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REVIEW

Knee osteoarthritis rehabilitation: an integrated framework of exercise, nutrition, biomechanics, and physical therapist guidance—a narrative review

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Abstract

Knee osteoarthritis (KOA) is a prevalent, debilitating chronic joint disease characterized by pain, stiffness, and functional limitations. Non-pharmacological rehabilitation is a fundamental management strategy. This narrative review synthesizes evidence on an integrated KOA rehabilitation framework, including: exercise therapy (aerobic, resistance, neuromuscular training), which reduces pain and improves function through enhanced muscle activation and joint stability; dietary interventions (weight management and anti-inflammatory diets), which lower mechanical load and systemic inflammation; biomechanical optimization (bracing, gait retraining), aimed at reducing joint stress; and physical therapist-guided strategies (individualized exercises, manual therapy, patient education) addressing pain and functional restoration. While these core components demonstrate synergistic potential and highlight the need for personalized approaches, the review notes suboptimal adherence to guideline-recommended therapies in clinical practice. Additionally, supplementary treatments such as manual therapy and acupuncture, although commonly used, lack strong evidence, characterized by low-quality Randomized controlled trials, insufficient sample sizes, and inconsistent findings. This situation warrants further robust research. Future studies should focus on personalized approaches that utilize machine learning, mobile health tools for real-time gait analysis, and novel biotechnologies to address the remaining challenges. This review aims to provide clinicians and researchers with a practical guide to optimize KOA rehabilitation, enhancing patient care and quality of life.

Keywords Knee osteoarthritis, Biomechanics, Rehabilitation, Exercise, Nutrition

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Introduction

Knee osteoarthritis (KOA) is a degenerative condition characterized by pain resulting from the deterioration of articular cartilage, fibrosis, fissuring, and ulceration [1]. KOA accounts for approximately 60.8% of the global disability burden associated with osteoarthritis. Recent data from the Global Burden of Disease Study 2021, published in The Lancet Rheumatology, provide updated insights, indicating that the global prevalence of KOA continued to rise until 2020, with projections suggesting a 74.9% increase by 2050 compared to 2020 levels [3]. Approximately 365 million adults worldwide were affected by KOA as of 2020, underscoring its growing public health impact [1]. KOA-related impairments significantly limit physical activity engagement and are frequently associated with multimorbidity, particularly cardiovascular events [2]. KOA has multiple etiologies and is often classified based on causation. Secondary osteoarthritis may be induced by factors such as calcium accumulation, anomalies, post-traumatic osteoarthritis, or other abnormalities [3]. Idiopathic OA may present as either localized or generalized KOA. As KOA impacts the whole joint and pain significantly influences clinical decision-making and healthcare resource utilization, a biopsychosocial therapeutic strategy is essential [4]. Current guidelines highlight conservative treatments as first-line interventions for KOA [5]. With exercise therapy as a cornerstone, it consistently reduces pain, improves function, and enhances muscle strength [6]. Diverse modalities are beneficial: aerobic exercises (e.g., walking, cycling) improve cardiovascular fitness and reduce pain; resistance training strengthens knee-stabilizing muscles, thereby reducing joint load; and neuromuscular exercises enhance balance, coordination, and proprioception —components critical for fall prevention and movement optimization [8]. Beyond exercise, dietary interventions play a crucial role, primarily via weight management, in reducing joint loading and systemic inflammation. Even modest weight loss in overweight/obese patients alleviates pain and improves function [7]. Anti-inflammatory diets rich in omega-3 fatty acids, antioxidants, and fiber may further modulate KOA-related inflammation [8]. Biomechanical optimization, including assistive devices (such as canes and braces), orthotics, gait retraining, and activity modifications, alleviates mechanical stress and corrects movement patterns. These synergize with physical therapist-guided care, which includes individualized exercises, manual therapy, and education on pain coping and self-management [9]. These non-pharmacological interventions are prioritized for their evidence in improving core symptoms, addressing pathophysiological facets (mechanical stress, inflammation, muscle weakness), and empowering self-management to delay or avoid invasive procedures [6]. However, integrating them into a holistic, individualized framework remains challenging.

However, despite the established benefits of these individual approaches, the existing literature also presents conflicting findings and inconsistencies, underscoring the need for a more integrated perspective. For instance, while exercise is broadly recommended, the optimal dose, intensity, and specific type of exercise for achieving maximal benefit in diverse KOA patient populations remain subjects of ongoing debate and variability in reported outcomes across studies [10]. Similarly, while weight loss from dietary interventions is consistently beneficial, the efficacy of specific anti-inflammatory diets or supplements often yields mixed results or requires further robust evidence [11]. Furthermore, patient heterogeneity in KOA, encompassing varying clinical phenotypes, disease severity, and individual treatment responses, often results in variable intervention effectiveness, rendering a"one-size-fits-all"approach suboptimal [12]. These inconsistencies highlight a gap in our comprehensive understanding of how these components interact and how to optimize their application.

This narrative review aims to synthesize current evidence on exercise, dietary interventions, biomechanical optimization, and physical therapist-guided strategies, proposing a comprehensive framework for KOA rehabilitation. By exploring the interplay and synergistic effects of these components, and acknowledging the nuances and challenges in their application, we aim to provide a practical guide for clinicians and researchers to optimize patient outcomes in KOA management.

Methods

We conducted a comprehensive search of PEDro, Web of Science, Embase, PubMed, and the Cochrane Library from their inception until June 1, 2025. Search terms included: KOA, physical therapy, intervention, exercise, strength, dietary, kinesiotherapy, and rehabilitation, and we expanded the"Search Strategy"subsection to include the exact search strings used for each database: for PubMed, ("Knee Osteoarthritis"[Mesh] OR "KOA") AND ("Exercise Therapy"[Mesh] OR "Physical Therapy"[Mesh] OR "Rehabilitation"[Mesh] OR "Dietary Intervention"[Mesh] OR "Intervention"[tiab] OR "Exercise"[tiab] OR "Strength"[tiab] OR "Kinesiotherapy"[tiab] OR "Dietary"[tiab]); for Embase, ("knee osteoarthritis"/exp OR "KOA") AND ("exercise therapy"/exp OR "physical therapy"/exp OR "rehabilitation"/exp OR "dietary intervention"/exp OR "intervention"/ab OR "exercise"/ab OR "strength"/ab OR "kinesiotherapy"/ab OR "dietary"/ab); for Cochrane Library, ("Knee Osteoarthritis" OR "KOA") AND ("Exercise Therapy"OR "Physical Therapy" OR

"Rehabilitation"OR "Dietary Intervention" OR "Intervention" OR "Exercise" OR "Strength" OR "Kinesiotherapy" OR "Dietary") in Title, Abstract, and Keywords. PEDro and Web of Science adopted search logic consistent with the above using relevant subject headings and free-text terms like ("Knee Osteoarthritis" OR "KOA") AND ("Exercise Therapy" OR "Physical Therapy" OR "Rehabilitation" OR "Dietary Intervention" OR "Intervention" OR "Exercise" OR "Strength" OR "Kinesiotherapy" OR "Dietary") to cover potential relevant literature. Two reviewers (H.L. and L.Q.) independently screened the literature using standard systematic review methodology. Initially, they screened titles and abstracts against the inclusion and exclusion criteria for potentially eligible studies. The same reviewers then retrieved and assessed the full texts of these candidate studies to determine their eligibility. They resolved any discrepancies through discussion and consensus; if disagreement persisted, a third reviewer (M.H.) was consulted to make the final decision. The screening process is summarized in a PRISMA 2020 flow diagram (Fig. 1). Inclusion criteria were (1) Participants meeting the American College of Rheumatology (ACR) classification criteria for KOA and (2) randomized controlled trials (RCTs) evaluating therapeutic interventions for KOA, including exercise programs, physical modalities, dietary interventions, or patient education initiatives. Exclusion criteria were (1) Non-English publications; (2) Non-human studies; (3) Studies without accessible full text; (4) Pharmacological intervention studies; (5) Studies employing unreliable outcome measures. Statistical analyses were performed using SPSS 26.0 (IBM Corp., Armonk, NY, USA) to summarize relevant data from included studies.

Pathophysiology of KOA

Synovial joints connect adjacent bones and are protected by articular cartilage and synovial bursae [13]. KOA is a multifaceted disease characterized by a complex interplay of mechanical stress, biochemical alterations, and inflammatory processes that culminate in structural joint degradation and debilitating clinical symptoms. The primary pathological hallmarks of KOA include the progressive degradation of articular cartilage, resulting in its softening, fibrillation, and eventual loss. These changes occur concurrently with alterations in subchondral bone (sclerosis, cyst formation, and bone marrow lesions), osteophyte development, and often low-grade synovial inflammation [14]. These pathological changes directly contribute to the hallmark symptoms and functional limitations experienced by individuals with KOA. The loss of articular cartilage and changes in subchondral bone fundamentally impair the knee joint's ability to smoothly articulate and absorb shock, leading to pain during movement, weight-bearing activities, and rest [15]. As the disease progresses, joint space narrowing and osteophyte formation contribute to joint stiffness and a restricted range of motion, severely impeding daily activities such as walking, stair climbing, and getting up from a chair. The presence of synovial inflammation, even if low-grade, further exacerbates pain and contributes to joint swelling, which can inhibit muscle function around the knee [16]. A crucial consequence of KOA pathology is the development of muscle weakness and atrophy, particularly in the quadriceps femoris. This muscle dysfunction is not merely a secondary effect but a significant contributor to impaired knee stability, reduced shock absorption, and altered gait mechanics, further amplifying joint stress and pain [17]. These combined deficits result in significantly reduced physical function, impaired balance, increased risk of falls, and substantially diminished quality of life [18]. Understanding these direct links between KOA pathology and its functional consequences is paramount for effective management. Rehabilitation strategies target these deficits: Exercise therapy directly addresses muscle weakness, improves joint stability, and enhances physical function. Biomechanical interventions aim to reduce detrimental mechanical loading on affected joint compartments. Dietary modifications, particularly those focused on weight management, can reduce joint stress and help modulate systemic inflammation. Physical therapist-guided interventions provide comprehensive approaches addressing pain, mobility, functional restoration, and the underlying pathological drivers of disability [19]. This integrated understanding forms the essential rationale for the multi-faceted rehabilitation framework explored in this review.

Overall treatment measures

KOA can damage articular or hyaline cartilage [20]. A mechanobiological disease process impairs joint structural integrity and functional capacity, leading to discomfort and disability that sustains the disease cycle. Multiple modifiable risk factors for KOA have been identified, including physical inactivity [21], obesity [22], abnormal limb alignment [23], gait biomechanical alterations [24], and joint injury/trauma [22]. Thus, various rehabilitation interventions targeting the modifiable risk factors of KOA aim to disrupt this self-perpetuating cycle (Fig. 2).

Exercise and weight reduction are additional biomechanical treatments that can be integrated to enhance the joint's biomechanical environment and alleviate dysfunction. Multiple studies suggest that a synergistic approach combining nutrition and exercise can significantly alleviate pain, improve physical function, and reduce systemic inflammatory markers [25]. Patients with KOA can benefit considerably from various modern physiotherapy

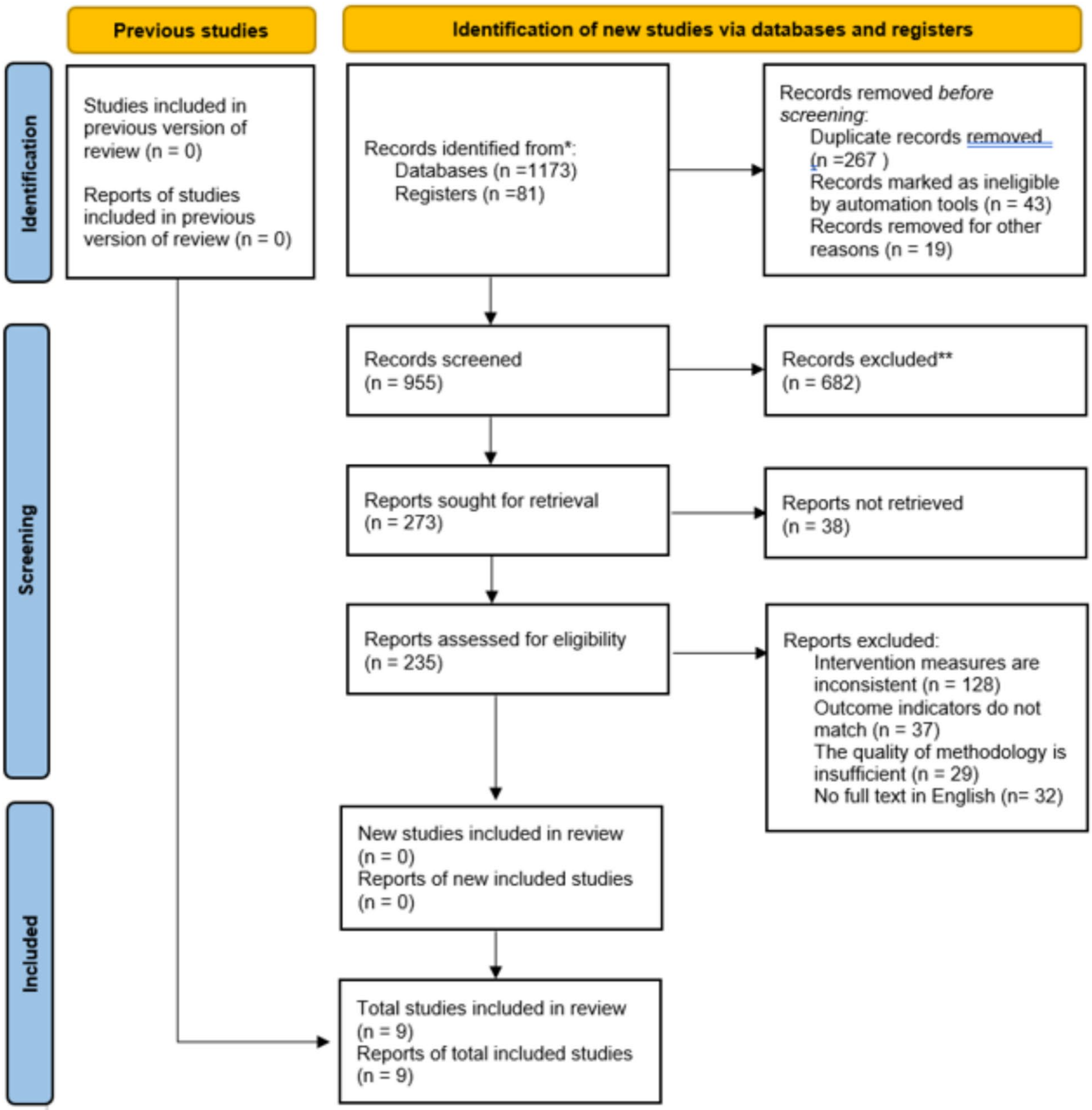


Fig. 1 Flow chart for research screening

programs and helpful tools, such as knee braces, orthopaedic insoles, and mobility aids, as well as treatments like ultrasound therapy, pulsed electromagnetic fields, low-energy laser therapy, and extracorporeal shock wave therapy. A substantial amount of evidence supports these methods (Table 1).

Numerous investigations have evaluated the effects of diverse training protocols on KOA, examining parameters such as pain intensity, joint range of motion, muscular strength, physical functional capacity, and psychological outcomes [35]. In a study examining different groups of people, we found that a lower ability to sense joint position was associated with greater knee pain, worse pain levels, and reduced physical function [36]. The Kellgren–Lawrence (KL) grading criteria indicate that as the structural severity of KOA increases, the way knee muscles are activated while walking changes gradually. These changes in how

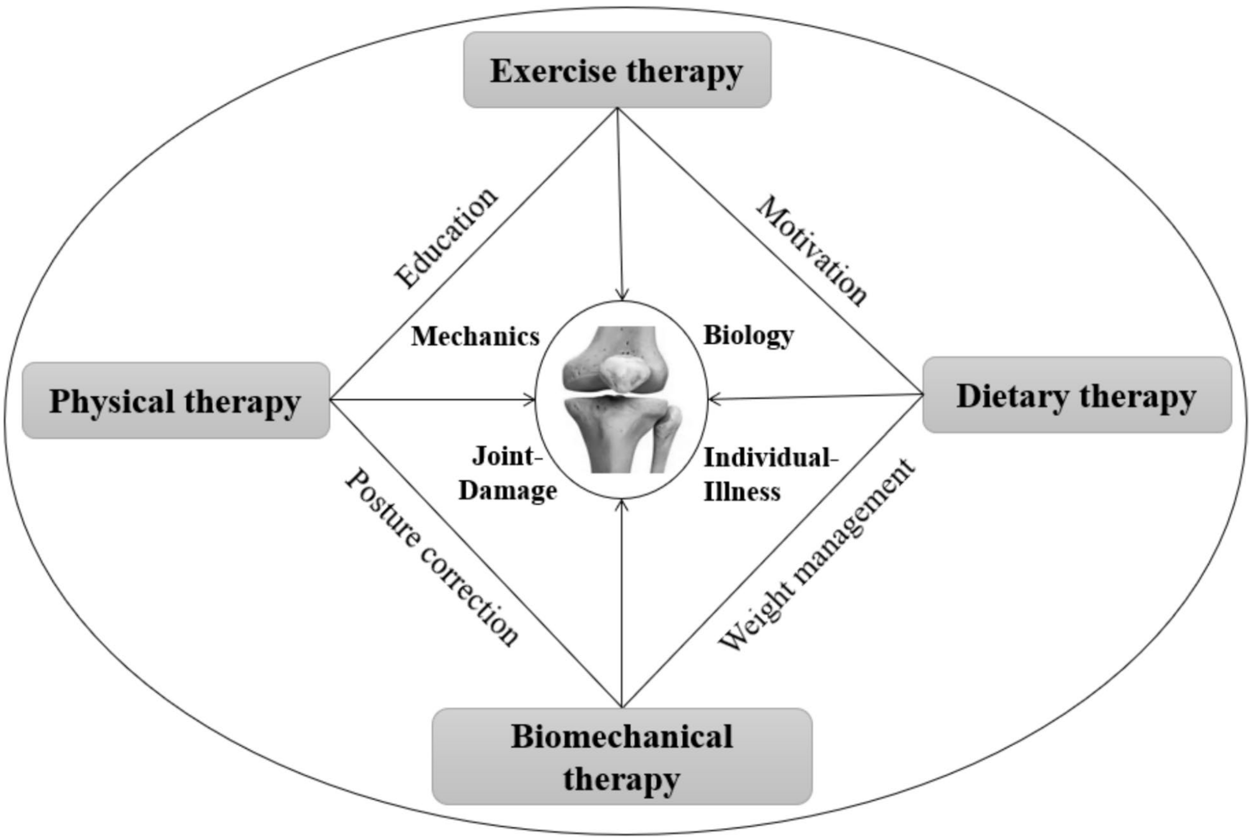


Fig. 2 Rehabilitation Intervention Strategies Targeting Modifiable Risk Factors in Knee Osteoarthritis

muscles activate are linked to a slower response time, a greater need for muscle stiffness while walking (especially when standing on one leg), reduced pressure on the inner part of the knee joint, and an increase in the severity of the condition [37]. Building upon the understanding of KOA pathology and its significant impact on functional disability, particularly muscle weakness and altered joint biomechanics, effective treatment strategies are crucial for pain alleviation and restoration of mobility. A comprehensive rehabilitation approach for KOA necessitates active interventions designed to mitigate these pathological consequences and improve patient outcomes. Among these, addressing changes in muscle activation and strength is paramount, as these are directly linked to pain, instability, and functional limitations. Therefore, structured programs, particularly exercise therapy, form the cornerstone of conservative management, aiming to restore neuromuscular control, enhance muscle performance, and improve overall physical function. This section will explore the various evidence-based non-pharmacological interventions that comprise the integrated framework for KOA rehabilitation.

Exercise therapy

The influence of exercise therapy on patients with KOA has been well researched, resulting in improvements in recovery, reduced pain, enhanced mobility, and improved overall well-being [6, 38]. Despite significant research, several critical dimensions of exercise therapy for KOA remain undefined. Evaluating the effect of exercise interventions on the progression of joint structural damage in KOA has consistently posed methodological challenges [39]. Exercise therapy for KOA should improve joint range of motion, muscle and tendon extensibility, strength and endurance, and reduce pain and load in the symptomatic compartments. It is expected that walking ability, daily activities, and exercise function will improve [40]. Exercise prescription for KOA is highly individualized, with its effectiveness contingent upon precise parameters including mode, frequency, intensity, and duration, tailored to patient-specific factors such as disease severity, comorbidities, and functional goals [41]. We want to explain the differences between physical activity (any movement that uses muscles and burns energy), exercise (planned and repeated activities to improve or maintain fitness), and kinesio-therapy

Table 1 Study on the effectiveness of physical therapy in the recovery of KOA Function

Author/Year	Research type	Sample size	Intervention measures	Intervention outcome	Conclusion	References
Ko et al. (2022)	RCT	42	Efficacy Comparison between Focused Extracorporeal Shockwave Therapy (f-ESWT) and Radial Extracorporeal Shockwave Therapy (r-ESWT) for KOA	The f-ESWT group demonstrated more pronounced improvements in VAS pain scores, WOMAC functional indices, and 6-min walk test performance	Superior effectiveness of f-ESWT in improving pain status and physical function has been observed in individuals with KOA	[26]
López et al. (2017)	RCT	34	Water Exercise Program	The experimental group exhibited significant improvements in WOMAC scores, 6-min walk test performance, and VAS pain intensity	Aquatic exercise improves KOA motor function and cardiopulmonary function, and reduces post-exercise heart rate and fatigue	[27]
Oğuz et al. (2021)	RCT	22	Sports training or sports training with kinesiology taping group	Both pain and function scores showed significant improvement after the intervention	Both exercise training alone and exercise training combined with kinesiology taping effectively ameliorate pain and physical function. However, no significant changes were observed in blood levels of COMP, MMP-1, and MMP-3	[28]
Wang et al. (2021)	RCT	71	Effects of Walking Exercise and Novel Sensor-Based Gait Retraining on Knee Joint Function in KOA Patients	The gait retraining group showed a significant decrease in KAM1 and VASP, while KOOS showed a considerable improvement	Immediate reductions in KAM1, KAAI, and knee discomfort, along with improvements in functional ability, are observed with sensor-based gait retraining that incorporates real-time visual feedback of the KAM curve	[29]
Afzal et al. (2021)	RCT	40	Eccentric and concentric isokinetic resistance training were administered to the eccentric training group and the concentric training group, respectively	Isometric concentric resistance training shows more significant functional changes	Isometric concentric resistance training is more suitable for patients with KOA (Grade 2 and 3)	[30]
Assaret et al. (2021)	RCT	36	Water sports, total resistance exercise, and a control group were evaluated using pain, balance, and knee joint function as indicators of their effectiveness	The aquatic exercise and total resistance exercise groups demonstrated significant improvements in patients'pain and balance abilities, with the total resistance exercise group experiencing a more rapid recovery of joint function	Water sports and total resistance exercise improve pain and balance in KOA patients similarly, but total resistance exercise is more suitable for functional improvement	[31]
Jahanjoo et al. (2019)	RCT	60	Consequently, the physical therapy group incorporated the Biodex Balance System to establish a balance training subgroup	Significant improvements in pain and function were observed in the balance training group compared with the conventional treatment group, with no substantial changes in fall risk scores	Superior functional recovery in patients with KOA is achieved through the integration of balance training and physical therapy	[32]
Harper et al. (2019)	RCT	35	The MIRT training group executed four lower limb exercises. In contrast, the low-load BFR resistance training group performed targeted lower limb exercises with external pressure applied to the proximal thighs of both legs	BFR can be used as an alternative exercise program to reduce pain in patients with KOA and enhance their functional abilities	BFR has been validated as a safe and effective therapeutic option for managing KOA in the elderly population	[33]

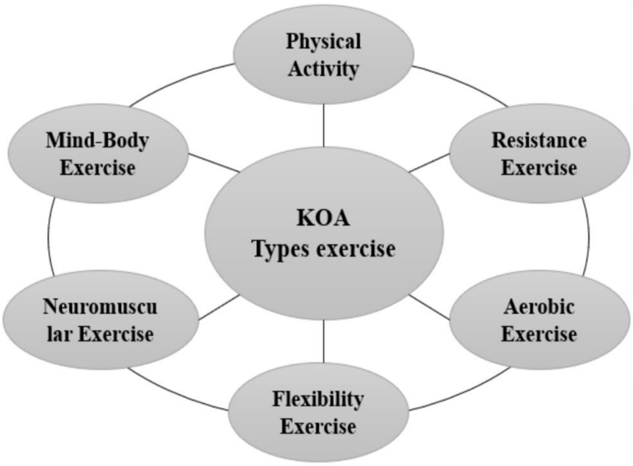
Table 1 (continued)

Author/Year	Research type	Sample size	Intervention measures	Intervention outcome	Conclusion	References
Sedaghatnezhad et al. (2021)	RCT	30	The intervention group received treadmill training at an 8-degree incline during each session, in addition to the conventional treatment regimen	The integration of uphill walking and physical therapy enhances stride length and walking speed, while exerting sustained effects on knee joint range of motion and stride length	Notable gait enhancements in patients with KOA are achieved by integrating uphill treadmill training with conventional physical therapy	[34]

(treatment methods aimed at restoring normal muscle and joint function for a specific health goal), based on research about exercise therapy are the most often recommended and studied interventions for KOA (Fig. 3). Exercise therapy is a cornerstone of non-pharmacological management for KOA, fundamentally impacting patient function, pain levels, and quality of life through multiple mechanisms. From a functional perspective, structured exercise programs significantly improve physical function, including walking speed, stair-climbing ability, and overall mobility, directly addressing the limitations imposed by KOA [6]. This improvement is primarily attributed to enhanced muscle strength and endurance, particularly in the quadriceps and hamstrings, which are often atrophied and weakened in patients with KOA. Strengthening these periarticular muscles provides greater joint stability, reduces abnormal loading across the knee joint, and improves shock absorption during weight-bearing activities [42]. Regarding muscle activation, exercise interventions, especially neuromuscular training, play a critical role in restoring proprioception and enhancing motor control. Patients with KOA often exhibit altered muscle activation patterns and reduced balance, which contribute to instability and an increased risk of falls. Targeted exercises help to re-educate the nervous system, optimize muscle recruitment, and improve coordination, leading to more efficient and safer movement patterns [43]. This optimized muscle activation directly translates to better functional performance and reduced knee pain. While exercise therapy is not typically expected to reverse established structural damage in articular cartilage, emerging evidence suggests it may exert beneficial effects on joint tissues and the overall joint environment. Regular physical activity can improve synovial fluid circulation, thereby enhancing nutrient delivery to the cartilage and facilitating waste removal. Moreover, exercise can reduce systemic and local inflammation within the joint, as demonstrated by decreases in inflammatory biomarkers, which contribute to pain reduction and may slow disease progression [44]. These therapeutic outcomes highlight that exercise therapy is not merely symptomatic relief but a fundamental intervention addressing various pathological and functional aspects of KOA.

Motion type and parameter selection

Notwithstanding extensive investigations, multiple pivotal aspects of exercise therapy for KOA still lack definitive characterization. The challenge of methodologically evaluating how exercise interventions influence the progression of joint structural damage in KOA has persisted consistently [45]. Exercise therapy may be administered in several formats, either individually or in groups, under the guidance of a physiotherapist, contingent upon aspects such as rhythm, duration, and technique [40]. Regarding the selection of exercise parameters, the third recommendation of the 2003 EULAR guidelines highlighted the importance of exercise and proposed effect sizes (ES) ranging from 0.57 to 1.00 [46]. The 2008 OARSI guidelines provide more comprehensive recommendations, promoting "regular aerobic exercise, muscle strengthening, and mobility exercises." The summary ES for pain alleviation was 0.52 for aerobic activity and 0.32 for muscular strengthening [47]. To enhance the operability and detail of exercise interventions for KOA, specific training parameters, including type, frequency, intensity, and duration, are crucial for effective rehabilitation [48]. Aerobic exercise, such as walking, cycling, or swimming (low-impact activities that minimize joint stress), is highly recommended for individuals with KOA [48]. While jogging has not been shown to exacerbate OA progression, low-impact options are generally considered the preferred choice for managing OA. For aerobic training, patients should aim to exercise at least three days per week (ideally most days) to accumulate at least 150 min of moderate-intensity activity weekly, with moderate intensity defined as the ability to maintain a conversation but not sing, and sedentary or pain-limited individuals advised to start at lower intensities, sessions can begin with 5 to 10-min bouts, gradually increasing to 20 to 30 min daily [48]. Resistance training is crucial for strengthening muscles around the affected joint, thereby reducing pain and improving function in KOA [49], and should be performed two to three non-consecutive days per week to allow muscle recovery [50], intensity should start relatively low (e.g., 10% of one-repetition maximum [1-RM]) and progress to 40–60% 1-RM or pain tolerance, with light intensity typically involving 15–20 repetitions and moderate intensity allowing 10–15 repetitions. Individuals generally perform at least one set of 10 to 15 repetitions per exercise [50]. Initial resistance exercises may include isometric contractions before advancing to dynamic training, targeting major muscle groups surrounding the knee (e.g., quadriceps, hamstrings, gluteal muscles). Additionally, aquatic resistance exercises are also beneficial for reducing joint stress [51]. Additionally, flexibility exercises (e.g., stretching) should be performed regularly to improve joint range of motion and reduce stiffness. Meanwhile, neuromuscular exercises enhance joint stability and control, both of which contribute to functional improvement in KOA [51].The Technical Expert Panel (TEP) of the 2012 American College of Rheumatology (ACR) strongly recommended that all patients with symptomatic KOA participate in an exercise regimen tailored to their competency level. Therefore, decisions should be made on an individual basis,



Physical Activity	Bodily motions generated by skeletal muscles, which elevate energy consumption beyond basal levels, constitute physical activity. This term has a wide scope, covering exercises, sports, and physical actions involved in daily routines, work, recreational activities, and modes of active travel.
Resistance Exercise	Resistance Exercise involves muscle contractions against an external load or resistance. This form of exercise is primarily intended to enhance muscular strength and promote muscle hypertrophy.
Aerobic Exercise	Aerobic exercise comprises rhythmic, continuous movements of major muscle groups over extended durations. Its main objective is to boost cardiovascular endurance and overall cardiorespiratory fitness.
Flexibility Exercise	Flexibility Exercise specifically tailored to maintain or expand the flexibility around joints. These activities focus on the full extent of possible joint movement without causing discomfort or injury.
Neuromuscular Exercise	Neuromuscular training aims to optimize sensorimotor function and achieve functional joint stability. Typically carried out in weight-bearing postures, it emphasizes the quality of movement patterns and proper alignment of the lower limbs.
Mind-Body Exercise	Mind-body exercise emphasizes the interconnectedness between the brain, physical body, mental state, and behavioral aspects. It integrates various combinations of movement, breathing techniques, and meditation practices to foster holistic well-being

Fig. 3 Diverse Types of Exercise Therapies for KOA

taking into account the patient's ability and willingness to engage in physical activity [52]. Exercise treatment strategies for individuals with KOA may vary and can be affected by numerous factors. Customized exercise treatment regimens are essential, and a biopsychosocial assessment that considers the patient's values, wants, and preferences can facilitate the process by addressing comorbidities and identifying the activities the patient is most likely to adhere to [53]. Self-efficacy programs and techniques can be combined with behavioural treatments, such as cognitive behavioural therapy, to enhance exercise adherence [54]. Data indicate that individualized programs may be more effective than home-based exercise regimens in alleviating pain and improving functionality [55]. The development of personalized training programs, tailored to the unique physical and mental characteristics of each patient, is crucial for optimising outcomes in KOA management. This approach necessitates a comprehensive, evidence-based assessment of both joint function and multi-dimensional psychological states within a biopsychosocial framework [56]. Physical therapists play a vital role in evaluating joint mechanics, including range of motion, muscle strength, and gait analysis. A thorough history and physical examination are essential for a clinical diagnosis and to assess pain, function, and disability due to KOA. This assessment informs the selection of specific exercises to improve knee extension, flexion, strength, balance, and proprioception [57]. While not direct exercise prescription methods, evaluation of knee instability through self-report has been associated with treatment response following exercise [58]. Psychological factors significantly influence pain intensity, physical activity levels, and adherence in patients with KOA [56]. Common psychological aspects to consider include depressive symptoms, anxiety, kinesiophobia (fear of movement), and self-efficacy for symptom management. Identifying and addressing these factors can significantly impact treatment outcomes [58]. Psychological interventions, such as cognitive-behavioural therapy, combined with exercise, have shown benefits in improving pain, functional disability, and particularly self-efficacy in KOA patients [59].

Exercise therapy is a highly effective, first-line intervention for knee osteoarthritis (KOA), consistently demonstrating significant improvements in patient-reported and objective functional outcomes [60]. Evidence from numerous systematic reviews and meta-analyses robustly supports its capacity to enhance walking, mobility, and overall physical function. Specifically, land-based therapeutic exercise provides short-term benefits in reducing knee pain and improving physical function [19]. Exercise interventions lead to improvements in muscle strength (e.g., knee extensor and flexor strength), maximal gait speed, chair stand time, and balance, all of which directly contribute to enhanced walking ability, mobility, and functional capacity [61]. Regularly doing strength and mobility exercises can relieve pain and improve joint function within a few weeks. Meta-analyses consistently indicate that exercise training can significantly reduce pain and improve physical function and quality of life in individuals with KOA [62, 63]. Authoritative guidelines strongly recommend regular aerobic, muscle-strengthening, and range-of-motion exercises to reduce pain and improve functional capacity in patients with KOA [64]. Outcome measures such as the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and the 36-Item Short Form Health Survey (SF-36) are popular tools for evaluating improvements in physical function and quality of life, further substantiating the benefits of exercise therapy [62].

While exercise therapy is unequivocally effective for symptom management and functional improvement in KOA, evaluating its direct impact on joint structural damage presents significant methodological challenges [65], which often hinder the definitive quantification of subtle structural changes and the establishment of a direct causal relationship between exercise and structural preservation. Practical difficulties include extended imaging follow-up cycles, as robust assessment of cartilage loss and other structural changes in longitudinal studies requires prolonged observation periods to capture meaningful alterations, posing a challenge for intervention studies [59]. Limitations exist in quantifying minor structural changes. Standard morphological MRI sequences, although essential, may lack sensitivity in detecting early, subtle, or reversible changes in articular cartilage and other joint tissues. Radiography, a primary imaging modality, is even more limited: it fails to visualize cartilage directly and only reveals significant disease after considerable cartilage loss [19]. Heterogeneity and variability in imaging assessment further complicate analysis. The diagnostic accuracy of MRI for KOA structural changes can be compromised by inconsistent reference standards and suboptimal methodological tools [67]. Additionally, quantitative cartilage morphometry may vary across different segmentation teams, requiring strict standardization in multi-centre studies [59]. Ambiguity persists regarding the role of imaging in the early stages of OA. The utility of imaging in routine clinical practice for early non-radiographic OA is unclear, with concerns about overutilization without clear clinical benefits [48]. Advanced compositional MRI techniques, despite their promise for detecting early biochemical changes, remain primarily research tools rather than routine clinical applications [59]. These challenges underscore the complexity of isolating the structural benefits of exercise, leading to a focus on more readily measurable clinical outcomes (pain, function) that are responsive to interventions [62].

Dietary intervention

Dietary interventions play a crucial role in the comprehensive management of KOA, primarily through their impact on body weight and systemic inflammation. For overweight or obese individuals with KOA, weight management is a cornerstone of therapy, as even modest weight loss can significantly reduce mechanical load on the knee joint, thereby alleviating pain and improving physical function. Losing 5–10% of body weight has been shown to result in clinically meaningful improvements in pain and function in patients with KOA [7].

Beyond direct mechanical load reduction, certain foods can affect inflammatory markers independently of weight loss, offering additional therapeutic benefits for KOA [8]. Specifically, diets rich in Omega-3 fatty acids, found abundantly in fatty fish (e.g., salmon, mackerel) and specific plant-based sources, have demonstrated anti-inflammatory properties. These fatty acids can modulate the production of inflammatory mediators, leading to reduced joint pain and stiffness in KOA patients [66].

Furthermore, diets high in dietary fiber, often found in fruits, vegetables, and whole grains, have been linked to lower levels of systemic inflammation. Dietary fiber promotes a healthy gut microbiome, which in turn can influence systemic inflammatory responses that contribute to the progression of KOA [67]. Research suggests that a higher intake of fruits and vegetables, indicative of a fiber-rich diet, is inversely associated with inflammatory biomarkers [68]. Antioxidants, such as vitamins C and E, and various phytochemicals present in colourful fruits and vegetables, also play a role by neutralising harmful free radicals and reducing oxidative stress, which are implicated in cartilage degradation and inflammation in KOA [69].In contrast, a Western-style diet, characterized by high intake of saturated fats, refined carbohydrates, and processed foods, tends to promote systemic inflammation and may exacerbate KOA symptoms [70]. Therefore, Weight reduction therapies have shown considerable efficacy for overweight or obese individuals suffering from knee osteoarthritis. An investigation [71] confirms that the degree of weight loss is correlated with pain alleviation. The extent of functional enhancement is proportionate. This review advocates for the integration of weight management and exercise therapy for the management of KOA. A dose–response association has been shown between the magnitude of weight reduction and the alleviation of symptoms, especially in overweight or obese patients [25]. Reduced gastrocnemius and hamstring muscle strength is observed in KOA patients who undergo weight loss via dietary or combined diet-exercise interventions, as opposed to those receiving exercise therapy alone. This signifies less co-contraction around the knee. The benefit of integrating weight reduction with exercise treatment is its ability to reduce knee joint stresses without compromising gait speed [72]. Weight reduction may influence systemic inflammatory markers, potentially benefiting osteoarthritis and its associated conditions [73]. Weight reduction may influence systemic inflammatory indicators, thereby benefiting osteoarthritis and its related conditions. Weight loss is associated with reduced levels of pro-inflammatory cytokines such as tumour necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and C-reactive protein (CRP), as well as adipokines like leptin and resistin, which are hypothesised to drive cartilage degradation and systemic inflammation in KOA [74]. The consumption of certain foods, independent of weight loss, may also positively influence inflammatory markers as part of a dietary intervention. This dietary pattern, emphasising anti-inflammatory foods, is applicable across broad populations for general health benefits and KOA symptom management. Conversely, a high-fat diet is similarly linked to enhanced radiographic development of knee osteoarthritis through pro-inflammatory mediators [75]. While low-carbohydrate diets may lead to weight loss and improved metabolic health, their direct impact on specific inflammatory cytokines in KOA beyond weight reduction requires more dedicated research. However, they may be applicable for individuals seeking significant weight loss and glycemic control. Consequently, weight reduction is crucial for those with overweight and obesity-related osteoarthritis.

Biomechanical intervention

A significant group of therapy modalities for KOA includes therapies aimed at improving the biomechanical conditions of the joints. Biomechanical factors associated with abnormal joint loading include obesity, muscular weakness, alterations in muscle activation patterns, limb malalignment, instability, and potential interactions among these elements. Various externally applied devices (support-related assistive devices) are particularly designed to modify joint stresses. Moreover, therapies designed to instruct patients on alternative joint loading techniques, such as gait retraining, using biofeedback to promote advantageous joint postures and motions while inhibiting detrimental ones, are receiving heightened attention. Biomechanical therapies can be incorporated into comprehensive treatment plans and are particularly relevant to individuals with biomechanical risk factors for KOA, thereby augmenting the effectiveness of primary interventions, such as exercise therapy. Biomechanical interventions for osteoarthritis aim to alter the magnitude and/or spatial distribution of knee joint stress. Typical strategies involve adjusting the orientation of vertical ground reaction forces during gait, directly improving joint stability, and enhancing proprioceptive function, among other methods. A 3D gait study indicates that the substantial decrease in the external adduction moment of the knee joint during ambulation, resulting from various biomechanical treatments, correlates with enhanced pain relief and functional outcomes [75]. Besides modifying the external moment of the knee joint, biomechanical therapies may diminish joint contact forces by lessening the muscles'contribution to aberrant joint loads [76].

Orthotic insoles, knee braces, and walkers are essential innovations for the supplementary management of KOA. Wedge orthotics effectively decrease the adduction angle and torque of the impacted knee. This biomechanical treatment, particularly beneficial for those with foot abnormalities, may alleviate stress on the medial knee joint. Lateral wedge insoles alleviate discomfort (SMD = 0.74, 95% CI 0.06–1.42) [77]. Statistical analyses were performed using RevMan 5.4 (Cochrane Collaboration, London, UK) to generate the effect sizes and confidence intervals. Knee braces have played a crucial role, demonstrating significant pain alleviation (SMD = 0.63, 95% CI 0.9 to 0.35) and functional enhancement (SMD = 0.71, 95% CI 1.14 to 0.28), attributable to biomechanical modifications targeting essential risk variables [78]. Furthermore, the walker not only mitigates discomfort (SMD = 1.72, 95% CI 1.14 to 2.30) and enhances function (SMD = 1.03, 95% CI 0.51 to 1.55), but also dramatically increases the migration rate, particularly evident in the increased distance achieved in the 6-min walk test. The raw data showed a mean improvement of 330 m in the cane group (baseline mean: 5079 ± 2278 m; post-intervention mean: 5409 ± 2773 m) and a mean improvement of 362 m in the control group (baseline mean: 5856 ± 3066 m; post-intervention mean: 5549 ± 2972 m)[79]. Wedge orthotics, particularly lateral wedge insoles, are designed to modify abnormal lower limb alignment, specifically knee varus malalignment, which is common in medial compartment KOA. By altering the foot's pronation or supination, these insoles shift the ground reaction force vector laterally, thereby reducing the external knee adduction moment (KAM) and consequently alleviating stress on the medial aspect of the knee joint. Although some meta-analyses report short-term benefits, the current OARSI guidelines (2019) advise against routine use due to low certainty of evidence. The proper adjustment of insoles may rely on each person's biomechanical characteristics, and some studies suggest that they may still be beneficial for a subset of patients with specific biomechanical factors, such as those with significant varus alignment or foot abnormalities [19]. The proper adjustment of insoles should rely on each person's unique biomechanical characteristics, and an individualized assessment is critical. However, the appropriate dose–response relationship remains understudied in the current literature. The use of gait assistive equipment (e.g., knee braces, walkers) is strongly recommended for KOA patients when ambulatory function and stability are substantially compromised, or when pain indicates a need for such devices [19]. The hand on the contralateral side of the afflicted knee joint may diminish the external adduction moment of the knee joint by as much as 10% particularly when ambulation and stability are markedly compromised. It is crucial for alleviating the burden on the knee joint.

Gait retraining

Additional biomechanical characteristics in individuals with knee osteoarthritis will undergo alterations. These individuals have an elevated knee adduction moment (KAM), which is correlated with increased radiographic severity, accelerated disease progression, and reduced function and discomfort [80]. KAM indirectly quantifies the mechanical load on the medial knee compartment by assessing the magnitude and offset of the ground reaction force vector relative to the knee joint centre. Consequently, the therapeutic approach designed to diminish it facilitates tibiofemoral unloading, mitigates symptoms, and decelerates the structural advancement of the condition [81]. Gait retraining is a practical approach for managing individuals with knee osteoarthritis.

Prior research has shown that it alters walking patterns, thereby decreasing internal knee strain [29, 82, 83]. Participants who received gait retraining demonstrated flexibility both during the training and across multiple sessions. The ability to absorb and integrate these modifications is critical. Gait retraining primarily aims to adjust the trajectory of ground reaction forces, reduce the knee adduction moment, and potentially alleviate stress on the medial compartment of the tibiofemoral joint. Most approaches utilize biofeedback mechanisms, such as instrumented gait analysis or in-shoe pressure sensors, to effectively modify specific gait biomechanics, including the knee adduction moment [84]. Gait strategies, such as trunk lean and medial push, have demonstrated significant efficacy in reducing the knee adduction moment [85]. These tactics involve laterally tilting the weight-bearing limb during walking to alter the centre of gravity and intentionally adducting the knee to decrease the varus angle. However, the biomechanical effects on adjacent joints (e.g., hip and ankle) remain undetermined [82]. These alterations may result in heightened co-contraction and an augmented external flexion moment at the knee joint, thereby elevating the load on the knee joint. Shorter strides effectively reduce the external adduction and flexion moments of the knee joint, particularly when combined with additional modifications [86]. A broader step width results in a slight decrease in the internal adduction moment of the knee joint, without a corresponding increase in muscle co-contraction [87].

Moreover, both bilateral toe-in and toe-out gaits have been shown to reduce the knee joint external adduction moment, though with somewhat heterogeneous outcomes [29]. In forefoot gait, heel external rotation shifts the centre of pressure laterally, thereby decreasing the knee adduction moment and shortening the frontal plane lever arm during early stance [88]. A significant reduction in knee joint adduction moment has been observed during forefoot gait; however, this is accompanied by increased activation of the flexor muscles, suggesting enhanced total muscular co-contraction [87]. The mechanisms underlying the decrease in peak knee joint abduction moment during toe-out gait appear to differ between the first and second peaks [89]. In the initial stance phase, toe-out gait seems to convert part of the knee adduction moment into an abduction moment by creating an offset along the knee joint axis, which influences the timing of the first peak knee adduction moment. The decrease in the second peak knee adduction moment during toe-out gait is thought to be associated with reduced frontal plane moment arm during the late stance phase [89]. The attenuation of the second peak knee joint adduction moment in toe-out gait (approximately 10–20°) is more consistent and has been observed in individuals with early-stage disease [90].

Gait retraining programs utilize biofeedback instruments, such as mirrors [91] or real-time knee adduction moment biofeedback devices[81], to enhance the toe-out gait technique and have been recently introduced in cases of KOA. Consequently, the accessible high-quality evidence is limited. A solitary walking regimen has shown improvements in discomfort and functionality; nevertheless, the incorporation of gait retraining has markedly decreased the knee adduction moment, suggesting an improvement in joint stress that may prevent disease development [91]. A rigorous investigation demonstrated sustained enhancement in KAM at a 6-month follow-up, suggesting the retention and enduring benefits of gait retraining [81]. These results underscore the therapeutic significance of gait modification techniques augmented by real-time biofeedback instruments in enhancing individual gait function. The utilization of wearable real-time biofeedback technologies, including haptic and virtual reality feedback systems, for gait retraining has been underexplored. Such wearable measurement tools may simplify the implementation of interventions and promote the adoption of this conservative therapy into standard clinical care [92] (Fig. 4).

Physical therapist intervention

Physical therapists play a vital role in evaluating joint mechanics, including range of motion, muscle strength, and gait analysis. A thorough history and physical examination are essential for clinical diagnosis and assessment of pain, function, and disability associated with KOA, which in turn informs the selection of specific exercises to improve knee extension, flexion, strength, balance, and proprioception. While not direct exercise prescription methods, evaluation of knee instability through self-report has been linked to treatment response following exercise [93]. Psychological factors significantly influence pain intensity, physical activity levels, and adherence in

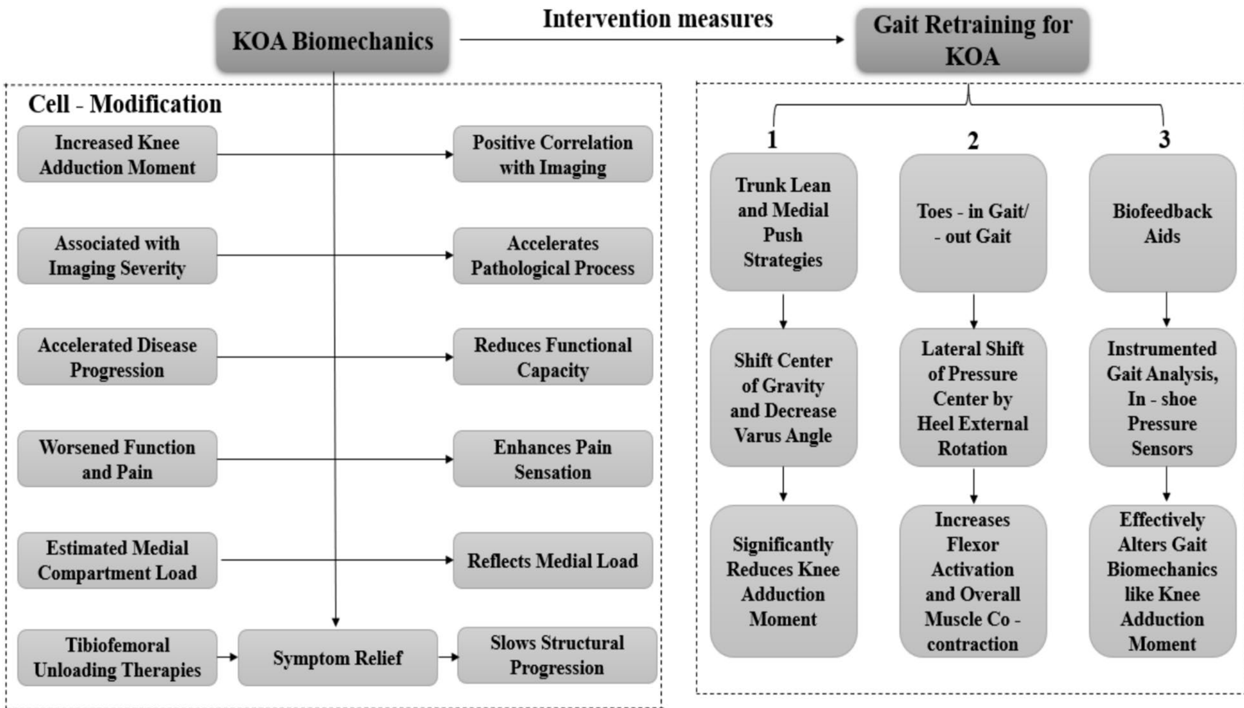


Fig. 4 Intervention Measures from KOA Biomechanics to Gait Retraining for KOA

patients with KOA. Common aspects to consider including depressive symptoms, anxiety, kinesiophobia (fear of movement), and self-efficacy for symptom management, with identification and addressing of these factors substantially impacting treatment outcomes. Psychological interventions such as cognitive-behavioural therapy, when combined with exercise, have demonstrated benefits in improving pain, functional disability, and particularly self-efficacy in KOA patients [94]. However, the effective implementation of exercise adherence and self-management strategies is often hindered by distinct barriers, particularly in specific populations such as those in China or individuals with low health literacy. For Chinese patients, barriers may include traditional illness beliefs, preference for passive treatments over active exercise, limited understanding of long-term self-management importance, and financial constraints. Individuals with low health literacy face challenges in comprehending complex medical instructions, interpreting health information, and navigating healthcare systems, which directly impair their ability to engage effectively in exercise and self-management [95].

To overcome these barriers, physical therapists must adopt targeted countermeasures. Firstly, family involvement is crucial, especially in collectivist cultures like China, where families often play a significant role in healthcare decision-making and support. Therapists should educate family members about the patient's condition, the benefits of exercise, and methods for providing practical and emotional support to foster a supportive home environment [96]. Secondly, community support programs can offer accessible, supervised exercise opportunities that promote social interaction and peer motivation, leveraging local resources and social networks to facilitate long-term adherence. Lastly, culturally tailored patient education materials and communication strategies are essential, involving culturally appropriate language, imagery, and examples that respect traditional health beliefs to enhance the relatability and actionability of information across diverse populations [95].

Furthermore, physical therapists require specific strategies to address patients' families' concerns, which often include fear of pain and misunderstandings about exercise or rehabilitation. Transparency and clear communication are paramount: therapists should address fear of pain by explaining the distinction between "good pain" (muscle soreness from exercise) and "bad pain" (indicating harm), emphasizing that exercise is gradually progressed and monitored to stay within tolerable limits, with controlled movement often reducing rather than increasing long-term pain [97]. Demonstrating exercises and allowing family members to observe or participate in sessions can build trust and reduce anxiety. They should also correct misconceptions, such as the belief that rest is always optimal for joint pain or that exercise will further"wear out"the joint, by explaining the scientific basis of exercise—highlighting its role in cartilage nourishment, muscle strengthening, and overall joint health —and providing simple, concise explanations about rehabilitation to set realistic expectations for improvement and adherence [95]. Utilizing visual aids, plain language, and"teach-back"methods to confirm understanding can significantly enhance family engagement and compliance [98]. By integrating these strategies, physical therapists can substantially improve exercise adherence and self-management in patients with KOA, particularly in culturally diverse contexts or among individuals with varying health literacy levels, thereby enhancing the practical implementation and long-term success of rehabilitation plans.

Self-management and education

Patient education is crucial for informed decision-making, self-management of the condition, and adherence to medication among patients with knee osteoarthritis [99]. The condition may significantly diminish patients'self-esteem, frequently making misery a key facet of their existence. The erroneous perception that osteoarthritis is an irreversible progressive condition linked to particular pathogenic factors may cause patients to diminish physical activity and embrace a more constrained lifestyle, leading to a notable sense of loss and isolation due to decreased social interactions. There is an urgent need to alleviate this adverse effect by the use of suitable patient education initiatives to enhance illness management and align patient expectations with treatment results. Patients'comprehension of this condition is inadequate [100]. Despite efforts by guideline organizations to disseminate health information to the public, the quality of most patient education materials for individuals with knee osteoarthritis remains subpar, and the readability level is frequently unsuitable, typically matching or exceeding the recommended level of 7th to 8th grade [101].

Healthcare workers, including physical therapists, must possess a comprehensive grasp of this condition to assist patients in acquiring high-quality health information. A consensus statement from specialists and patients with osteoarthritis from 13 countries and regions highlighted 21 essential pieces of information to be conveyed to patients [102]. The initial three points pertain to the capacity of regular physical exercise and tailored exercise regimens to diminish pain, avert decline, and enhance daily functioning in KOA; The benefits of weight loss for overweight or obese individuals, coupled with the advantages of maintaining a healthy weight through dietary and exercise interventions; the potential for substantial alleviation of KOA symptoms without surgical intervention. Additional pertinent facts on illness comprehension, pharmacological consumption, and diagnostic techniques. This information is essential for facilitating the translation of data into patient understanding and enhancing interactions between patients and clinicians, consequently offering insights into educating KOA patients and improving decision-making.

Manipulative therapy

The evidence for manual treatment approaches to enhance the functionality of individuals with knee osteoarthritis is limited, with other suggested therapies being considered [103]. Evidence suggests that incorporating manual therapy into exercise treatment with KOA may alleviate pain in the short term, or that manual therapy can be used independently of exercise. While exercise, dietary interventions, and biomechanical aids form the cornerstone of KOA management, other physical therapy modalities, including manual therapy, taping, and acupuncture, are explored as adjunctive treatments. Recent high-quality evidence offers updated perspectives on their efficacy. Manual therapy, which includes mobilization and manipulation techniques and aims to restore joint mechanics, reduce pain, and improve range of motion, was evaluated in randomized controlled trial regarding its effects on pain in KOA patients; the analysis showed that both manual therapy and strengthening exercise reduced pain immediately after the intervention, with manual therapy providing superior short-term pain relief (effect size = 0.799 for VAS scale in the MT group). Still, it noted that its long-term effects remain inconclusive with low to very low levels of evidence [104], suggesting it can be a valuable short-term adjunct for pain management, especially when integrated with exercise programs. Kinesio taping, used to provide support, reduce pain, and facilitate muscle function in musculoskeletal conditions, was categorized as having low evidence quality, mixed or inconclusive results, or insufficient efficacy to strongly support its routine use in a July 2024 umbrella review summarizing non-pharmacological and non-surgical interventions for KOA [105], indicating that current high-quality evidence from recent comprehensive reviews does not strongly advocate for it as a primary KOA intervention and its role may be limited or require further high-quality research. Acupuncture, a traditional Chinese medicine technique for pain management, has been the subject of recent meta-analyses; a June 2025 meta-analysis on combining Thunder Fire Moxibustion with other TCM modalities (including acupuncture) for KOA showed potential effectiveness with minimal adverse reactions but low overall evidence quality [106]. The need for high-quality randomised clinical studies for most of the previously identified adjunctive therapies remains unfulfilled. Moreover, the question of whether adjuvant therapies, in conjunction with standard KOA treatment, demonstrate synergistic advantages—such as the interaction between cryotherapy and exercise interventions—warrants further exploration[107]. Consequently, in light of the existing data, we advise that physical therapists refrain from using these techniques in clinical practice. Nevertheless, if this treatment remains under consideration, we recommend that it be attuned to patient preferences, and therapists must provide patients with a comprehensive and lucid explanation to substantiate the evidence for its use in KOA.

Adjuvant therapy

Beyond core exercise and lifestyle modifications, various adjuvant therapies are often employed to manage symptoms and potentially improve outcomes in KOA. While these interventions are generally considered supplementary to primary rehabilitation strategies, their efficacy and mechanisms of action vary, and their integration into a comprehensive management plan requires careful consideration of the evidence.

One widely utilized class of adjuvant therapies involves intra-articular injections. Among these, hyaluronic acid (HA) injections are commonly used to supplement the synovial fluid, which is often diminished and degraded in KOA. The proposed mechanisms include improved joint lubrication, reduced friction, shock absorption, and anti-inflammatory effects [108]. Numerous studies have investigated the efficacy of intra-articular HA for KOA, with meta-analyses suggesting that HA injections can provide moderate pain relief and functional improvement, particularly in the short to medium term (up to 6 months) for patients who have not adequately responded to conservative measures [109]. However, the magnitude of effect can vary, and some larger studies or systematic reviews have questioned its long-term benefits or cost-effectiveness compared to placebo or other interventions [108].

Another non-pharmacological adjuvant approach gaining attention is laser therapy, specifically low-level laser therapy (LLLT), also known as photobiomodulation therapy. LLLT involves the application of low-power lasers to the affected joint, with proposed mechanisms including anti-inflammatory effects, pain modulation through endorphin release, and promotion of tissue repair at the cellular level [109]. Research indicates that LLLT can lead to significant reductions in pain and improvements in physical function in patients with KOA, with several systematic reviews and meta-analyses supporting its short-term efficacy [110]. The optimal dosage, wavelength, and treatment parameters are still areas of ongoing research, but its non-invasive nature and favorable safety profile make it an attractive option for some patients.

Other adjuvant therapies include topical agents (e.g., NSAID creams, capsaicin), transcutaneous electrical nerve stimulation (TENS), and various forms of thermal treatment (heat/cold). Topical NSAIDs offer localized pain relief with reduced systemic side effects compared to oral formulations [111]. While their effects are generally less pronounced than exercise or weight loss, these therapies can contribute to symptom management, particularly for acute pain flares or when oral medications are contraindicated. The selection of an adjuvant therapy should be individualized, considering patient preferences, comorbidities, and the specific pain mechanisms involved, always within the context of an overall rehabilitation program.

Prospect of KOA treatment

Despite more than a century of study on KOA, this analysis revealed that no effective medications exist to halt or slow the progression of joint degradation. Nonetheless, technological breakthroughs are yielding novel techniques and interventions to assist these individuals. Biomaterials associated with innovative cell-based methodologies, particularly in cartilage regeneration—including scaffolds, hydrogels, microspheres, and nanofibers—show potential for the restoration of osteoarthritic joints [114]. However, robust clinical data remain limited [112]. Computer technology, particularly data mining and machine learning (ML) techniques, offers significant potential for advancing KOA management. These technologies can be combined to develop predictive models that analyze extensive patient data and inform targeted, personalized therapeutic strategies. Specifically, such ML models integrate diverse input variables, including clinical indicators (e.g., age, sex, BMI, comorbidities, pain scores via VAS or WOMAC, functional assessments such as 6-min walk test) [113]., biomechanical parameters (e.g., knee adduction moment, stride length, muscle strength, balance metrics from gait analysis) [114], imaging features (e.g., joint space width from X-rays, cartilage volume and bone marrow lesions from MRI), and emerging omics data (genomics, proteomics, metabolomics) [115]. The output targets of these models are clinically impactful, predicting treatment response rates to specific interventions (e.g., exercise regimens, dietary strategies), disease progression risk (e.g., radiographic worsening, need for joint replacement), pain management efficacy, and functional recovery trajectories [116]. The technical feasibility of these models is supported by advancements in computational power, access to large-scale datasets (e.g., electronic health records, national registries), and sophisticated algorithms (e.g., deep learning, random forests) [117]. Utilizing this modeling approach has the potential to conserve medical resources and reduce societal costs by alleviating disease burden, while facilitating advancements in imaging, electronic medical record management, genetic analysis, and serum profiling to enhance KOA symptom stratification [118]. Mobile health leverages smartphone functionalities and integrated sensors to collect real-world patient data [119]. Sensor-derived data can quantify movement patterns critical for physical function assessments, with studies showing reduced recall bias in symptom monitoring [120].

Conclusions

This narrative review synthesizes current evidence on KOA rehabilitation, emphasizing that non-surgical interventions—including exercise therapy, dietary modification, biomechanical optimization, and physical therapist-guided strategies—form the cornerstone of management. Exercise therapy, encompassing resistance, aerobic, neuromuscular, and mind–body exercises, demonstrates robust evidence in alleviating pain, improving functional capacity, and reducing joint loading. Combining exercise with dietary interventions yields synergistic benefits, particularly in weight loss and modulation of systemic inflammation, which are critical for mitigating disease progression. Biomechanical interventions, including unloader braces and gait retraining methods (e.g., trunk lean and toe-out strategies), have been shown to decrease KAM and medial compartment loading effectively. However, their long-term effects on joint structural preservation require additional validation. Notably, the review highlights gaps in current practice: suboptimal adoption of guideline-recommended therapies (e.g., < 50% of patients receive evidence-based care); limited evidence for adjunctive therapies (e.g., manual therapy, acupuncture); and inadequate personalisation of interventions, particularly regarding patient-specific factors (e.g., biomechanics, comorbidities). Future research should prioritize developing precision rehabilitation models using machine learning and patient-derived biomarkers, investigating the long-term effects of biomechanical interventions on joint structure, harnessing mobile health technologies for real-time gait analysis and adherence monitoring, and evaluating the efficacy of emerging biologic approaches (e.g.,scaffold-based cartilage regeneration)—all of which align with the evolving landscape of KOA management, characterized by rapid advancements across diagnostic, therapeutic, and prognostic fronts. While novel technologies such as artificial intelligence (AI), mobile health (mHealth), and large-scale database mining offer transformative potential, their true impact hinges on successful clinical translation and integration into routine practice: mobile health (mHealth) platforms, for instance, are increasingly leveraged for the long-term follow-up of KOA patients, facilitating continuous symptom monitoring, medication adherence tracking, and the provision of educational resources, enabling proactive management and personalized feedback to enhance patient engagement and self-management capabilities; similarly, AI algorithms are emerging as powerful tools for developing individualized exercise prescription programs, as they can analyze patient-specific data (e.g., activity levels, pain scores, joint kinematics) to tailor rehabilitation protocols, representing a significant step towards precision medicine in KOA. Concurrently, cutting-edge biological and regenerative approaches, including advanced biomaterials and scaffold-based cartilage regeneration, hold considerable promise for addressing the underlying pathological processes of KOA. However, despite encouraging preclinical and early-stage clinical results, these technologies remain largely experimental, with limited evidence for their widespread clinical translation. This necessitates the conduct of extensive, well-designed trials to establish their long-term efficacy, safety, and cost-effectiveness. In summary, advancing KOA management will require synergistically integrating advanced digital technologies for personalized care delivery with rigorous, evidence-based adoption of novel biological therapies, balancing technological innovation with practical applicability and cautious optimism regarding experimental interventions to evolve clinical practice toward more targeted, patient-centred strategies that combat disease progression and improve quality of life.

Author contributions

H.L. (Hao Liu) and L.Q. (Lei Qin) conducted the literature search, collected and organized relevant information, and wrote the main body of the manuscript. Y.L. (Yanhong Liu) was responsible for data extraction and analysis, and helped with the revision of the manuscript. X.M. (Xiangxiang Meng) prepared the figures and tables in the manuscript. C.L. (Chunjun Li) carried out the critical review of the manuscript and provided valuable suggestions for improvement. M.H. (Ming He) supervised the whole research process, coordinated the work among different authors, and finalized the manuscript. All authors reviewed and approved the final version of the manuscript.

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Declarations

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