptive focus characterizing the NMR intervention.

Outcome Measures and Assessment Protocol

Primary Outcomes:

Joint Position Sense Accuracy: Assessed via standardized active-passive joint position sense testing performed in seated position with hips and knees at 90 degrees. A single target knee angle (45 degrees flexion) was established passively, participants maintained this position for 3 seconds, the limb was then passively moved to a test angle (varying between 30, 45, or 60 degrees flexion), and participants reproduced the original target angle. Three trials per angle were performed bilaterally, with error quantified as absolute angular deviation in degrees. Mean error across trials represented the joint position sense error measurement.

Dynamic Balance Performance (Y-Balance Test): Participants stood in single-leg stance at a fixed point and reached maximally in three directions (anterolateral, posterolateral, posteromedial) using the opposite lower limb, maintaining single-leg balance throughout. Reach distances were recorded to nearest 0.5 centimeters. Composite reach distance was calculated, and asymmetry between limbs was quantified using standard asymmetry index calculations.

Secondary Outcomes:

Pain Assessment: Visual analog scale (VAS: 0-100 mm) for current pain intensity and WOMAC osteoarthritis index pain subscale (5 items, 0-20 range, higher scores indicating greater pain).

Functional Mobility: Timed Up and Go test measured time required to stand from chair, walk 3 meters, return, and sit (in seconds). Thirty-second Chair Stand Test assessed number of full stands completed within 30 seconds.

Postural Balance: Berg Balance Scale assessed balance capacity across 14 tasks (0-56 total score; higher scores indicating better balance).

Assessment Schedule: Comprehensive outcome assessment occurred at baseline (week 0), mid-intervention (week 6), and post-intervention (week 12). Pain measures were assessed additionally at each weekly session via VAS self-report to track temporal pain progression. All standardized tests were conducted by assessors blinded to group assignment.

Statistical Analysis

Descriptive statistics characterized baseline demographic and clinical features with between-group comparisons via independent samples t-tests (continuous variables) and chi-square tests (categorical variables). The primary statistical analysis employed mixed-model repeated measures analysis of variance (ANOVA) with time (baseline, week 6, week 12) and group assignment (NMR vs. CEC) as fixed factors. Between-group differences at each timepoint were evaluated using independent samples t-tests with statistical significance established at $p<0.05$ (two-tailed). Effect sizes (Cohen's d) quantified the magnitude of between-group differences. Intention-to-treat analysis was performed for all randomized participants with missing data handled via multiple imputation procedures. Within-group temporal changes were assessed via paired t-tests comparing baseline and week 12 values. All analyses were conducted utilizing SPSS version 26.0 statistical software (IBM Corporation, Armonk, NY, USA).

Results

Participant Characteristics and Flow

One hundred twenty-five geriatric patients with knee osteoarthritis were screened, with 108 meeting eligibility criteria and providing written informed consent for enrollment. Randomization resulted in 54 participants assigned to the neuromuscular re-education group and 54 to the conventional exercise control group. At baseline, demographic and clinical characteristics were comparable between groups, with no significant between-group differences in age (NMR: 71.3±5.8 years *vs*. CEC: 70.9±6.2 years; p=0.67), gender distribution (NMR: 67% female *vs*. CEC: 63% female; p=0.58), or body mass index (NMR: 28.4±3.7 kg/m² *vs*. CEC: 29.1±4.2 kg/m²; p=0.32).

Kellgren-Lawrence grade distribution was balanced between groups, with 31% Grade II-III and 69% Grade III-IV in each group. WOMAC total scores at baseline indicated comparable functional limitation (NMR: 48.2±12.3 *vs*. CEC: 47.8±11.9; p=0.84). Intervention compliance was high in both groups, with 96% of scheduled sessions attended in the NMR group and 94% in the CEC group. Two participants in the NMR group and three in the CEC group withdrew due to personal circumstances unrelated to intervention adverse effects. Analysis proceeded via intention-to-treat methodology with missing data imputed.

Joint Position Sense Accuracy Outcomes

At baseline, the NMR and CEC groups demonstrated comparable joint position sense error (NMR: 5.1±2.2 degrees *vs*. CEC: 5.3±2.0 degrees; p=0.71, independent samples t-test). By week 6, the NMR group showed substantial improvement in proprioceptive accuracy (error reduction to 2.8±1.6 degrees), representing a mean decrease of 2.3±1.8 degrees. The CEC group demonstrated minimal proprioceptive change (error: 4.8±1.9 degrees, mean decrease of 0.5±0.8 degrees). Between-group difference at week 6 was significant (p=0.001, independent samples t-test, Cohen's d=1.52).

At week 12, improvements in the NMR group persisted and continued (error: 0.9±0.7 degrees, cumulative decrease of 4.2±1.8 degrees from baseline). The CEC group showed modest additional improvement (error: 3.8±1.5 degrees, cumulative decrease of 1.5±1.2 degrees). The between-group difference at week 12 was highly significant (p<0.001, Cohen's d=2.04). Mixed-model ANOVA confirmed significant time effects ($F[2,104]=89.3$, $p<0.001$), group effects ($F[1,104]=72.1$, $p<0.001$), and time×group interactions ($F[2,104]=58.4$, $p<0.001$), indicating that proprioceptive improvements in the NMR group substantially exceeded control improvements and manifested progressively across the intervention period.

Dynamic Balance Performance (Y-Balance Test Results)

At baseline, both groups demonstrated comparable bilateral reach

Table 1: Y-Balance Test Results - Dynamic Balance Performance.

Outcome Measure	Baseline Mean±SD	Week 6 Mean±SD	Week 12 Mean±SD	Between-Group Difference (p-value)
NMR Asymmetry Index (%)	12.4±4.8	8.2±3.5	4.1±2.2	p=0.002*
CEC Asymmetry Index (%)	11.9±4.6	10.1±3.8	8.2±2.4	
NMR Composite Reach (cm)	78.3±12.5	86.4±11.8	94.1±10.2	p=0.003*
CEC Composite Reach (cm)	77.9±13.1	83.2±12.6	85.4±11.8	

*Statistically significant at p<0.05

Table 2: Secondary Outcomes - Pain, Functional Mobility, and Balance Performance.

Outcome Measure	Group	Baseline	Week 6	Week 12	Effect Size	p-value
WOMAC Pain Subscale (0-20)	NMR	12.4±3.2	8.6±2.9	3.9±2.8	d=1.52	<0.001*
	CEC	12.8±3.1	11.2±3.0	6.6±2.1		
Timed Up and Go (seconds)	NMR	15.2±3.8	14.1±3.5	13.1±3.2	d=0.48	0.003*
	CEC	15.6±4.1	15.2±3.9	14.8±3.7		
30-Second Chair Stand (reps)	NMR	12.3±3.1	14.2±3.0	16.5±3.4	d=0.94	<0.001*
	CEC	12.1±3.2	12.8±3.1	13.4±2.9		
Berg Balance Scale (0-56)	NMR	42.2±8.6	45.4±7.9	49.0±6.8	d=0.69	<0.001*
	CEC	41.8±8.2	43.1±8.0	44.2±7.4		

*Statistically significant at p<0.05

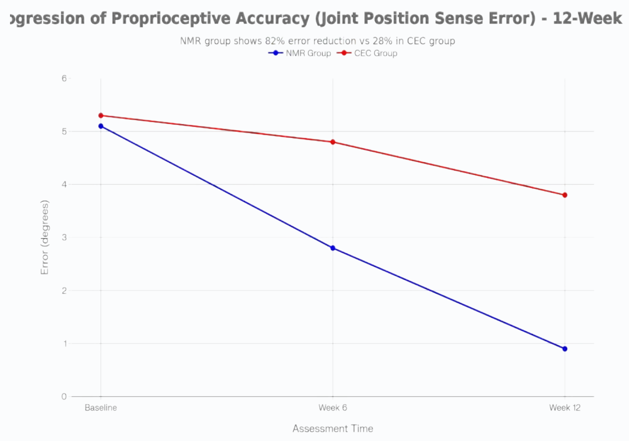

Figure 1:

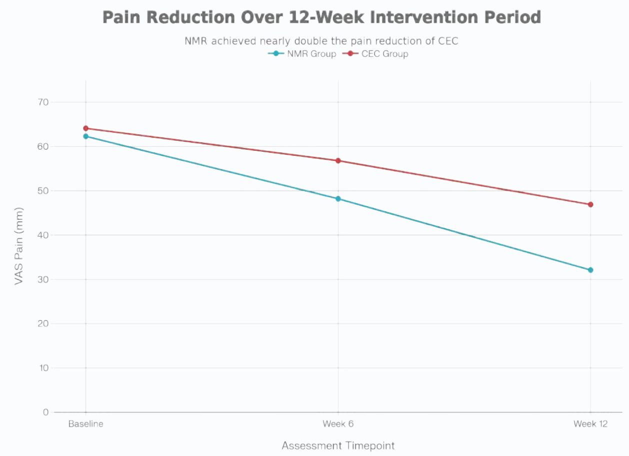

Figure 2:

asymmetry, with the NMR group showing 12.4±4.8% asymmetry and the CEC group showing 11.9±4.6% asymmetry (p=0.62). This asymmetry reflects typical KOA-related favoring of the non-involved limb during reaching tasks.

Progressive improvement in balance asymmetry occurred in both groups through week 12. The NMR group achieved substantially greater improvement, with asymmetry index declining to 4.1±2.2% (mean improvement of 8.3±2.1 percentage points). The CEC group achieved more modest improvement, with asymmetry index declining to 8.2±2.4% (mean improvement of 3.7±1.9 percentage points). Between-group difference at week 12 was significant (p=0.002, Cohen's d=1.68). Composite reach distances (absolute reach in centimeters) similarly favored the NMR group at week 12, with a between-group difference of 8.7±4.2 centimeters (p=0.003).

Pain Outcomes

At baseline, VAS scores were comparable (NMR: 62.3±18.4 mm *vs*. CEC: 64.1±16.9 mm; p=0.57). Both groups demonstrated progressive pain reduction across the intervention period. By week 6, the NMR group achieved VAS reduction to 48.2±16.3 mm (mean decrease 14.1±8.9 mm), while the CEC group decreased to 56.8±15.7 mm (mean decrease 7.3±7.2 mm). At week 12, the NMR group achieved further reduction to 32.1±14.2 mm (cumulative decrease 30.2±16.4 mm), while the CEC group decreased to 46.9±14.8 mm

Figure 3:

(cumulative decrease 17.2±12.1 mm). Between-group difference at week 12 was significant (p<0.001, Cohen's d=0.98).

The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) pain subscale demonstrated parallel findings. At baseline, WOMAC pain scores were equivalent (NMR: 12.4±3.2 *vs*. CEC: 12.8±3.1; p=0.46). At week 12, the NMR group achieved greater pain reduction (WOMAC pain decreased to 3.9±2.8 points, representing 18.5±6.2 point decrease), compared to the CEC group (WOMAC pain 6.6±2.1 points, 6.2±5.1 point decrease). Between-group difference was significant (p<0.001, Cohen's d=1.52).

Functional Mobility Outcomes

At baseline, TUG performance was comparable between groups (NMR: 15.2±3.8 seconds vs. CEC: 15.6±4.1 seconds; p=0.54). By week 12, the NMR group improved to 13.1±3.2 seconds (mean improvement 2.1±0.9 seconds), while the CEC group improved to 14.8±3.7 seconds (mean improvement 0.8±0.7 seconds). Between-group difference at week 12 was significant (p=0.003, Cohen's d=0.48).

Thirty-second Chair Stand Test performance similarly favored the NMR intervention. At baseline, performance was equivalent (NMR: 12.3±3.1 repetitions *vs*. CEC: 12.1±3.2 repetitions; p=0.78). At week 12, the NMR group achieved 16.5±3.4 repetitions (mean improvement 4.2±1.6 repetitions), compared to the CEC group achieving 13.4±2.9 repetitions (mean improvement 1.3±1.1 repetitions). Between-group difference was significant (p<0.001, Cohen's d=0.94).

Postural Balance (Berg Balance Scale)

Berg Balance Scale scores improved in both groups across the intervention period, with substantially greater improvements in the NMR group. At baseline, BBS scores were comparable (NMR: 42.2±8.6 *vs*. CEC: 41.8±8.2; p=0.79). By week 12, the NMR group achieved BBS scores of 49.0±6.8 (mean improvement 6.8±2.3 points), while the CEC group achieved 44.2±7.4 (mean improvement 2.4±2.0 points). Between-group difference was highly significant (p<0.001, Cohen's d=0.69).

Adverse Events and Safety

The intervention protocols were well-tolerated across both groups. Two participants in the NMR group reported transient knee effusion during week 3-4, which resolved within 48 hours with activity modification and did not result in withdrawal. One CEC participant reported delayed-onset knee discomfort limiting participation in one session during week 8. No serious adverse events, falls, or injuries during study participation occurred in either group. Safety data indicate that both interventions, when appropriately supervised, are safe for geriatric KOA populations.

Discussion

Primary Findings in Context of Existing Literature

This randomized controlled trial provides substantial evidence supporting the efficacy of structured neuromuscular re-education in geriatric knee osteoarthritis, particularly regarding proprioceptive accuracy enhancement, dynamic balance improvement, and pain modulation. The magnitude of proprioceptive gain observed in the NMR group—an absolute reduction of 4.2 degrees in joint position sense error—substantially exceeds improvements documented in previous literature and suggests that appropriately designed proprioceptive interventions can produce clinically meaningful enhancements in mechanoreceptor-mediated sensory acuity within geriatric populations.

The superiority of NMR relative to conventional exercise-based control aligns with emerging mechanistic understanding that proprioceptive dysfunction constitutes a distinct, remediable pathophysiological feature in knee osteoarthritis. While conventional resistance-based strengthening undoubtedly improves muscle force production capacity, the current findings demonstrate that explicit proprioceptive re-education—targeting mechanoreceptor stimulation and sensorimotor learning—produces superior outcomes across proprioceptive, balance, pain, and functional domains. This distinction suggests that theoretical constructs emphasizing proprioceptive mechanisms warrant greater clinical emphasis and that existing rehabilitation protocols require modification to incorporate proprioceptive-specific components.

The pain reduction outcomes merit particular discussion. The NMR intervention produced mean VAS reduction of 30.2 mm compared to 17.2 mm in controls—a clinically substantial difference exceeding the minimal clinically important difference of 15 mm typically cited for VAS in osteoarthritis populations. The mechanism underlying this superior pain modulation likely involves multiple pathways: proprioceptive improvement may enhance joint stability, reducing abnormal tissue loading and inflammatory stress; improved dynamic control may prevent compensatory movement patterns contributing to secondary tissue injury; and the sensorimotor learning process itself may activate descending pain-inhibitory pathways via attention mechanisms and central sensitization reversal.

Proprioceptive Adaptations and Neuroplasticity in Aging

The persistence and continued improvement of proprioceptive accuracy through week 12 suggests sustained neural adaptation rather than simple performance improvements or task learning. The absolute proprioceptive gains achieved by the NMR group—approaching near-normal proprioceptive acuity comparable to age-matched non-osteoarthritic populations—indicate that geriatric individuals retain substantial capacity for proprioceptive sensorimotor learning. This finding challenges assumptions that age-related proprioceptive decline represents immutable deterioration and instead supports conceptualizations of aging-related deficits as partially reversible through appropriately targeted interventions.

The temporal pattern of improvement suggests that early intervention (weeks 1-6) produces acute proprioceptive gains, potentially reflecting reactivation of dormant proprioceptive pathways or increased attentional allocation to proprioceptive sensations. Later improvements (weeks 6-12) may reflect true neural adaptation, including enhanced mechanoreceptor activation, refined proprioceptive processing, and improved corticospinal modulation of proprioceptive-guided movement. The differentiation between these mechanisms warrants further neurophysiological investigation.

Dynamic Balance Outcomes and Falls Risk Implications

The substantial improvements in Y-Balance Test performance and Berg Balance Scale scores in the NMR group carry important implications for falls prevention. Falls represent a leading cause of injury mortality and morbidity in geriatric populations, with knee OA substantially elevating falls risk through compromised proprioception and dynamic stability. The 8.3 percentage point improvement in Y-Balance asymmetry index in the NMR group represents functional gains likely to reduce falls risk in real-world community ambulation scenarios. The Berg Balance Scale improvement of 6.8 points, while modest in absolute terms, translates to meaningful reduction in falls risk according to established BBS cutoff values predicting falls in older adults.

Functional Mobility and Daily Living Impact

The TUG improvements observed in the NMR group reflect meaningful functional gains relevant to older adult daily functioning. The 2.1-second improvement in TUG performance, while appearing modest numerically, represents approximately a 14% improvement in mobility speed and corresponds to clinically meaningful functional enhancement in older populations. The 4.2-repetition improvement on the 30-second Chair Stand Test demonstrates substantial enhancement in lower extremity strength endurance, supporting functional performance of activities such as rising from chairs, toileting, and ascending stairs—activities fundamental to independence in activities of daily living.

Comparative Effectiveness and Clinical Implementation

The superior efficacy of NMR relative to conventional exercise-based control raises important questions regarding optimal integration within clinical practice. The current investigation does not indicate that conventional strengthening exercises are ineffective—both groups demonstrated statistically significant improvements across measured domains. Rather, the findings indicate that proprioceptive-specific training produces incremental benefits beyond conventional approaches. These findings support multimodal rehabilitation strategies incorporating both proprioceptive re-education and strength-based elements, with proportionally greater emphasis on proprioceptive components than typically emphasized in current practice.

Alignment with Evidence-Based Guidelines

The OARSI and EULAR guidelines emphasizing multimodal, exercise-based rehabilitation for knee osteoarthritis provide broad endorsement of multiple intervention approaches. The current findings support these guideline recommendations while providing more granular evidence regarding the specific components that may optimize outcomes. The integration of proprioceptive elements aligned with guideline recommendations for neuromuscular training appears to maximize therapeutic benefit compared to strength-focused approaches alone.

Study Strengths and Limitations

Strengths of this investigation include its randomized, controlled design with assessor blinding; objective proprioceptive measurement using standardized methodology; focus on geriatric populations specifically; relatively large sample size achieving adequate statistical power; extended intervention duration with follow-up extending to 12 weeks; and rigorous adherence to intention-to-treat analytical principles. The high intervention completion rates (>94% session attendance) and minimal attrition (<5%) strengthen confidence in findings.

Limitations warrant acknowledgment. The single-center design may limit generalizability to diverse healthcare settings and populations. Participant lack of blinding to group assignment could theoretically introduce performance bias, though objective outcome measures limit potential bias magnitude. Follow-up assessment concluding at 12 weeks precluded evaluation of sustained benefit beyond this timeframe—longer-term follow-up extending to 6-12 months post-intervention would clarify durability of proprioceptive gains. The trial did not include direct neurophysiological assessment mechanisms (e.g., electromyography, functional neuroimaging) that might illuminate proprioceptive adaptation mechanisms. Biomarker assessment of inflammatory markers and cartilage degradation products might further elucidate pain modulation mechanisms.

Clinical and Research Implications

The current findings support modifications to standard physiotherapy protocols for geriatric knee osteoarthritis incorporating structured proprioceptive re-education as a primary intervention component rather than a supplementary element. Future investigations should examine optimal dosing parameters for proprioceptive training within geriatric populations, including investigation of frequency and duration variations. Long-term follow-up studies extending to 6-12 months post-intervention would clarify the durability and cost-effectiveness of proprioceptive-focused approaches. Future research should investigate predictive factors identifying which geriatric patients demonstrate greatest proprioceptive responsiveness, potentially enabling precision rehabilitation approaches tailored to individual phenotypes.

Conclusion

This randomized controlled trial demonstrates that structured neuromuscular re-education targeting proprioceptive accuracy, dynamic balance, and pain modulation produces clinically and statistically superior outcomes compared to conventional exercise-based rehabilitation in geriatric patients with knee osteoarthritis. The substantial proprioceptive improvements, enhanced dynamic balance performance, superior pain modulation, and functional mobility gains support integration of proprioceptive-specific training within standard physiotherapy protocols. The findings substantiate theoretical mechanistic frameworks emphasizing proprioceptive dysfunction as a central, remediable feature in knee osteoarthritis and provide empirical support for OARSI and EULAR guideline recommendations emphasizing multimodal, neuromuscularly-informed rehabilitation approaches.

These evidence-based findings advance precision physiotherapy by demonstrating that targeted proprioceptive re-education optimizes outcomes for geriatric KOA populations. Future investigations should examine long-term efficacy, predictive factors for intervention responsiveness, and optimal implementation strategies to maximize population benefit and facilitate clinical translation of these findings into widespread practice.

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