Core stabilization with biofeedback-guided quadriceps–hamstring strengthening in knee osteoarthritis: a randomized trial

Estabilización del core con fortalecimiento cuádriceps–isquiotibiales guiado por biofeedback en osteoartritis de rodilla: ensayo aleatorizado

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Abstract

Introduction: Appropriate exercise therapies are still being investigated for primary knee osteoarthritis, which greatly contributes to chronic pain and functional impairment in older adults.
Objective: The purpose of this study was to evaluate the effectiveness of adding core stability to biofeedback-assisted quadriceps-hamstring strengthening for individuals with primary osteoarthritis of the knee.
Methodology: Participants between the ages of 50 and 65 participated in a parallel-group, randomized controlled study conducted at a single location. For six weeks, participants participated in twice-weekly supervised exercise sessions. The Western Ontario and McMaster Universities Osteoarthritis Index was used to assess functional status at baseline and on a weekly basis, while the Numeric Rating Scale was used to measure the intensity of pain.
Results: Forty participants were randomized, with 39 completing the study. Both groups showed gradual improvements in pain and functional outcomes. Significant between-group differences in pain emerged from week four, and by week six, the combined intervention group showed lower pain levels compared to the strengthening-only group. Functional outcomes also showed significant differences at week six, favoring the combined intervention. Statistical analysis revealed significant time-by-group interactions for both pain and functional measures.
Discussion: The addition of core stabilization appears to enhance the effectiveness of strengthening exercises, possibly by improving neuromuscular control and joint stability.
Conclusions: Incorporating core stabilization into strengthening programs provides additional short-term benefits in reducing pain and improving function in individuals with primary knee osteoarthritis.

Keywords

Core stabilization; exercise therapy; functional outcome; knee osteoarthritis; randomized controlled trial.

Resumen

Introducción: La osteoartritis primaria de rodilla es un factor importante en la generación de dolor crónico y limitaciones funcionales en las personas mayores, y se sigue investigando sobre las mejores estrategias de ejercicio.
Objetivo: Evaluar la eficacia de añadir estabilización del core al fortalecimiento de cuádriceps–isquiotibiales guiado por biofeedback en pacientes con osteoartritis primaria de rodilla.
Metodología: Se realizó un ensayo controlado aleatorizado de grupos paralelos en un solo centro, con participantes de 50 a 65 años. Los sujetos realizaron sesiones de ejercicio supervisado dos veces por semana durante seis semanas. Se utilizó la Escala Numérica para llevar a cabo la evaluación de la intensidad del dolor, mientras que la función se determinó utilizando el índice WOMAC tanto al inicio como semanalmente.
Resultados: Se aleatorizaron 40 participantes, de los cuales 39 completaron el estudio. Ambos grupos mostraron mejoras progresivas en dolor y función. Las diferencias entre grupos en dolor aparecieron desde la cuarta semana, y en la sexta semana el grupo con intervención combinada presentó menores niveles de dolor. Los resultados funcionales también mostraron diferencias significativas a favor del grupo combinado. El análisis estadístico mostró interacciones significativas tiempo por grupo.
Discusión: La inclusión de estabilización del core mejora la eficacia del fortalecimiento, posiblemente mediante una mejoría en el control neuromuscular y la estabilidad articular.
Conclusiones: La estabilización del core, cuando se integra, proporciona beneficios adicionales en la reducción del dolor y la mejora de la función en pacientes que padecen osteoartritis primaria de rodilla.

Palabras clave

Ejercicio terapéutico; ensayo controlado aleatorizado; estabilización del core; osteoartritis de rodilla; resultado funcional.

Introduction

One of the most common chronic joint conditions in the world, knee osteoarthritis (KOA) is a major cause of pain and impairment in the elderly (Geng et al., 2023). The 2019 Global Burden of Disease (GBD) Study acknowledged musculoskeletal disorders, particularly osteoarthritis, as significant contributions to years lived with disability globally, with the burden escalating due to population ageing and demographic shift (Vos et al., 2020). The GBD 2021 analysis estimated that approximately 595 million individuals were affected by osteoarthritis worldwide in 2020, constituting 7.6% of the global population. Projections suggest significant increases in case numbers by 2050, primarily due to population growth and aging, with high body mass index contributing to roughly 20% of the attributable burden (Steinmetz et al., 2023). The clinical impact of knee osteoarthritis is significant, characterised by chronic and persistent pain as the dominant symptom, accompanied by functional limitation, reduced mobility, and significant impairment in quality of life (Hunter & Bierma-Zeinstra, 2019).

Muscle weakness is an acknowledged and potentially modifiable risk factor for knee osteoarthritis, with meta-analytic evidence indicating that weakness in the knee extensors elevates the probability of disease onset (Øiestad et al., 2015). In people with or at risk of KOA, diminished quadriceps strength correlates with inferior physical function and decreased physical activity trajectories (Christensen et al., 2022). Global clinical guidelines therefore strongly advise structured exercise programs that include strengthening exercises targeting the major lower-limb muscle groups, such as the quadriceps and hamstrings, as crucial components of conservative treatment for knee osteoarthritis (Bannuru et al., 2019; Kolasinski et al., 2020). People with knee osteoarthritis who get land-based exercise therapy report moderate improvements in pain and physical capability when compared to non-exercise controls (Fransen et al., 2015). Similarly, a recent meta-analysis published in Retos reported that aquatic therapy may reduce pain and joint stiffness and support physical function in individuals with knee osteoarthritis, further emphasizing the relevance of exercise-based rehabilitation for this population (Trisnowiyanto et al., 2026). A revised Cochrane review that included 139 studies found that exercise likely improves pain, physical function, and quality of life in the short term. However, the clinical significance of these effects may vary depending on established minimal meaningful difference thresholds. (Lawford et al., 2024). Uniform results across chronic musculoskeletal disorders, such as low back pain, further endorse exercise therapy as a safe and effective approach for mitigating discomfort and enhancing functional outcomes (Viderman et al., 2025). Nonetheless, despite these recognized advantages, a significant percentage of patients fail to attain maximal enhancement, suggesting the possible necessity for alternative or supplementary neuromuscular approaches.

Recent research highlights the importance of proximal muscle weakness and impaired lumbopelvic control, in addition to localised knee extensor weakness, in affecting abnormal lower-extremity biomechanics in individuals with knee osteoarthritis. Recent biomechanical research has identified weakness in the hip abductors, modified knee adduction moments, and compensatory movement patterns in individuals with knee osteoarthritis, indicating a proximal influence on the disease's pathomechanics (Yang et al., 2024). From a kinetic chain perspective, core musculature plays a fundamental role in controlling trunk position over the pelvis, enabling optimal force transfer and load distribution to the lower extremities, a concept described as “proximal stability for distal mobility” (Kibler et al., 2006). Given these interrelationships, integrating core muscle strengthening into rehabilitation has been proposed as a potential strategy to enhance lower-limb biomechanics and functional outcomes in KOA, although high-quality clinical evidence remains limited (Thomas et al., 2024). Impaired proximal muscle control may lead to excessive dynamic knee valgus and modified joint loading patterns, which are linked to aberrant lower-limb biomechanics (Kibler et al., 2006; Sahabuddin et al., 2021). Studies in lower-limb musculoskeletal conditions indicate that core stabilization training can enhance neuromuscular regulation of the torso and lower limbs and reduce knee valgus moments during dynamic tasks (Saki et al., 2023; Sasaki et al., 2019). Core-focused therapies have demonstrated a reduction in hip and knee joint moments during landing activities, suggesting reduced mechanical stress across the lower-extremity kinetic chain (Fatahi et al., 2019). However, despite these biomechanical benefits observed in athletic and ACL-related populations, the comparative effectiveness of core stabilization training in individuals with primary knee osteoarthritis remains underexplored. In knee-related rehabilitation, recent evidence in Retos has also emphasized that integrated approaches combining therapeutic modalities with structured exercise

education may improve pain, range of motion, muscle strength, balance, and functional activity after ACL injury (Setiawan et al., 2026).

Neuromuscular biofeedback has been proposed as an adjunct strategy to enhance voluntary muscle activation and improve motor control. A systematic review reported that electromyographic biofeedback may augment quadriceps strength, with the largest effects observed in pathological populations, including individuals with knee osteoarthritis, although confidence intervals were wide and overall conclusions remained cautious (Lepley et al., 2012). In addition, pressure biofeedback combined with conventional rehabilitation has been shown to facilitate early quadriceps activation following lower-limb orthopedic surgery, potentially helping to mitigate arthrogenic muscle inhibition (Achens et al., 2022). Although electromyographic biofeedback appears to enhance quadriceps activation and reduce pain in knee-related conditions, current evidence does not consistently demonstrate superiority over conventional exercise or rehabilitation methodologies, especially in osteoarthritis of the knee (Karaborklu Argut et al., 2022; Raeissadat et al., 2018)

Although quadriceps and hamstring strengthening are widely recommended as key components of conservative management for knee osteoarthritis, some patients may continue to experience pain, impaired movement control, and functional limitation despite conventional exercise therapy (Bannuru et al., 2019; Fransen et al., 2015; Kolasinski et al., 2020; Lawford et al., 2024). This suggests the need for complementary strategies that address not only local periarticular muscle strength but also proximal stability and neuromuscular coordination. Core stabilization may be clinically relevant in this context because trunk and lumbopelvic control contribute to lower-limb alignment, force transfer, and movement efficiency during functional activities, consistent with the concept of proximal stability for distal mobility (Kibler et al., 2006). Previous studies have suggested that core stabilization may influence lower-limb biomechanics and neuromuscular control during functional tasks (Fatahi et al., 2019; Saki et al., 2023; Sasaki et al., 2019). However, although proximal stabilization has shown favorable effects on lower-limb biomechanics and electromyographic biofeedback has been used to enhance muscle activation in knee-related conditions, limited evidence has examined whether adding core stabilization to biofeedback-guided quadriceps–hamstring strengthening provides additional benefits in individuals with primary knee osteoarthritis (Lepley et al., 2012; Raeissadat et al., 2018; Thomas et al., 2024).

Therefore, the present study aimed to evaluate the effectiveness of adding core stabilization exercises to a biofeedback-guided quadriceps–hamstring strengthening program in individuals with primary knee osteoarthritis. Specifically, this study compared pain intensity and functional outcomes between participants receiving quadriceps–hamstring strengthening alone and those receiving quadriceps–hamstring strengthening combined with core stabilization. We hypothesized that both interventions would improve pain and physical function, but that the addition of core stabilization would result in greater improvements due to its potential contribution to proximal stability, neuromuscular control, and lower-limb movement efficiency.

Method

Study Design and Participants

This single-center, parallel-group randomized controlled trial evaluated the effectiveness of integrating core stabilization exercises into a biofeedback-guided quadriceps-hamstring strengthening program to reduce pain and enhance functional outcomes in those with primary osteoarthritis of the knee. The study was carried out at the Physical and Rehabilitation Medicine Outpatient Clinic at Hasanuddin University Hospital in Makassar, Indonesia, between September and December of 2025. Participants with a confirmed diagnosis of knee osteoarthritis were recruited consecutively from clinic patients. Individuals aged 50–65 years who met the clinical and radiographic criteria of the American College of Rheumatology (ACR) for primary knee osteoarthritis, were in stable general health, and were able to attend supervised exercise sessions twice weekly for six weeks were eligible to participate. The exclusion criteria included intra-articular knee fracture, hip osteoarthritis, acute or chronic low back pain, inflammatory arthritis, previous lower-limb joint replacement, spinal surgery, lower-limb surgery within the preceding six months, planned knee surgery during the study period, uncontrolled cardio-

vascular disease or other contraindications to exercise, severe untreated psychiatric disorders, pregnancy, or inability to comply with the study procedures. Before enrolment, all participants provided written informed consent.

Participants were randomly allocated into two groups: (1) a control group that received surface electromyography (sEMG) biofeedback-guided quadriceps–hamstring strengthening, or (2) an intervention group that received sEMG biofeedback-guided quadriceps–hamstring strengthening combined with core stabilization exercises. Randomization was performed using a computer-generated sequence prepared by an independent researcher. Allocation concealment was maintained using opaque, sealed envelopes. Due to the nature of the exercise intervention, participants and therapists could not be blinded; however, outcome assessments were conducted by a blinded assessor.

Sample Size

Based on previously published data that showed expected variance and mean differences in clinical outcomes after exercise therapy in individuals with osteoarthritis in the knee, the sample size was determined (Hernandez et al., 2019). At a 95% confidence level and 90% statistical power, the minimum necessary sample size was found to be 14 people per group. In anticipation of a possible 30% dropout rate, the sample size was expanded to 20 individuals each group. As a result, forty participants were gathered and divided into two groups at random. One participant withdrew after allocation, resulting in 39 participants who completed the study (quadriceps–hamstring strengthening group, n = 19; core stabilization plus quadriceps–hamstring strengthening group, n = 20).

Intervention Procedures

For six weeks, participants in both groups attended twice-weekly supervised exercise sessions in the biofeedback therapy room of the outpatient rehabilitation unit. Each session lasted approximately 30–45 minutes, depending on participant tolerance, and included adequate rest intervals between exercise sets to minimize fatigue. All exercises were performed within a pain-free or tolerable range under therapist supervision.

Before each session, participants received brief education regarding the use of surface electromyography (sEMG) biofeedback and proper exercise technique. The skin over the target muscles was cleaned with alcohol swabs to improve electrode conductivity. Surface EMG electrodes were placed over the relevant muscles and connected to a biofeedback device that converted muscle activation signals into real-time visual feedback. For the intervention group, electrodes were positioned over the rectus abdominis, external oblique, erector spinae, quadriceps, and hamstring muscles according to the exercise performed. For the control group, electrodes were positioned over the quadriceps and hamstring muscles only.

Before training, participants performed voluntary contractions to determine their maximum voluntary isometric contraction or reference activation level. This value was used to adjust the individualized activation threshold during exercise. Participants were instructed to observe the visual feedback while performing each contraction in order to optimize muscle activation and neuromuscular control. Therapists provided standardized verbal cues to correct exercise technique and regulate contraction intensity based on the EMG feedback.

The intervention group performed core stabilization exercises in addition to quadriceps–hamstring strengthening. Core exercises targeted the rectus abdominis, external oblique, and erector spinae muscles and included curl-up or trunk flexion exercises and superman or prone trunk extension exercises. Quadriceps–hamstring strengthening was performed by both groups using the same sEMG biofeedback procedures to ensure comparability between groups. The control group performed quadriceps and hamstring strengthening exercises only. Exercise progression in both groups was individualized according to participant tolerance, movement quality, and ability to achieve the target activation threshold. Progression was applied by gradually increasing repetitions, contraction duration, or target activation level when the participant could complete the previous exercise level without increased pain or excessive fatigue. If participants reported increased pain, excessive fatigue, dizziness, or difficulty maintaining correct movement patterns, the exercise intensity was reduced or maintained at the previous level until tolerance improved.

Participants in both groups were also instructed to perform home exercises once daily. Adherence and technique were monitored through WhatsApp by asking participants to record and send videos of their exercise performance. The researcher reviewed the videos, provided corrective feedback, and monitored any complaints or adverse effects. At the end of each supervised session, sEMG outcomes, exercise duration, participant response, and any adverse events were documented.

Outcome Measures

Throughout the six-week intervention period, outcome indicators were assessed both at baseline and on a weekly basis. Measurement 1 represented the initial assessment before the intervention. Follow-up assessments carried out at weeks 2, 3, 4, 5, and 6, respectively, matched measurements 2, 3, 4, 5, and 6. Pain severity was measured using the Numeric Rating Scale (NRS), a validated 11-point scale that ranges from 0 (no pain) to 10 (worst imaginable pain). The average degree of knee pain experienced throughout the preceding week was to be rated by the participants. Functional outcomes were evaluated using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), a validated tool with 24 items broken down into subscales for pain, stiffness, and physical function. Each item was assessed using a Likert scale with a range of 0 to 4; higher values indicate more severe symptoms and functional impairment.

Data Analysis

For statistical analysis, SPSS version 30.0 (IBM Corp., Armonk, NY, USA) was utilised. The Shapiro-Wilk test was used to determine whether the data was normal. Baseline age was compared using the Mann-Whitney U test, and baseline categorical data was evaluated using Fisher's exact test. Mixed repeated measures ANOVA was used to assess results over time between groups, with time serving as the within-subject factor and group as the between-subject factor. The main effects of time, group, and the combination of time and group were analyzed. Effect sizes were expressed using partial eta squared (η^2). The threshold for statistical significance was established at $P < 0.05$.

Ethical consideration

The study was authorized by Hasanuddin University's Health Research Ethics Committee on August 29, 2025, and it followed the Declaration of Helsinki (protocol code 618/UN4.6.4.5.31/PP36/2025).

Results

Table 1 illustrates that the baseline demographic characteristics were comparable between the two groups. There was no statistically significant difference in the distribution of sexes between the intervention and control groups ($p = 0.127$). In a similar vein, the groups' ages did not differ significantly ($p = 0.612$). The findings show that the groups were similar at baseline, suggesting that demographic imbalances at baseline are unlikely to have an impact on later differences in pain or functional outcomes.

Table 1. Baseline Characteristics of Participants

Variable	Control Group (n = 19)	Intervention Group (n = 20)	p-value
Sex			0.127[1]
Male	6 (31.6%)	2 (10%)	
Female	13 (68.4%)	18 (90%)	
Age (years)	57.32±4.30	58.15±4.87	0.612[2]

[1]Fisher's Exact Test; 2Mann Whitney test; *p<0.05

Table 2 shows that there were no significant differences between the groups' baseline NRS ratings ($p = 0.504$) during the early stages of the intervention (Measurements 2 and 3). Significant between-group differences began to emerge from Measurement 4 onwards. At the final assessment (Measurement 6), the intervention group had a significantly lower mean NRS score compared with the control group ($p < 0.001$; 2.50 ± 0.69 vs. 3.53 ± 0.51). This corresponds to an approximate mean difference of 1.03 points in favor of the intervention group. Overall, pain scores decreased over time in both groups, with a larger reduction observed in the intervention group.

Table 2. Pain Scores (NRS) Across Measurement Points

Variable	Control Group (n = 19)	Intervention Group (n = 20)	p-value
NRS – Measurement 1	4.63±0.68	4.55±0.69	0.504[1]
NRS – Measurement 2	4.26±0.56	4.20±0.70	0.836[1]
NRS – Measurement 3	4.05±0.52	3.90±0.79	0.576[1]
NRS – Measurement 4	3.79±0.54	3.40±0.68	0.046[1]*
NRS – Measurement 5	3.74±0.45	3.10±0.72	0.001[1]*
NRS – Measurement 6	3.53±0.51	2.50±0.69	<0.001[1]*

[1]Mann Whitney test; *p<0.05

The mixed repeated measures ANOVA revealed a significant main impact of time on NRS scores ($F(5,185) = 79.94$, $p < 0.001$, partial $\eta^2 = 0.684$), as Table 3 illustrates. This implies that during the intervention period, both groups' levels of discomfort significantly decreased. The considerable effect size suggests that time accounted for a major portion of the variance in pain assessments. Furthermore, a significant main influence of group was discovered ($F(1,37) = 5.49$, $p = 0.025$, partial $\eta^2 = 0.129$), indicating that the overall pain levels of the two groups were different. A significant time × group interaction was also found ($F(5,185) = 8.77$, $p < 0.001$, partial $\eta^2 = 0.192$), indicating that the pattern of pain reduction differed between groups, with a larger decrease observed in the intervention group over time.

Table 3. Mixed Repeated Measures ANOVA Results for Pain Scores (NRS)

Effect	df	F	p-value	Partial η^2
Time	5, 185	79.94	<0.001[1]*	0.684
Group	1, 37	5.49	0.025[1]*	0.129
Time × Group	5, 185	8.77	<0.001[1]*	0.192

[1]Mixed repeated measures ANOVA; *p<0.05

According to Table 4, the groups' baseline WOMAC ratings were similar ($p = 0.833$), suggesting a similar functional condition at the beginning of the experiment. Measurements 2 through 5 showed no statistically significant between-group differences; however, the intervention group consistently had lower mean WOMAC scores over time. A significant difference emerged at the final assessment (Measurement 6), where the intervention group showed a markedly lower mean WOMAC score compared to the control group (25.07 ± 9.98 vs. 35.87 ± 10.90, $p = 0.003$). This represents an approximate mean difference of 10.8 points in favor of the intervention group. Overall, WOMAC scores improved over time in both groups, with a larger functional improvement observed in the group receiving additional core stabilization.

Table 4. WOMAC Scores Across Measurement Points

Variable	Control Group (n = 19)	Intervention Group (n = 20)	p-value
WOMAC – Measurement 1	44.79±9.82	42.99±12.87	0.833[1]
WOMAC – Measurement 2	42.49±9.87	39.81±12.35	0.509[1]
WOMAC – Measurement 3	41.43±10.10	37.34±12.18	0.346[1]
WOMAC – Measurement 4	39.60±10.25	33.16±11.06	0.091[1]
WOMAC – Measurement 5	37.74±10.30	30.49±11.31	0.052[1]
WOMAC – Measurement 6	35.87±10.90	25.07±9.98	0.003[1]*

[1]Mann Whitney test; *p<0.05

A significant main effect of time on WOMAC scores ($F(5,185) = 105.08$, $p < 0.001$, partial $\eta^2 = 0.740$) was found by the mixed repeated measures ANOVA, as shown in Table 5, suggesting significant functional improvement over the intervention period in both groups. The substantial effect size implies that a significant amount of the variance in functional outcomes was explained by changes over time. Overall WOMAC scores did not substantially change across groups at any time point, according to the main effect of group, which was not statistically significant ($F(1,37) = 2.62$, $p = 0.114$, partial $\eta^2 = 0.066$). Nevertheless, a significant time × group interaction was found ($F(5,185) = 12.22$, $p < 0.001$, partial $\eta^2 = 0.248$), suggesting that the trajectory of functional improvement differed between groups, with greater improvement observed in the intervention group over time.

Table 5. Mixed Repeated Measures ANOVA Results for WOMAC Scores

Effect	df	F	p-value	Partial η^2
Time	5, 185	105.08	<0.001[1]*	0.740
Group	1, 37	2.62	0.114[1]	0.066
Time × Group	5, 185	12.22	<0.001[1]*	0.248

Note: [1]Mixed repeated measures ANOVA; *p<0.05

Discussion

This randomized controlled trial showed that both strengthening interventions were associated with reductions in pain intensity and improvements in functional outcomes in patients with primary knee osteoarthritis over a six-week intervention period. Compared with quadriceps–hamstring strengthening alone, the addition of core stabilization under biofeedback guidance was associated with a greater reduction in pain and a more favorable trajectory of functional improvement. These findings suggest that integrating proximal stabilization with periarticular strengthening may provide additional clinical benefits in knee osteoarthritis rehabilitation.

Strengthening exercise is a key component of conservative therapy for knee osteoarthritis, and both groups had considerable pain decreases over time (Bennell et al., 2011; Zeng et al., 2021). Increased pain and worse functional results have been related with quadriceps weakness, a well-known and treatable disability connected to knee osteoarthritis (Glass et al., 2013) In addition to increasing periarticular muscles' capacity to absorb and redistribute mechanical pressures during functional activities, strengthening the quadriceps and hamstrings also increases dynamic joint stability.

From a pathophysiological standpoint, articular cartilage itself is not the source of pain in osteoarthritis because cartilage is aneural. Rather, the subchondral bone, synovium, capsule, ligaments, and periarticular tissues, which are rich in nociceptors, are the main sources of nociceptive input (Loeser et al., 2012; Mora et al., 2018). The ability of articular cartilage to efficiently distribute mechanical loads is diminished by progressive deterioration, which puts more strain on subchondral bone and other tissues that are sensitive to pain (Loeser et al., 2012; Mora et al., 2018). Strengthening periarticular muscles may therefore reduce abnormal joint loading and contribute to the pain reduction observed in both groups.

Mechanical alignment also plays a critical role in determining joint loading patterns. Coronal plane malalignment, such as varus or valgus positioning, alters the lower limb's mechanical axis and increases compartment-specific joint loading (Sharma et al., 2001, 2010). Musculoskeletal modeling studies have confirmed that changes in alignment substantially modify tibiofemoral contact forces (Van Rossom et al., 2019). By improving muscular support and dynamic stabilization of the knee joint, strengthening exercises may help mitigate excessive focal loading and thereby contribute to pain reduction.

Another mechanism that may explain the reduction in pain is improved neuromuscular control. Individuals with knee osteoarthritis frequently demonstrate altered muscle activation patterns, including increased co-contraction between quadriceps and hamstrings as a compensating tactic to keep the joint stable (Preece et al., 2016). Although co-contraction can enhance joint stability, excessive co-contraction may increase compressive factors that affect the knee joint and cause discomfort.

Surface electromyography (sEMG) biofeedback provides real-time visual feedback that allows patients to adjust muscle activation patterns during exercise. This augmented feedback can enhance voluntary activation, improve motor learning, and promote more efficient muscle recruitment (Draper et al., 1991). Reducing maladaptive co-contraction has been shown in earlier neuromuscular research, may lead to meaningful reductions in pain even without large increases in maximal muscle strength (Preece et al., 2016). These mechanisms may partly explain the progressive pain reduction observed in the present study.

The group that received additional core strengthening showed a greater reduction in pain, suggests that proximal stabilization may provide additional biomechanical and neuromuscular benefits. The concept of the kinetic chain emphasizes that trunk and lumbopelvic stability influence lower-limb alignment and movement patterns during functional activities (Lee, 2021; Myer et al., 2008). Insufficient proximal control can lead to altered lower-limb mechanics and increased mechanical stress on the knee joint.

Trunk control and neuromuscular synchronisation between the trunk, pelvis, and lower limbs are both improved by core stabilization training (Lee, 2021). Increased proximal stability may lessen compensatory movement patterns that put additional strain on the knee joint and enable more effective force transfer through the kinetic chain. According to earlier research, trunk stabilization exercises can lessen dynamic knee valgus during functional tasks and enhance neuromuscular control (Myer et al., 2008). Additionally, clinical research indicates that adding core strengthening to rehabilitation regimens may help people with osteoarthritis in their knees have less discomfort. Hernandez et al. (2019) found that the addition of core strengthening exercises to conventional rehabilitation reduced discomfort and functional limitation more than the use of conventional exercise alone. These findings support the possibility that improved proximal stability may partly explain the greater pain reduction observed in the intervention group.

In addition to reducing pain, both interventions significantly improved functional outcomes as measured by the WOMAC index. Functional improvement in knee osteoarthritis is strongly associated with reductions in pain, improvements in muscle strength, and enhanced joint stability. It has been repeatedly demonstrated that exercise-based therapies improve knee osteoarthritis patients' physical functioning (Fransen et al., 2015; Zeng et al., 2021).

The knee joint's capacity to withstand mechanical pressures during activities like walking, getting out of a chair, and climbing stairs is enhanced by strengthening the quadriceps and hamstrings. Previous studies have similarly demonstrated significant improvements in WOMAC scores following strengthening programs targeting periarticular muscles (Al-Johani et al., 2014; Ramadan Hafez et al., 2013). These findings are consistent with the progressive decrease in WOMAC scores observed in both groups in the present study.

Better proximal control and neuromuscular coordination could account for the larger functional gain shown in the group receiving additional core strengthening. Maintaining balance and regulating the centre of mass during functional movement depend heavily on the stability of the trunk and pelvis (Myer et al., 2008). Improved trunk stability may therefore enhance movement efficiency and reduce compensatory strategies that limit functional performance.

From a clinical perspective, the findings of this study support the inclusion of core stabilization exercises as a complementary component of rehabilitation programs for individuals with knee osteoarthritis. Although quadriceps and hamstring strengthening remains an essential element of conservative management, rehabilitation should not focus solely on the affected knee joint. Addressing proximal stability, trunk control, and lumbopelvic coordination may help improve lower-limb alignment, optimize load distribution, and enhance movement control during functional activities. Therefore, an integrated rehabilitation program combining periarticular strengthening with core stabilization may provide a more comprehensive therapeutic approach for reducing pain and improving functional performance in patients with knee osteoarthritis.

This study has several strengths. First, the randomized controlled design with random allocation allowed comparison between quadriceps–hamstring strengthening alone and quadriceps–hamstring strengthening combined with core stabilization. Second, the use of validated outcome measures, including the Numeric Rating Scale and WOMAC index, supported systematic evaluation of pain and functional outcomes. Third, pain and function were monitored weekly during the intervention period, allowing observation of changes over time. Fourth, the intervention was clearly structured and clinically applicable, with both groups receiving supervised exercise sessions of comparable frequency, duration, therapist guidance, and sEMG biofeedback procedures. Finally, the high participant completion rate strengthened the internal validity of the findings.

This study also has several limitations. First, the sample size was relatively small, which may limit statistical power and reduce the generalizability of the findings to broader knee osteoarthritis populations. Second, the study was conducted in a single center, which may limit external validity across different clinical settings. Third, the intervention lasted only six weeks, and no long-term follow-up assessment was conducted; therefore, the durability of the observed improvements remains uncertain. Fourth, this study did not include direct biomechanical or electromyographic analyses to confirm changes in neuromuscular activation patterns, movement control, or joint loading mechanisms. Future studies should

involve larger sample sizes, multicenter designs, longer intervention periods, and follow-up assessments to confirm the long-term effectiveness of this integrated rehabilitation approach.

In summary, both strengthening interventions were associated with reductions in pain and improvements in functional outcomes in individuals with primary knee osteoarthritis. The addition of core stabilization to biofeedback-guided quadriceps–hamstring strengthening was associated with greater improvements in pain and functional recovery than quadriceps–hamstring strengthening alone. These findings suggest that integrating periarticular strengthening with proximal stabilization may constitute a more comprehensive rehabilitation approach for individuals with knee osteoarthritis, although further studies are needed to confirm the long-term effects of this strategy.

Conclusions

In this randomized controlled trial, both strengthening interventions were associated with reduced pain intensity and improved functional outcomes in adults with primary knee osteoarthritis. The addition of core stabilization to sEMG biofeedback-guided quadriceps–hamstring strengthening was associated with greater pain reduction and functional improvement compared with quadriceps–hamstring strengthening alone. These findings suggest that incorporating proximal stabilization into rehabilitation programs may provide additional clinical benefits by supporting neuromuscular control and load distribution across the lower extremity. However, given the limited sample size, short intervention duration, and absence of long-term follow-up, these findings should be interpreted with caution. Further studies with larger sample sizes, longer intervention periods, and follow-up assessments are needed to confirm the long-term effectiveness of this integrated approach.

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