

Aquatic Exercise and Other Physical Therapies for Knee Osteoarthritis: A Narrative Review of Clinical Efficacy, Mechanisms and Future Perspectives

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ABSTRACT

Knee osteoarthritis (OA) is a common disease, especially among the elderly, and poses a serious global health burden. This review aims to analyze the clinical efficacy of aquatic exercise and other physical therapies in the treatment of knee osteoarthritis, focusing on its mechanism of action, efficacy and future prospects. The review emphasizes the role of aquatic exercise. Due to the buoyancy and resistance of water, water exercise provides a low-impact but effective treatment that can reduce pain, improve function and enhance joint stability. This review compares water exercise with other non-drug treatments, such as land-based exercise, manual therapy and electrotherapy, to evaluate their biomechanical and physiological effects. Although clinical research results generally support the value of water therapy, its benefit mechanism and its impact on joint load, muscle activation and exercise efficiency are not fully clarified. Filling these research gaps is crucial to the development of more personalized and sustainable rehabilitation programs. This review further explores the potential role of emerging technologies, including wearable sensors and digital monitoring tools, in promoting precise rehabilitation. In addition, this article also discusses the future development direction, emphasizes the importance of long-term clinical trials, and the necessity of combining biomechanics and biomedical engineering to improve and optimize the physical therapy strategy for patients with knee osteoarthritis.

KEYWORDS

Knee osteoarthritis; Aquatic exercise; Physical therapy; Rehabilitation; Biomechanics; Clinical efficacy; Public health; Personalized rehabilitation

1. INTRODUCTION

Knee osteoarthritis is one of the most common musculoskeletal diseases among the elderly around the world. The disease affects about 16% of the adult population, and the prevalence of adults after the age of 40 has increased significantly [1]. The main risk factors associated with knee osteoarthritis include aging, overweight or obesity, and repeated joint weight. Clinically, knee osteoarthritis is characterized by chronic pain, joint stiffness and progressive dysfunction, which leads to decreased mobility and reduced quality of life.

Knee osteoarthritis not only affects individuals but also poses great challenges to the public health system and economy. Data from the Global Disease Burden Report shows that between 1990 and 2021, the burden of the disease has been increasing, and there are significant regional differences [2]. In high-income countries, the aging of the population and the rising obesity rate have led to an increase in the prevalence of knee osteoarthritis and the demand for health care; while in low-income countries, the current incidence of knee osteoarthritis is low. However, it is expected that by 2050, the number of cases in low-income countries will increase due to the improvement of lifestyle and

health care [3]. The cost of treatment and nursing of knee osteoarthritis accounts for a large proportion of global health expenditure, including drug treatment, rehabilitation and surgical intervention [4].

Currently, the treatment strategies for knee osteoarthritis include drug treatment, surgical intervention and non-drug treatment. Among non-drug treatment, physical therapy is widely recommended as a first-line non-drug treatment because it can relieve pain, improve joint function and enhance muscle strength [5]. Common physical therapy methods include land exercise, water exercise, manual therapy, electrotherapy and other auxiliary treatments. As an alternative or adjuvant therapy, aquatic exercise is receiving increasing attention among patients with knee osteoarthritis. Its treatment principle is based on the biomechanical properties of water—buoyancy can reduce joint load, while water resistance provides a controllable environment for muscle strengthening and joint stability [6]. Clinical research shows that water exercise can effectively reduce pain and improve function, especially for patients who find it difficult to do land exercise due to pain or limited movement [7].

Although aquatic exercise is widely used in clinical practice, there are still research gaps. Existing research mainly focuses on the overall clinical efficacy, while the research on the biomechanics and physiological mechanisms behind different physical therapy methods is very limited. There is little evidence to compare aquatic exercise with other physical therapies in terms of joint load, muscle activation and exercise efficiency. The inadequacy of this mechanism research restricts the formulation and implementation of personalized rehabilitation strategies.

Therefore, this review will comprehensively analyze and evaluate the current evidence of aquatic exercise and other physical therapy interventions for the treatment of knee osteoarthritis, paying special attention to the potential biomechanics and physiological mechanism, clinical efficacy and broader public health significance. By analyzing the advantages and limitations of different treatment methods, this review aims to provide reference for the formulation of more targeted, effective and sustainable rehabilitation strategies for patients with knee osteoarthritis.

2. PATHOLOGICAL MECHANISMS OF KNEE OSTEOARTHRITIS

The main characteristics of knee osteoarthritis are cartilage degeneration, subchondral bone changes and intra-articular inflammation. As the disease worsens, substances such as matrix metalloproteinase (MMPs) begin to decompose the extracellular matrix of cartilage and destroy important components such as proteoglycans and collagen fibers. This will lead to rough joint surface, limit joint movement, and cause pain due to bone sliding damage [11]. After the cartilage wears out, the bones below will harden and form new bone tissue, further exacerbating pain and stiffness [13]. Intra-articular inflammation is characterized by increased production of pro-inflammatory cytokines, which will further amplify the inflammatory cascading reaction, accelerate cartilage degeneration, and further damage the joints. These cytokines accelerate cartilage degeneration and affect bone formation [14]. In addition, factors such as obesity and metabolic problems can put additional pressure on the joints, thus exacerbating knee osteoarthritis [15]. Therefore, knee osteoarthritis is not only a local joint problem but also affected by systemic inflammation and metabolic status.

3. BIOMECHANICAL AND PHYSIOLOGICAL TARGETS OF PHYSICAL THERAPY

Physical therapy of knee osteoarthritis mainly targets the factors that cause knee pain and limited function. Excessive joint load and abnormal mechanical stress are key factors of cartilage degeneration and subchondral bone changes. Therefore, reducing joint load and improving the load distribution during exercise are the core goals of treatment [16]. In addition, the weakening of muscle strength, especially the weakening of the quadriceps femoral muscle and neuromuscular control defects, will reduce joint stability and motor efficiency, and further increase the mechanical stress of

the knee joint [18]. Physical therapy intervention enhances muscle function and coordination to support joint stability and optimize move patterns. Pain regulation and weakening of inflammatory response are also important physiological targets, because chronic pain and low-grade inflammation are closely related to the decline in function and quality of life in patients with knee osteoarthritis [13]. By targeting these interrelated biomechanical and physiological targets, physical therapy can effectively relieve symptoms and improve function. Specific intervention strategies will be discussed in the following chapters.

4. MECHANISMS OF PHYSICAL THERAPY INTERVENTIONS

4.1. Mechanisms of Land-Based Exercise

For knee osteoarthritis, land-based exercise is one of the most widely recommended non-drug interventions. Its main mechanism is to improve joint stability and reduce biomechanical load by improving muscle strength. Resistance training and strength training, especially training for the lower limbs, can enhance muscle mass and neuromuscular function, thus improve joint support and reduce excessive mechanical stress on the knee joint [19]. Aerobic land-based exercises, such as slow walking, can promote blood circulation and synovial fluid flow, help improve joint lubrication, and reduce joint stiffness in daily activities [21]. In addition, land-based exercise has been shown to improve balance, coordination and ontological sensation, which may reduce the risk of falls and secondary injuries in elderly knee osteoarthritis patients. From a physiological point of view, regular exercise is also related to the alleviation of systemic inflammation and helps weight management. For overweight people, weight loss can effectively reduce the load on the knee joint and slow down the rate of cartilage degeneration. Through the joint action of these biomechanical and physiological mechanisms, land-based exercise plays an important role in reducing knee pain and improving knee function.

4.2. Mechanisms of Aquatic Exercise

The effect of aquatic exercise on knee osteoarthritis is mainly reflected in the buoyancy and resistance of water, which together create a low impact but effective training environment. The buoyancy of water can reduce the load pressure on the knee joint, thus reducing the load and exercise pain of the knee joint, especially for patients with severe symptoms or obesity [6]. At the same time, the resistance of water helps to enhance muscle strength and stabilize joints, and will not cause excessive mechanical stress, thus improving function. And there is evidence that aquatic exercise can reduce pain and dysfunction, which may be related to the reduction of mechanical stress and potential changes in inflammatory activity, although there is still insufficient direct evidence at the molecular or cartilage level [8]. In addition, a warm environment can promote blood circulation and synovial fluid flow, thus relieve joint stiffness and improve exercise comfort. Through the combined effect of mechanical unloading, resistance strengthening and physiological regulation, aquatic exercise provides a safe and accessible intervention to improve the pain, function and long-term compliance of patients with knee osteoarthritis.

4.3. Mechanisms of Manual and Adjunct Physical Therapy

Manual treatment and adjunct physical therapy mainly assist the treatment of knee osteoarthritis by reducing pain, improving soft tissue activity and promoting joint activity. Manual therapy techniques, including joint and soft tissue loosening, are to reduce muscle tension and improve flexibility, to expand the range of joint movement and improve functional comfort [23], while improving local blood circulation, which helps patients' activities and participation in rehabilitation plans [24]. Cryotherapy mainly relieves inflammation and acute pain through tissue cooling and vasoconstriction, while thermotherapy promotes muscle relaxation and increases blood flow, thus helping to reduce

joint stiffness and improve joint mobility [26]. Therapeutic ultrasound uses mechanical sound waves to enhance microcirculation and promote soft tissue repair, thus helping to relieve pain and improve function [29]. In general, these techniques and adjunct interventions with supplementing exercise therapy is suitable for patients with severe pain, insufficient exercise tolerance or in the early stage of recovery, and the overall rehabilitation effect is achieved by improving exercise ability [32].

5. CLINICAL EFFECTIVENESS

5.1. Pain Reduction

Clinical evidence consistently shows that all physical therapy methods can effectively reduce the pain of patients with knee osteoarthritis, but their effects and duration are different. Systematic evaluation and meta-analysis evidence shows that in a specific patient group, aquatic exercise can reduce short-term to medium-term pain more effectively than land sports, especially in a warm or spa environment [8]. Randomized controlled trials and meta-analysis show that structured land-based exercise programs can significantly improve short-term pain [20]. However, due to the low impact and support of water, aquatic exercise may provide more lasting pain relief for patients with high baseline pain or limited tolerance for loading activities [33]. Manual treatment and adjunct physical therapy also help to reduce pain, but if there is no simultaneous exercise intervention, the effect is often short [35]. Electrotherapy, including percutaneous nerve electrical stimulation, can produce analgesic effects through nerve regulation, but evidence shows that its effect is limited and the duration is relatively short [24]. Cryotherapy can effectively reduce swelling by inhibiting inflammatory reactions, but it is common for symptoms to recur after stopping treatment [28]. Therapeutic ultrasound can help reduce pain by promoting soft tissue healing, but its long-term efficacy is still not as stable as active exercise therapy [29].

5.2. Functional Improvement

Both aquatic and land-based exercise have been conformed to improve knee function, although they affect functional results through different biomechanical pathways. Systematic evaluation and meta-analysis show that water sports can effectively enhance lower limb muscle strength, joint mobility and gait performance, especially suitable for patients with limited function or decreased exercise endurance due to pain [6]. In a low-impact environment, the improvement of exercise quality and neuromuscular participation may further promote the improvement of patients' functions in daily activities. There is evidence that land exercise can effectively improve functional results, including walking ability and joint control ability [36]. However, some patients may limit the intensity of training and reduce the effect of functional improvement if they have insufficient tolerance for pain, fatigue or weight-bearing activities. In contrast, manual therapy and assisted physical therapy seem to have limited effect on long-term functional improvement. Manual treatment may temporarily increase the range of joint activity, but without continuous active muscle involvement, these benefits tend to be weakened [37]. Electrotherapy and cryotherapy mainly target pain and inflammation and have little direct effect on muscle strength or functional activity. Similarly, although therapeutic ultrasound may help soft tissue recovery, its impact on long-term joint stability and functional performance is still limited as an independent intervention.

5.3. Quality of Life

Both aquatic and land-based exercise interventions have a positive impact on the improvement of the quality of life of patients with knee osteoarthritis, mainly due to the reduction of pain and the enhancement of physical function. Aquatic exercise seems to have a particularly positive impact on the quality of life, because it can reduce joint load and allow patients to participate in physical activities, so that they can live a better independent life. Previous studies have shown that aquatic

exercise can improve joint flexibility and muscle strength, thus helping to improve physical function and perceived health [8]. In addition to physical benefits, systematic evaluation also shows that aquatic exercise may alleviate psychological symptoms such as anxiety and depression by improving pain control, enhancing exercise self-confidence and improving exercise tolerance [7]. Although land-based exercise has also been shown to improve the quality of life, its effect may vary depending on the severity of the disease and the individual's tolerance for weight-bearing activities. High mechanical load and exercise-related discomfort may limit the participation or long-term persistence of some patients, thus reducing their overall impact on the quality of life [19]. The impact of manual treatment and auxiliary physical therapy on long-term quality of life seems to be more limited. Although manual treatment may temporarily improve joint mobility, these short-term mechanical improvements cannot continue to translate into improvements in daily function or mental health [37].

5.4. Treatment Adherence

The compliance of rehabilitation intervention varies from method to physical therapy and plays a crucial role in determining the long-term clinical efficacy of knee osteoarthritis. For aquatic exercise, patients usually have a high degree of compliance, which is mainly due to their low impact and buoyancy to help reduce joint load, which enables patients with pain, obesity or limited mobility to exercise more comfortably and confidently [7]. Patients who participate in water or spa programs generally believe that these interventions are more likely to persist for a long time, which may help increase participation and support longer-term treatment results [7]. In contrast, there is a big difference in the compliance of land-based exercise. High mechanical load and discomfort during exercise may prevent some patients from persisting in exercise, especially those who are more seriously ill or sensitive to pain [20]. Factors such as fatigue, fear of aggravation of pain, and fear of injury have been considered obstacles to continuous weight-bearing or high-intensity land movement. The effect of manual treatment and auxiliary physical therapy usually requires repeated clinical treatment to be maintained. Frequent treatment may limit the long-term compliance of patients, especially when these therapies are not combined with active exercise programs [35]. In addition, relying on passive symptom relief strategies may reduce the enthusiasm of patients to participate in self-managed physical exercise, resulting in long-term compliance instability.

6. FUTURE DIRECTIONS

6.1. Innovative Treatment Technologies and Personalized Rehabilitation Strategies

In recent years, aquatic exercise and a variety of physical therapy methods have shown reliable clinical value in the rehabilitation of knee osteoarthritis. Looking to the future, the research should focus on exploring how to deeply integrate these traditional therapies with emerging technologies to further enhance the treatment effect and achieve individualized intervention. Combining water training with land exercise, intermittent manual therapy or neuromuscular control training may play a complementary role at different stages, improve pain management and promote functional recovery [5]. At the same time, the rapid development of intelligent wearable devices and digital monitoring technology has also provided new ideas for precise rehabilitation. By continuously monitoring gait characteristics, joint activity amplitude and load distribution, the treatment plan can be adjusted according to real-time data, so as to improve safety and rehabilitation efficiency. Designing targeted plans based on individual differences of patients, such as age, body mass index, disease severity and functional baseline - can not only enhance compliance, but also achieve more significant improvements in long-term efficacy.

6.2. Integration of Biomedical Engineering and Biomechanics

The progress of biomedical engineering and biomechanics is providing new technical support for knee osteoarthritis rehabilitation research, and also opening up new ways for the evaluation and optimization of intervention methods. Using three-dimensional motion capture, gait analysis, surface electromyoelectricity and foot pressure measurement and other technologies, the joint force distribution, muscle activation mode and energy consumption mode under water and land movement conditions can be more detailed. These objective indicators provide an important basis for understanding the regulation mechanism of different rehabilitation interventions at the biomechanical level. When biomechanical evaluation is combined with a data-driven analysis framework, researchers can more accurately compare the actual effects of various treatment methods, thus providing quantitative references for the formulation of individualized programs. This interdisciplinary integration idea helps to connect the relationship between clinical manifestations and mechanical adaptation, and deepens the insight into the mechanism of action of exercise therapy [16].

6.3. Long-Term Clinical Trials and Follow-up Studies

At present, most of the evidence on physical therapy interventions for knee osteoarthritis comes from short-term or medium-term studies, and the information on its long-term efficacy and structural changes is still relatively limited. Future research should pay more attention to clinical trials with perfect design and extended follow-up cycle, so as to systematically evaluate the lasting impact of treatment on pain control, function maintenance and quality of life improvement. In particular, the development of longitudinal research will help to judge whether water exercise and related interventions can play a role in slowing the progression of the disease, protecting joint structure or inhibiting cartilage degeneration [7]. Moreover, systematic long-term follow-up is equally important for verifying the differences in therapeutic effects between different rehabilitation methods. By establishing a unified efficacy evaluation index and standardized follow-up process, the comparability and extrapolation value of the research results can be improved, and a solid evidence-based basis can be provided for the optimization of clinical rehabilitation plans. Such research can not only help determine the optimal timing and duration of intervention, but also provide more comprehensive scientific support for the long-term management and prognosis assessment of knee osteoarthritis.

7. CONCLUSION

In general, a large number of research results show that a variety of physical treatments such as aquatic exercise, land-based exercise, manual treatment, electrotherapy, cold therapy and therapeutic ultrasound can improve the clinical outcome of patients with knee osteoarthritis to varying degrees. They help relieve pain, improve joint function and improve quality of life through their own unique biomechanical and physiological mechanisms. However, there is no single therapy that can be applied to all patients at present, and its specific efficacy still depends on the severity of the disease, the functional state and the difference in individual tolerance to weight and exercise.

For patients with obvious pain, limited joint mobility or difficulty in carrying weight on land, aquatic exercise is a particularly suitable choice. The buoyancy of water can significantly reduce joint pressure, while water resistance provides a controllable training environment for muscle activation and joint stability, so that the treatment is both safe and effective, and helps patients to continue to participate in exercise and maintain long-term functional improvement. In contrast, land-based exercise is still the basic part of the rehabilitation system, because it can effectively enhance muscle strength, improve joint stability and improve overall exercise ability, but in patients with severe symptoms or unable to stick to high-intensity exercise, its scope of application will be limited to a

certain extent. Manual intervention and auxiliary physical therapy are mostly used to relieve acute or short-term symptoms and improve soft tissue flexibility and joint mobility. They are especially suitable for patients with low exercise tolerance; however, if you rely only on such passive treatment, it is often difficult to maintain long-term efficacy.

Overall, from the perspective of public health, promoting patients' safe and continuous participation in rehabilitation activities, especially low-impact and high-admission water sports, helps to reduce dependence on drugs and surgical treatment, thus alleviating the burden on the medical system caused by chronic disease management. This sustained rehabilitation model with exercise as the core and patient-centered is more in line with the goal of long-term functional independence and cost-effectiveness. In the face of accelerating population aging, building a low-risk, adaptable and generalisable physical therapy strategy is of far-reaching social health significance for promoting the healthy aging of elderly osteoarthritis patients and maintaining activity capacity and quality of life.

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