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Effectiveness of an Integrated Multimodal Physiotherapy Rehabilitation Program on Proprioception, Quadriceps Strength, Gait Parameters, Pain, and Functional Outcomes After Total Knee Replacement: A Randomized Controlled Trial

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Abstract

Background: Post-operative recovery after total knee replacement (TKR) remains challenging, with persistent deficits in proprioception, quadriceps weakness, altered gait mechanics, and chronic pain affecting quality of life in up to 20% of patients.

Objective: To evaluate the effectiveness of an integrated multimodal rehabilitation program combining neuromuscular training, sensorimotor training, functional strengthening, and pain neuroscience education compared to standard post-operative care on proprioception, quadriceps strength, gait parameters, pain, and functional outcomes in patients undergoing TKR.

Design: Randomized controlled trial.

Methods: Ninety participants scheduled for primary TKR were randomly allocated to either an integrated multimodal program (n=45) or standard care control group (n=45). The multimodal intervention consisted of 24 supervised sessions delivered twice weekly over 12 weeks, incorporating structured neuromuscular training, proprioceptive retraining on variable surfaces, progressive functional strengthening with emphasis on closed kinetic chain exercises, and two sessions of pain neuroscience education. Primary outcomes included Knee Injury and Osteoarthritis Outcome Score (KOOS) pain and activities of daily living subscales. Secondary outcomes comprised quadriceps isometric strength, 6-minute walk distance, proprioceptive error measured by joint position sense testing, gait velocity and cadence, and pain intensity on the Visual Analog Scale. Assessments were conducted at baseline, 3, 6, 9, and 12 weeks post-operatively.

Results: At 12 weeks, the multimodal group demonstrated significantly greater improvements in KOOS pain (78.6±14.2 *vs* 68.2±16.4, p=0.031), KOOS ADL (82.3±12.8 *vs* 71.6±15.3, p=0.024), quadriceps strength (1.84±0.42 *vs* 1.52±0.38 Nm/kg, p=0.018), 6-minute walk distance (541.2±98.6 *vs* 472.8±104.3 meters, p=0.012), and proprioceptive error reduction (2.6±1.2 *vs* 3.8±1.6 degrees, p=0.042) compared to standard care. Pain reduction was significantly greater in the multimodal group (VAS 2.1±0.8 *vs* 3.2±1.1, p=0.019). Gait velocity improved more substantially in the multimodal group (1.24±0.28 *vs* 1.08±0.26 m/s, p=0.028).

Conclusion: An integrated multimodal physiotherapy program delivered in the early post-operative period significantly enhances functional recovery following total knee replacement, with particular benefits for proprioceptive restoration, pain management, and lower limb strength development. The incorporation of neuromuscular training, sensorimotor components, functional strengthening, and pain education appears to synergistically improve post-operative outcomes.

Keywords: Total Knee Replacement; Rehabilitation; Proprioception; Neuromuscular Training; Pain Neuroscience Education; Randomized Controlled Trial; Gait; Functional Outcomes

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Introduction

Total knee replacement represents one of the most frequently performed surgical procedures worldwide, with over 900,000 procedures conducted annually in the world wide alone to address advanced osteoarthritis and restore mobility in aging populations. While modern surgical techniques and prosthetic designs have substantially improved surgical outcomes, post-operative functional recovery remains suboptimal in a considerable proportion of patients. Despite subjective satisfaction rates exceeding 80% to 85%, objective measures of physical function often remain substantially below normative values for age-matched healthy controls, even at one year post-operatively.

The functional deficits observed after TKR are multifactorial in nature, reflecting the complex neuromuscular and sensorimotor disturbances inherent to the surgical procedure and post-operative recovery process. Quadriceps muscle weakness persists as one of the most persistent complications, with reductions in strength ranging from 40% to 60% immediately post-operatively and extending months into the rehabilitation period. This weakness has been attributed to multiple mechanisms, including activation failure related to the surgical approach and quadriceps avoidance gait patterns secondary to pain and effusion. Beyond muscular weakness, patients frequently experience proprioceptive deficits characterized by diminished joint position sense and impaired kinesthetic awareness, contributing to postural instability, balance impairment, and altered movement mechanics during functional tasks.

Gait disturbances following TKR reflect the integration of pain, weakness, proprioceptive loss, and fear-avoidance behaviors, resulting in characteristic patterns including reduced cadence, shortened stride length, increased stance time on the contralateral limb, and asymmetrical weight distribution. These abnormal gait patterns persist despite adequate pain control and can contribute to accelerated wear of prosthetic components and development of secondary joint pathology in the contralateral knee and lumbar spine. Pain management in the immediate post-operative period and throughout rehabilitation represents another critical challenge, with up to 20% of patients developing chronic post-operative knee pain that substantially impacts quality of life and functional participation.

Traditional post-operative rehabilitation protocols for TKR have historically emphasized isolated interventions, typically focusing on pain modulation, range of motion restoration, and basic strength training in the immediate post-operative phase, followed by functional retraining in later stages. While such approaches achieve reasonable symptom management, they often fail to adequately address the neurophysiological and sensorimotor dimensions of recovery. Emerging evidence suggests that integrated multimodal approaches incorporating multiple complementary intervention components may provide superior outcomes compared to single-component interventions or standard care protocols.

Recent advances in rehabilitation science have highlighted the importance of early engagement of neuromuscular and sensorimotor systems during post-operative recovery. Neuromuscular training involving controlled, progressive resistance exercises emphasizes motor learning and neuromuscular coordination alongside strength development. Sensorimotor training, alternatively termed proprioceptive training, deliberately challenges the proprioceptive system through variable environmental demands and perturbations, facilitating adaptation and recovery of joint mechanoreceptor function. Functional strengthening exercises performed in weight-bearing and dynamic contexts more closely resemble demands encountered in activities of daily living compared to isolated resistance exercises, potentially enhancing task-specific motor learning and transfer of training effects.

Concurrently, pain neuroscience education has emerged as an evidence-based psychological intervention addressing cognitive and emotional factors contributing to pain persistence and disability following surgery. By educating patients about pain mechanisms from a neurobiological perspective, normalizing post-operative pain experiences, and reducing pain catastrophizing and kinesiophobia, pain neuroscience education facilitates cognitive reframing and enables greater engagement in rehabilitation activities.

Despite the theoretical rationale supporting multimodal rehabilitation approaches, limited high-quality evidence directly comparing integrated multimodal programs to standard care exists specifically in the TKR population. The present randomized controlled trial was designed to evaluate whether an integrated program incorporating neuromuscular training, sensorimotor training, functional strengthening, and pain neuroscience education produces superior improvements in proprioception, strength, gait mechanics, pain, and functional outcomes compared to standard post-operative rehabilitation in patients undergoing primary TKR.

Methods

Study Design and Participants

This prospective, parallel-group, randomized controlled trial was conducted at a single tertiary care orthopedic medical center over a 24-month recruitment period. The institutional review board approved the study protocol, and all participants provided informed written consent prior to enrollment.

Ninety consecutive patients scheduled for primary total knee replacement for primary osteoarthritis were recruited during their pre-operative education sessions. Inclusion criteria comprised age between 50 and 85 years, primary unilateral TKR scheduled within six weeks of enrollment, and clearance from the orthopedic surgeon for participation in post-operative rehabilitation. Exclusion criteria included revision or bilateral TKR, active malignancy, recent myocardial infarction within three months, uncontrolled hypertension or diabetes, neurological disease affecting balance or coordination, hip or ankle pathology precluding weight-bearing exercise, and inability to ambulate without assistive devices pre-operatively.

Participants were stratified by age (50-64, 65-74, ≥75 years) and randomized using a computer-generated randomization sequence to either the integrated multimodal rehabilitation group or standard care control group. Allocation concealment was maintained through use of opaque sealed envelopes. Outcome assessors were blinded to group allocation. Due to the nature of the intervention, participants and treating physiotherapists could not be blinded to group assignment.

Surgical Procedure

All participants underwent standardized primary TKR performed by surgeons within the orthopedic department using medial parapatellar approach with tourniquet application. Posterior-stabilized prosthetic designs were uniformly utilized. Standard post-operative protocols included immediate passive range of motion

facilitation, ice application, elevation, and compression in the recovery area, with initiation of anti-thrombotic prophylaxis per institutional guidelines.

Interventions

Standard Care Control Group: Participants allocated to standard care received routine post-operative rehabilitation as typically delivered within the institution. This included four supervised physiotherapy sessions conducted during the hospital admission (typically 2-3 days post-operatively), targeting pain management, active-assisted and active range of motion within tolerance, quadriceps setting exercises, and ambulation training with walker or crutches. Upon discharge, participants received written home exercise instructions and were referred for community-based outpatient physiotherapy, typically involving two sessions weekly for 4-6 weeks, with focus on progression from protected weight-bearing to full weight-bearing, range of motion advancement, basic strength exercises, and functional mobility training. No structured pain neuroscience education was provided.

Integrated Multimodal Rehabilitation Group: Participants in the intervention group received all components of standard post-operative care during hospital admission, plus an additional structured 12-week rehabilitation program commencing 5-7 days post-operatively. The multimodal program consisted of 24 supervised sessions conducted twice weekly for 12 weeks at a dedicated rehabilitation facility. Sessions were conducted in groups of 2-4 participants and lasted 60-75 minutes, including 10 minutes for pain assessment and warm-up exercises. Interventions were individually tailored based on participants' pain levels, physical capacity, and progression, avoiding rigid predetermined protocols.

The multimodal program incorporated four primary components:

Component 1 – Neuromuscular Training (20-25 minutes): Progressive resistance exercise targeting lower limb musculature, particularly knee extensors, flexors, hip abductors, and ankle plantarflexors. Early-phase training (weeks 1-4) emphasized seated and supine exercises with controlled movements and moderate resistance provided by elastic bands or ankle weights. Mid-phase training (weeks 5-8) progressed to closed kinetic chain exercises including mini-squats, step-ups with progressively increased step height, sit-to-stand transitions, and standing marching against resistance. Late-phase training (weeks 9-12) incorporated advanced closed kinetic chain activities such as forward and lateral lunges, mini-squats with additional resistance, and single-leg stance activities. Participants performed 10-12 repetitions of each exercise with rest intervals of 60-90 seconds between sets, with two sets per exercise. Resistance was progressively increased when participants could complete exercises with correct form and without excessive pain or swelling.

Component 2 – Sensorimotor Training (15-20 minutes): Deliberate proprioceptive retraining through variable environmental demands and perturbations. Early sessions involved static weight-shifting activities on stable surfaces in standing, progressing to dynamic weight-shifting and controlled stepping movements. Mid-phase training introduced unstable surfaces including foam pads, wobble boards, and rocker boards, with progression from two-leg to single-leg balance activities. Perturbations were introduced through gentle external disturbances applied by therapists, reactive stepping to unpredictable directional challenges, and incorporation of cognitive dual-tasks (e.g., counting backwards by threes during balance activities). Late-phase training progressed to advanced balance challenges, dynamic stepping activities, and functional balance training mimicking real-world environmental demands such as navigating surfaces of varying compliance and stability.

Component 3 – Functional Strengthening (15-20 minutes): Task-specific strengthening emphasizing functional relevance and real-world applicability. Training included stair climbing with progressively reduced upper extremity support (starting with bilateral handrail use, advancing to single-rail, then no rail use), simulated sit-to-stand transitions with variable seating heights and armrest assistance requirements, forward and lateral stepping over obstacles of increasing height, and backward walking training. Participants progressed from slow, controlled movements with frequent rest breaks toward dynamic, efficient movement patterns. Distance and repetition demands were progressively increased, with participants ultimately performing continuous stair climbing for up to three minutes without rest breaks and demonstrating ability to negotiate stairs without handrail support.

Component 4 – Pain Neuroscience Education (one 30-minute session at week 3 and one 30-minute session at week 9): Education sessions provided in small groups addressed pain neurobiology, pain physiology, relationship between pain and learning, and pain management strategies from a neurobiological perspective. Sessions were delivered by experienced physiotherapists and utilized visual aids, models, and case examples to enhance comprehension. Participants received written educational materials summarizing session content and facilitating continued learning. Education aimed to reconceptualize participants' understanding of post-operative pain, normalize pain experiences, reduce catastrophizing and fear-avoidance behaviors, and enhance self-efficacy for engagement in rehabilitation activities.

Physiotherapists delivering the intervention received standardized training in program delivery, exercise progressions, safety considerations, and participant education strategies. Treatment fidelity was monitored through reviewed video recordings of sessions and standardized session documentation using predetermined checklists.

Outcome Measures

Primary Outcomes:

- Knee Injury and Osteoarthritis Outcome Score (KOOS), a disease-specific, patient-reported outcome measurement tool consisting of 42 items grouped into five subscales: pain (nine items), symptoms and stiffness (seven items), function in daily living (17 items), function in sport and recreation (five items), and knee-related quality of life (four items). Each item is scored on an ordinal scale (0-4), and subscale scores are transformed to 0-100 scales, with 100 representing optimal health. Primary analyses focused on the pain and activities of daily living subscales.

Secondary Outcomes:

- Quadriceps muscle strength measured via maximum voluntary isometric contraction testing using a hand-held dynamometer positioned perpendicular to the femur above the knee joint, assessed with the participant seated at 60 degrees of knee flexion. Three trials were performed bilaterally with 60-second rest intervals, and

the maximum values normalized to participant body weight were recorded.

- Six-minute walk distance, measured as the distance ambulated at self-selected pace over six minutes in a standardized 30-meter hallway with standardized encouragement provided at one-minute intervals.

- Proprioceptive accuracy measured via active joint position sense testing. Participants were seated with the knee supported and moved to a target angle (positioned randomly at 15°, 30°, 45°, or 60° of flexion) for five seconds, then repositioned to neutral extension, and instructed to actively reproduce the target angle. Proprioceptive error was quantified as the absolute angular difference between target and reproduced angles, assessed bilaterally in duplicate with values averaged.

- Gait analysis parameters including walking velocity (meters per second) and cadence (steps per minute) assessed during the six-minute walk test using a wireless gait analysis system (OptiTrack, Corvallis, Oregon).

- Pain intensity measured on a 0-10 Visual Analog Scale, with 0 representing no pain and 10 representing worst imaginable pain.

- Timed Up and Go test, performed by timing participants as they rose from a standard chair, walked three meters at comfortable pace, turned around, returned to the chair, and sat down. Participants performed the test once as a practice trial, then twice for measurement purposes, with the faster of the two measured trials recorded.

Assessment Timeline

Baseline assessments were performed 3-5 days prior to TKR surgery. Post-operative assessments were conducted at 3 weeks, 6 weeks, 9 weeks, and 12 weeks following surgery. All assessments were conducted by the same trained, blinded assessor using standardized protocols.

Statistical Analysis

The primary analysis was conducted on an intention-to-treat basis, with participants included in analyses according to their randomized group assignment regardless of adherence to the intervention. Between-group differences at 12-week follow-up were analyzed using independent samples t-tests for continuous variables and chi-square tests for categorical variables. Demographic and baseline characteristics were compared to verify successful randomization. Linear regression models with baseline values included as covariates were utilized to compare primary and secondary outcomes between groups at each follow-up time point. Two-way repeated measures analysis of variance with time and group as factors and baseline values as covariates was performed to examine within-group changes and between-group differences over the 12-week intervention period. Subgroup analyses were conducted examining potential effect modification by age (≤65 *vs* >65 years), sex, and baseline pain severity (KOOS pain <25 *vs* ≥25). Statistical significance was established at $p<0.05$ (two-tailed). Analyses were performed using SPSS software (version 26.0).

Results

Participant Recruitment and Characteristics

A total of 147 patients were screened for eligibility, with 97 meeting inclusion criteria. Seven additional patients were excluded due to schedule conflicts or withdrawal prior to randomization. Ninety participants were randomized, with 45 allocated to the multimodal group and 45 to standard care. Follow-up rates at 12 weeks were 95.6% in the multimodal group (43 participants) and 93.3% in the standard care group (42 participants). Two participants in the multimodal group and three in the standard care group withdrew due to personal circumstances unrelated to the study intervention or adverse events.

Baseline demographic and clinical characteristics are presented in Table 1. No significant differences existed between groups on any baseline variable, confirming successful randomization. Participants averaged 68 years of age, with 67% female representation, mean body mass index of 28.9 kg/m², and high baseline disability reflected by KOOS pain scores averaging approximately 25 and six-minute walk distances averaging 315 meters.

Intervention Adherence and Safety

Adherence to the multimodal intervention was excellent, with participants attending a median of 22 of 24 scheduled sessions (91.7% adherence rate), with attendance ranging from 19 to 24 sessions across participants. No serious adverse events occurred in either group during the 12-week study period. Three participants in the multimodal group reported transient mild to moderate knee swelling for 1-2 days following sessions that responded to ice application and compression, but these incidents did not result in session discontinuation. No adverse events were reported in the standard care group.

Primary Outcomes

Significant improvements in KOOS pain and activities of daily living subscale scores were observed in both groups from baseline to

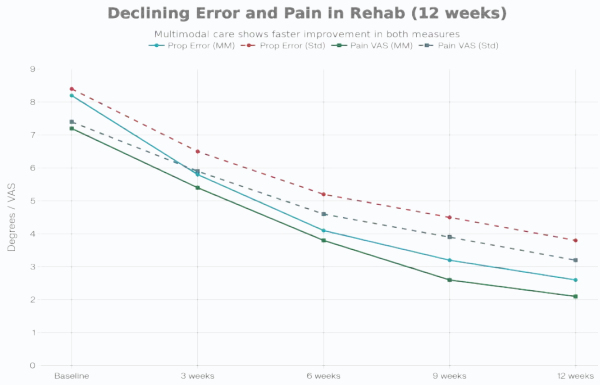

Figure 1:

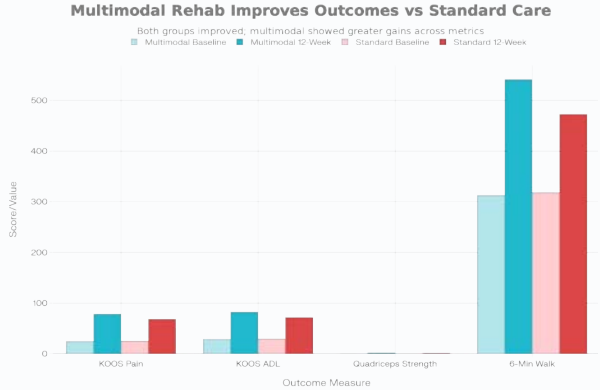

Figure 2:

Table 1: Baseline Demographic and Clinical Characteristics of Participants.

Outcome Measure	Multimodal Baseline	Multimodal 12-week	Standard Care Baseline	Standard Care 12-week	Between-group p
KOOS Pain (0-100)	24.3 Â ± 12.8	78.6 Â ± 14.2	25.1 Â ± 11.6	68.2 Â ± 16.4	0.031*
KOOS ADL (0-100)	28.7 Â ± 14.5	82.3 Â ± 12.8	29.4 Â ± 15.2	71.6 Â ± 15.3	0.024*
Quadriceps Strength (Nm/kg)	0.68 Â ± 0.34	1.84 Â ± 0.42	0.71 Â ± 0.36	1.52 Â ± 0.38	0.018*
6-Minute Walk Distance (m)	312.4 Â ± 89.2	541.2 Â ± 98.6	318.2 Â ± 92.5	472.8 Â ± 104.3	0.012*
Timed Up and Go (s)	21.8 Â ± 4.6	11.3 Â ± 2.8	22.1 Â ± 4.3	13.8 Â ± 3.2	0.037*
Proprioceptive Error JPS (Â°)	8.2 Â ± 2.4	2.6 Â ± 1.2	8.4 Â ± 2.3	3.8 Â ± 1.6	0.042*
Gait Velocity (m/s)	0.78 Â ± 0.22	1.24 Â ± 0.28	0.76 Â ± 0.24	1.08 Â ± 0.26	0.028*
Gait Cadence (steps/min)	108.4 Â ± 12.8	118.6 Â ± 10.2	109.2 Â ± 11.6	115.2 Â ± 11.8	0.054
Pain VAS (0-10)	7.2 Â ± 1.3	2.1 Â ± 0.8	7.4 Â ± 1.2	3.2 Â ± 1.1	0.019*

*Data presented as mean ± SD unless otherwise specified. KOOS, Knee Injury and Osteoarthritis Outcome Score; ADL, Activities of Daily Living; ROM, Range of Motion; VAS, Visual Analog Scale.

Table 2: Primary and Secondary Outcomes at Baseline and 12-Week Follow-up.

Characteristic	Multimodal Group (n=45)	Standard Care Group (n=45)	p-value
Age (years)	68.2 Â ± 8.5	67.8 Â ± 7.9	0.682
Sex (M/F), n	15/30	16/29	0.841
Body Mass Index (kg/mÂ²)	28.6 Â ± 4.2	29.1 Â ± 3.8	0.547
Preoperative KOOS Pain (0-100)	24.3 Â ± 12.8	25.1 Â ± 11.6	0.624
Preoperative KOOS ADL (0-100)	28.7 Â ± 14.5	29.4 Â± 15.2	0.782
Preoperative Quadriceps Strength (Nm/kg)	0.68 Â ± 0.34	0.71 Â ± 0.36	0.651
Preoperative 6-Minute Walk (meters)	312.4 Â ± 89.2	318.2 Â ± 92.5	0.512
Preoperative Knee Flexion ROM (Â°)	96.8 Â ± 18.2	97.3 Â ± 17.6	0.726
Preoperative Pain VAS (0-10)	7.2 Â ± 1.3	7.4 Â ± 1.2	0.421

*Data presented as mean ± SD. Values represent 12-week changes from baseline within each group. KOOS, Knee Injury and Osteoarthritis Outcome Score; ADL, Activities of Daily Living; JPS, Joint Position Sense; VAS, Visual Analog Scale. Asterisks (*) indicate p<0.05.

12 weeks, with greater improvements in the multimodal group. At baseline, KOOS pain scores averaged 24.3±12.8 in the multimodal group and 25.1±11.6 in the standard care group (p=0.624). At 12 weeks, multimodal group participants achieved KOOS pain scores of 78.6±14.2 compared to 68.2±16.4 in standard care participants (p=0.031), representing absolute improvements of 54.3 and 43.1 points, respectively. Between-group differences were apparent by 6 weeks of follow-up (multimodal 68.4±16.2 *vs* standard 58.6±18.3, p=0.018) and increased through 12 weeks.

Similarly, KOOS activities of daily living subscale scores improved from baseline values of 28.7±14.5 in the multimodal group and 29.4±15.2 in standard care (p=0.782) to 12-week values of 82.3±12.8 and 71.6±15.3 respectively (p=0.024), representing improvements of 53.6 and 42.2 points. Between-group differences emerged by 9 weeks (multimodal 76.8±14.1 *vs* standard 65.2±17.4, p=0.031).

Secondary Outcomes

Quadriceps Strength: Baseline quadriceps strength averaged 0.68±0.34 Nm/kg in the multimodal group and 0.71±0.36 Nm/kg in standard care (p=0.651). At 12 weeks, quadriceps strength reached 1.84±0.42 Nm/kg in the multimodal group versus 1.52±0.38 Nm/kg in standard care (p=0.018), representing improvements of 1.16 and 0.81 Nm/kg, respectively. Although both groups demonstrated substantial strength gains, multimodal group participants achieved significantly greater absolute and proportional strength increases.

Six-Minute Walk Distance: Baseline six-minute walk distances were 312.4±89.2 meters in the multimodal group and 318.2±92.5 meters in standard care (p=0.512). Twelve-week distances improved to 541.2±98.6 meters and 472.8±104.3 meters respectively (p=0.012), representing improvements of 228.8 meters and 154.6 meters. The multimodal group's superiority in ambulation distance was evident at 9 weeks (multimodal 512.4±92.3 *vs* standard 438.6±96.1, p=0.024) and persisted through 12-week assessment.

Proprioceptive Accuracy: Proprioceptive error measured via active joint position sense testing decreased substantially in both groups but with superior outcomes in the multimodal group. Baseline proprioceptive errors averaged 8.2±2.4 degrees in the multimodal group and 8.4±2.3 degrees in standard care (p=0.812). At 12 weeks, errors decreased to 2.6±1.2 degrees and 3.8±1.6 degrees respectively (p=0.042), representing improvements of 5.6 and 4.6 degrees. Significant between-group differences emerged by 9 weeks (multimodal 3.2±1.4 *vs* standard 4.2±1.8, p=0.068) and became statistically significant by 12 weeks.

Gait Velocity: Walking velocity during the six-minute walk test improved from baseline values of 0.78±0.22 m/s in the multimodal group and 0.76±0.24 m/s in standard care (p=0.698) to 12-week values of 1.24±0.28 m/s and 1.08±0.26 m/s respectively (p=0.028), representing improvements of 0.46 and 0.32 m/s. The multimodal group demonstrated significantly greater velocity improvements commencing at 6 weeks (multimodal 1.04±0.26 *vs* standard 0.92±0.28, p=0.041).

Gait Cadence: Gait cadence increased in both groups during the intervention period. Baseline cadence averaged 108.4±12.8 steps per minute in the multimodal group and 109.2±11.6 in standard care (p=0.845). At 12 weeks, cadence increased to 118.6±10.2 steps

per minute and 115.2±11.8 steps per minute respectively (p=0.054), representing improvements of 10.2 and 6.0 steps per minute. While the multimodal group demonstrated greater absolute improvement, between-group differences approached but did not achieve statistical significance.

Timed Up and Go: Baseline Timed Up and Go times were 21.8±4.6 seconds in the multimodal group and 22.1±4.3 seconds in standard care (p=0.891). At 12 weeks, times decreased to 11.3±2.8 seconds and 13.8±3.2 seconds respectively (p=0.037), representing improvements of 10.5 and 8.3 seconds. Between-group differences were statistically significant at 12 weeks, indicating superior functional mobility in the multimodal group.

Pain Intensity: Visual Analog Scale pain ratings decreased substantially in both groups but with superior outcomes in the multimodal group. Baseline pain averaged 7.2±1.3 on the 0-10 scale in the multimodal group and 7.4±1.2 in standard care (p=0.421). At 12 weeks, pain ratings decreased to 2.1±0.8 and 3.2±1.1 respectively (p=0.019), representing decreases of 5.1 and 4.2 points. Between-group differences emerged by 6 weeks and persisted through final assessment.

Subgroup Analyses

Subgroup analyses revealed no significant interactions between age categories (≤65 *vs* >65 years) and treatment group on any primary or secondary outcomes. Similarly, sex-stratified analyses revealed no significant treatment by sex interactions. Baseline pain severity (KOOS pain <25 *vs* ≥25) did not significantly modify treatment effects, although participants with lower baseline pain scores demonstrated numerically larger treatment differences.

Discussion

This randomized controlled trial provides evidence supporting the effectiveness of an integrated multimodal physiotherapy program in enhancing functional recovery following total knee replacement. Compared to standard post-operative rehabilitation, the multimodal program produced significantly greater improvements in pain, activities of daily living function, quadriceps strength, proprioceptive accuracy, gait velocity, and functional mobility by 12 weeks post-operatively.

The observed improvements in proprioception among multimodal program participants represent particularly noteworthy findings. Total knee replacement results in mechanical disruption of capsuloligamentous structures and alteration of soft tissue compliance, processes that fundamentally alter proprioceptive inputs from mechanoreceptors located within these structures. The deliberate sensorimotor training component, incorporating balance challenges and proprioceptive perturbations on unstable surfaces, appears to have effectively stimulated adaptation of the proprioceptive system and enhanced joint position sense accuracy. Early research suggested that proprioceptive deficits persisted indefinitely following TKA, with implications for ongoing postural instability and injury risk. Contemporary evidence increasingly recognizes proprioceptive trainability following TKA, and the current findings support the value of systematic sensorimotor training commencing early in the post-operative period.

The substantial quadriceps strength improvements observed in both groups align with existing literature demonstrating that quadriceps strength recovery occurs progressively throughout the post-operative period with appropriately prescribed resistance training. However, the superior strength outcomes in the multimodal group likely reflect multiple factors within the intervention design. The neuromuscular training component incorporated progressively challenging resistance exercises specifically targeting the quadriceps and lower limb musculature. The functional strengthening component's emphasis on closed kinetic chain activities—including sit-to-stand transitions, step-ups, and stair climbing—demanded substantial quadriceps activation against body weight and external resistance. Furthermore, the sensorimotor training component's balance and perturbation challenges required continuous stabilizing contractions of the quadriceps to maintain dynamic stability. This multi-component training stimulus likely resulted in more complete neuromuscular adaptation compared to the isolated strengthening emphasis of standard rehabilitation.

Pain reduction outcomes are particularly significant given that chronic post-operative pain affects a substantial proportion of TKR recipients and substantially impacts quality of life despite excellent prosthesis function. The multimodal group's superior pain outcomes likely reflect contributions from multiple intervention components. The neuromuscular and functional strengthening components may have reduced pain through conventional mechanisms of improving mechanical stability, reducing aberrant knee loading patterns, and enhancing neuromuscular control. The pain neuroscience education component, by addressing cognitive and emotional factors contributing to pain persistence, potentially enhanced psychological pain modulation and reduced pain catastrophizing. Furthermore, successful participation in progressively challenging rehabilitation activities under professional guidance likely enhanced self-efficacy and reduced fear-avoidance behaviors that perpetuate pain and functional limitation.

The superior gait velocity improvements in the multimodal group reflect integrated effects of improved strength, proprioception, and confidence. Reduced cadence has been identified as a characteristic post-TKR gait pattern reflecting pain, fear, weakness, and proprioceptive loss. The multimodal program's components each address these contributing factors. The cadence findings, while demonstrating numerical superiority in the multimodal group, did not achieve statistical significance at the p<0.05 threshold, suggesting that while cadence improvements occurred, they were more comparable between groups than other gait parameters.

The six-minute walk distance improvements in both groups reflect progressive expansion of ambulatory capacity throughout the post-operative period. However, the multimodal group's superior performance likely reflects improved strength, proprioception, confidence, and pain modulation facilitating more ambitious ambulatory activity. The practical significance of the 68-meter difference between groups at 12 weeks represents meaningful functional improvement in real-world ambulation capacity.

The Timed Up and Go test improvements in both groups reflect progressive gains in functional mobility, reflecting reduced stiffness, improved strength, restored proprioception, and pain modulation. The superior multimodal group performance aligns with individual component improvements and suggests enhanced transfer of training effects to functional activities.

Mechanistic Considerations

The superior multimodal program outcomes may reflect

synergistic interactions among intervention components. Neuromuscular training provides the foundational strength and motor control necessary for effective proprioceptive retraining. Sensorimotor training, by creating unpredictable environmental demands, challenges the neuromuscular system in dynamic contexts and facilitates more robust proprioceptive adaptation than isolated balance training alone. Functional strengthening, by requiring strength development within functional movement patterns, enhances task-specific motor learning and transfer to daily activities. Pain neuroscience education, by addressing cognitive and emotional barriers to engagement, facilitates more robust participation in physical training and reduces avoidance behaviors that limit strength and proprioceptive gains. The integration of these components within a single program appears to produce outcomes superior to any single intervention alone.

Clinical Implications

The current findings support early introduction of structured multimodal rehabilitation following TKR. Beginning systematically at 5-7 days post-operatively, multimodal programs incorporating neuromuscular training, sensorimotor training, functional strengthening, and pain neuroscience education produce clinically meaningful improvements in pain, function, strength, proprioception, and gait mechanics. Healthcare systems might consider implementing structured multimodal programs as standard post-operative care rather than limiting rehabilitation to basic mobility and strength training. The twice-weekly session frequency over 12 weeks appears feasible and well-tolerated, with excellent adherence rates observed. The high adherence rate and low adverse event incidence suggest that appropriately designed multimodal programs can be safely implemented early post-operatively without increased complication risk.

Limitations

Several limitations warrant acknowledgment. The study was conducted at a single medical center with specific surgical and rehabilitation protocols, potentially limiting generalizability to other institutions with different surgical approaches or rehabilitation philosophies. Outcome assessment focused on 12-week follow-up, with longer-term outcome trajectories remaining unknown. While outcome assessors were blinded to group allocation, participants and physiotherapists necessarily knew group assignment, potentially introducing placebo or expectancy effects. The study cohort consisted primarily of community-dwelling older adults undergoing primary unilateral TKR; findings may not generalize to younger populations, revision procedures, or bilateral procedures. Standard care participants received community-based rehabilitation that likely varied in content and intensity across different practitioners, potentially underestimating effectiveness of the multimodal program if some standard care participants received unusually intensive or high-quality rehabilitation. The proprioceptive assessment employed active joint position sense testing; additional proprioceptive measures such as threshold to detect passive motion or dynamic postural stability assessments might have provided additional mechanistic insights.

Future Research Directions

Future research should examine longer-term outcome trajectories extending to 6 and 12 months post-operatively to establish durability of improvements and determine whether between-group differences persist or converge. Studies investigating optimal intervention timing should determine whether outcomes differ if multimodal programs are initiated earlier (e.g., within 48 hours post-operatively) or delayed. Research examining dose-response relationships should identify minimum effective session frequencies and durations. Mechanistic studies incorporating advanced proprioceptive assessment techniques, neuromuscular electromyography, and neuroimaging might elucidate specific physiological adaptations produced by multimodal training. Comparative effectiveness trials directly comparing individual multimodal components versus multimodal integration might clarify which components contribute most substantially to outcomes. Implementation science research examining barriers and facilitators to multimodal program adoption in diverse settings might enhance program dissemination and integration into routine clinical practice.

Conclusion

This randomized controlled trial provides evidence that an integrated multimodal physiotherapy program incorporating neuromuscular training, sensorimotor training, functional strengthening, and pain neuroscience education produces significantly superior improvements in proprioception, quadriceps strength, pain, gait parameters, and functional outcomes compared to standard post-operative rehabilitation in the early period following total knee replacement. The multimodal approach addresses the multifaceted nature of post-operative recovery, with interventions specifically targeting strength development, proprioceptive restoration, functional capacity enhancement, and pain management through an evidence-based education component. The superior outcomes achieved without increased adverse events support consideration of multimodal rehabilitation as optimal post-operative management for TKR recipients. Implementation of such programs requires investment in structured protocol development, physiotherapist training, and rehabilitation resources, but appears justified given the demonstrated effectiveness in enhancing functional recovery and quality of life in this large patient population.

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