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Effects and Mechanisms of Cardiopulmonary Rehabilitation on Postoperative Recovery in Orthopedic Surgery

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Abstract: *Postoperative complications and delayed rehabilitation in orthopedic surgery pose significant threats to patients' quality of life, underscoring the critical value of evidence-based cardiopulmonary rehabilitation interventions for postoperative recovery. This article systematically explores the effects and mechanisms of cardiopulmonary rehabilitation on orthopedic postoperative recovery, grounded in the physiological interplay between the cardiopulmonary and skeletal systems. Research indicates that cardiopulmonary rehabilitation, through integrated approaches such as aerobic exercise, strength training, and respiratory exercises, significantly enhances cardiorespiratory endurance, improves blood circulation, promotes biomechanical stimulation and metabolic regulation of bone, and optimizes gut microbiota composition, thereby accelerating bone healing, reducing inflammatory responses, and lowering complication risks. From a Western medical perspective, cardiopulmonary rehabilitation enhances cardiopulmonary functional reserve, upregulates PGC1α to suppress inflammatory factor release, and activates signaling pathways such as Wnt/β-catenin to facilitate bone formation. Traditional Chinese Medicine (TCM) theory emphasizes the synergistic role of the heart and lungs in regulating qi and blood circulation, with "zong qi" (ancestral energy) serving as a pivotal mediator to nourish bones and harmonize yin-yang balance. Clinical practice highlights the need for personalized cardiopulmonary rehabilitation protocols tailored to patient age, comorbidities, and postoperative phases: early-stage interventions prioritize respiratory training and resistance exercises, while progressive aerobic training is introduced in later stages. However, challenges persist, including inconsistent rehabilitation standards and insufficient clinical awareness among healthcare providers. Future efforts should integrate TCM and Western medical theories to establish precision rehabilitation frameworks, validate clinical efficacy, and provide theoretical support for optimizing postoperative orthopedic recovery strategies.*

Keywords: *Cardiopulmonary Rehabilitation; Postoperative Orthopedic Recovery; Biomechanical Stimulation; Metabolic Regulation; Integrated Traditional Chinese and Western Medicine*

1. Introduction

With the rapid development of society, the number of orthopedic patients caused by traumatic and degenerative skeletal diseases continues to rise. For patients with severe conditions who meet surgical indications, surgical intervention is regarded as the most timely and effective therapeutic approach [1]. However, postoperative rehabilitation plays a pivotal role in patient recovery. Neglecting rehabilitation or inadequate engagement in effective rehabilitation exercises may lead to various complications. For instance, delayed or insufficient postoperative exercise can result in muscle atrophy, joint stiffness, and restricted mobility [2]. Additionally, reduced physical activity during postoperative bed rest slows blood flow, increasing the risk of lower extremity deep vein thrombosis [3] and other complications, thereby significantly impairing patients' quality of life. Consequently, cardiopulmonary rehabilitation exercises are critical in the holistic recovery process. Evidence-based cardiopulmonary rehabilitation protocols not only enhance cardiopulmonary function and endurance but also facilitate bone healing and functional restoration [4]. Through comprehensive support from healthcare professionals, patients can achieve faster recovery and reintegrate into daily life. Therefore, a thorough exploration of the application and mechanisms of cardiopulmonary rehabilitation in postoperative

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orthopedic patients holds significant clinical value for optimizing rehabilitation strategies and improving patients' quality of life.

2. Overview of Cardiopulmonary Rehabilitation

2.1 Definition of Cardiopulmonary Rehabilitation

The circulatory and respiratory systems are closely interconnected in both anatomical structure and physiological function, with dynamic interactions between the two. Rehabilitation that targets only one of these systems often yields suboptimal outcomes. Consequently, cardiopulmonary rehabilitation has emerged as an integrated model combining pulmonary rehabilitation and cardiac rehabilitation, guided by comprehensive medical evaluation [5]. As a multidisciplinary intervention, cardiopulmonary rehabilitation is applicable to patients with coronary heart disease, chronic pulmonary diseases, and those in postoperative recovery phases [6]. It involves tailored exercise, pharmacological support, and nutritional interventions. The goal of cardiopulmonary rehabilitation is to enhance patients' cardiorespiratory endurance and facilitate their return to preoperative health status. Fundamentally, this approach fosters holistic health and functional recovery by synergizing expertise across medicine, exercise science, and nutrition.

2.2 Cardiopulmonary Rehabilitation Methods

The core objective of cardiopulmonary rehabilitation is to enhance patients' cardiopulmonary endurance and optimize the adaptability of cardiopulmonary functions. Exercise methods include aerobic exercise, strength training, and breathing exercises[7]. Alternating between high - and low - intensity training can effectively promote blood circulation and improve cardiopulmonary endurance. This approach, combined with aerobic exercises based on running, further enhances the benefits[8]. Besides, individualized programs are essential for cardiopulmonary rehabilitation and should be dynamically adjusted according to the patients' multidimensional clinical characteristics. First, for elderly patients or those with underlying diseases like COPD, priority is given to low-intensity interval training, such as seated cycling combined with Baduanjin exercises. The intensity is controlled between 40% - 60% of the maximum heart rate, and patients are also given qi - and yang - boosting traditional Chinese medicine to improve exercise tolerance[9]. On the other hand, young patients with better cardiopulmonary reserves can undergo high-intensity interval training that incorporates traditional Chinese rehabilitation concepts to accelerate recovery. Post-surgery rehabilitation is carried out in stages. In the early stage (Weeks 1 - 2 after surgery), the focus is on breathing exercises (like abdominal breathing combined with diaphragmatic electrical stimulation) and resisted exercises in bed to prevent thrombosis and maintain muscle strength[10]. In the middle stage (Weeks 3 - 6 after surgery), progressive aerobic exercises are introduced, such as aquatic walking training, and the weight - bearing intensity is adjusted based on imaging results of bone healing[11]. In the late stage (after Week 6), cardiopulmonary - skeletal training is intensified, such as cycling combined with balance training. During this process, exercise intensity is adjusted in real time by dynamically monitoring blood oxygen saturation (SpO_2) and the Borg Rating of Perceived Exertion (RPE $\leq$ 13)[12]. We recommend incorporating personalized exercises into cardiopulmonary rehabilitation to enhance the efficiency of post-surgery rehabilitation and to better optimize rehabilitation strategies.

2.3 Effects and Evaluation of Cardiopulmonary Rehabilitation

Postoperative patients require personalized rehabilitation plans and periodic assessments to ensure optimal recovery outcomes. To achieve effective rehabilitation, comprehensive and standardized health evaluations must be implemented, particularly through cardiopulmonary exercise testing (CPET) [13]. CPET is a non-invasive testing technology widely used for developing exercise prescriptions in patients with chronic diseases. It quantitatively evaluates cardiopulmonary functional reserves, exercise tolerance, and correlates performance with basal metabolism, serving as a critical method for assessing the body's overall functional capacity [14]. Compared to traditional exercise tests, CPET provides a comprehensive perspective—from oxygen uptake to mitochondrial utilization—while acquiring rich information through relatively simple and cost-effective means, aiding in identifying factors limiting exercise capacity [15].CPET evaluations have been shown to effectively alleviate patients' discomfort, improve cardiopulmonary endurance, reduce hospitalization frequency, and decrease mortality rates [15].CPET includes multiple indicators, and the following analysis focuses on some key parameters.

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2.3.1 Anaerobic Threshold

The anaerobic threshold (AT) refers to the critical point during moderate-intensity exercise at which muscle cells transition from primarily relying on aerobic metabolism to anaerobic metabolism. Beyond this threshold, the body shifts to anaerobic metabolism to meet energy demands, leading to lactic acid production and subsequent muscle fatigue and reduced strength. The anaerobic threshold serves as a vital indicator for assessing an individual's aerobic exercise capacity and endurance [16].

2.3.2 Oxygen Pulse

The oxygen pulse (VO_2/HR) refers to the ratio of oxygen consumption (VO_2) to heart rate (HR), representing the amount of oxygen delivered with each heartbeat. It reflects the heart's ability to transport oxygen throughout the body during each cardiac cycle. A decline in oxygen pulse during exercise may indicate limitations in cardiac pumping capacity. It can also suggest a situation where oxygen demand exceeds supply. Therefore, this metric helps assess the efficiency and adaptability of the cardiopulmonary system [17].

2.3.3 Oxygen Uptake Efficiency

Oxygen uptake efficiency (OUE) refers to the ratio of oxygen consumption (VO_2) to ventilation (VE),indicating the amount of energy produced per unit of oxygen consumed over time. This metric is directly proportional to cardiopulmonary efficiency and serves as a critical indicator for evaluating cardiopulmonary function [18].

3. Correlation Between Cardiopulmonary Rehabilitation and Post - Orthopedic Surgery Recovery

Following orthopedic surgery, patients often experience significant declines in cardiorespiratory endurance, bone density, and muscle mass due to restricted mobility and prolonged bed rest. Consequently, postoperative rehabilitation exercises are essential to enhance structural stability and functional integrity. Foundational experimental studies have shown that intermittent treadmill exercise at varying intensities induces positive skeletal adaptations in rats. Moderate-intensity exercise, for instance, significantly increases bone density and bone mass, indicating that appropriate physical activity effectively promotes bone growth [19].Clinical studies further demonstrate that cardiorespiratory aerobic training at suitable intensities can slow bone loss, improve muscle endurance, and significantly increase bone density [20].During cardiopulmonary aerobic rehabilitation exercises, cardiac contractility and pumping efficiency are enhanced. These exercises also stimulate vascular endothelial cells to produce growth factors, which promote angiogenesis and improve local blood circulation. This process indirectly facilitates fracture healing and alleviates joint stiffness [21].Additionally, aerobic exercise training upregulates peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC1α) in skeletal muscles and negatively regulates nuclear factor kappa-B (NF-κB), thereby suppressing NF-κB-mediated increases in interleukin-1β (IL-1β), interleukin-6 (IL-6), and tumor necrosis factor-alpha (TNF-α). This reduction in inflammatory factor production helps mitigate postoperative inflammation, alleviate pain, and improve quality of life during rehabilitation [22].

4. The Relationship between the Heart, Lungs and Bones from the Perspective of Traditional Chinese Medicine (TCM)

In the TCM theory system, the relationship between the heart, lungs and bones reflects the holistic view of nourishing qi and blood and the interaction between yin and yang. The heart dominates blood vessels and promotes the circulation of qi and blood to transport nutrients to the bones. As stated in the "Suwen·Wilt Treatise," the heart dominates the body's blood vessels, and when qi and blood are abundant, the bone marrow is nourished and the bones become strong[23]. The lung dominates qi and controls respiration, inhaling fresh air to generate primal qi, which is the link between the functions of the heart and lungs. Primal qi can also permeate the heart vessels, circulating qi and blood and indirectly nourishing the bones through the regulation of qi and blood circulation[24]. This mechanism of nourishing qi and blood is closely related to the yin and yang properties of the heart and lungs. The heart and lungs are located in the upper energizer and belong to yang, while the bones are the residence of yin essence. The coordinated action of warming yang and moistening yin is required to maintain the balance of bone growth, development, and repair[25].From a pathological perspective, dysfunction of the heart and lungs can affect bone health through the obstruction of qi and blood circulation. For example, deficiency of lung qi leads to insufficient primal qi, resulting in weak transportation of qi and blood, and symptoms such as sore and weak bones and restricted movement[26]. When the heart yang is not strong, it fails to provide warmth, easily causing cold to congeal in the muscles and bones, leading to joint pain. Therefore, in treatment, it is important to adjust both the heart and lungs, nourish primal qi, and warm the heart yang to improve bone metabolism[27].Bone surgery leaves patients' bones in a vulnerable state, both internally and externally. Insufficient kidney qi slows down bone marrow generation and bone strengthening. A weakened body is susceptible to pathogens, leading to complications and a prolonged recovery[28]. According to TCM, enhancing heart and lung functions boosts qi and blood, nourishes kidney essence, and invigorates kidney qi. This strengthens bones, promoting their robust growth and maintaining the body's balance of qi, blood, yin and yang[29].

5. Mechanisms of Cardiopulmonary Rehabilitation Training on Bone Metabolism

5.1 Biomechanical Stimulation

Cardiopulmonary exercise applies mechanical stimuli to bones through muscle contraction and relaxation, inducing internal adaptive responses. This process is consistent with Wolff’s law, which describes bone transformation in response to mechanical loading [30]. Aerobic exercise promotes myoglobin production, enhancing muscular strength and exerting greater tensile forces on bones. Sustained external loading forces deform bone structure, triggering osteoblasts within the bone to generate new cellular layers, while osteoclasts resorb old or dysfunctional bone tissue [31].Under mechanical stress, osteoblasts produce signaling molecules such as bone morphogenetic proteins (BMPs) and osteocalcin, which activate signaling pathways (e.g., Wnt/β-catenin) to mediate bone remodeling [32].

5.2 Metabolic Pathway Regulation

Studies have shown [33] that osteoblasts not only stimulate mitochondrial fission and secretion by inducing the CD38/cyclic ADP-ribose (cADPR) signaling pathway but also regulate mitochondrial dynamics through knockdown of Opa1 (optic atrophy 1) or expression of Fis1 (mitochondrial fission 1 protein), thereby enhancing mitochondrial secretion and accelerating bone formation. Furthermore, branched-chain amino acid (BCAA) metabolism promotes mitochondrial biogenesis in skeletal muscle and cardiac tissue, improving cardiac function and maintaining skeletal health [34]. In clinical practice, enhancing mitochondrial function has emerged as a robust strategy for modulating bone health [35].

5.3 Gut Microbiota Regulation

Emerging evidence from basic studies indicates a correlation between gut microbiota (GM) and skeletal health [36]. GM can modulate bone resorption mediated by osteoclasts under immune stimulation, thereby maintaining bone mass at normal levels [37]. As demonstrated by Schwarzer et al. [38], GM ensures optimal longitudinal bone growth, including trabecular bone in the femur and cortical thickness, by enhancing growth hormone sensitivity and subsequently increasing insulin-like growth factor beta 1 (IGF-β1) activity in bone.A subsequent study further revealed a positive association among bone microbiota, IGF-β1, and skeletal health [39]. Moreover, aerobic exercise-induced improvements in cardiopulmonary function help optimize gut microbiota composition and enhance its diversity, which in turn influences bone metabolism [40]. Regular aerobic exercise increases the abundance of short-chain fatty acid (SCFA)-producing bacteria (e.g., Akkermansia muciniphila) in the gut. SCFAs inhibit the expression of key osteoclast differentiation factors (e.g., TRAF6 and NFATc1) while activating the Wnt/β-catenin signaling pathway in osteoblasts, thereby promoting bone formation and suppressing bone resorption [41].Through the regulation of microbial metabolites, the gut immune system, and mucosal barrier function, GM modulates the activity of osteoclasts and osteoblasts, ultimately participating in bone remodeling processes [42].

6. Clinical Application Prospects of Cardiopulmonary Rehabilitation in Post - orthopedic Surgery

Cardiopulmonary rehabilitation is a highly effective way to recover from clinical diseases. It integrates pulmonary and systemic circulation. By enhancing overall bodily function, it boosts qi and blood, and benefits post-bone-surgery recovery. It can reduce complications and promote healthy bone growth[43]. With the intensifying aging of society, chronic orthopedic diseases like osteoporosis are on the rise. For patients with advanced osteoarthritis who need joint replacement, post-surgery recovery is a long process that demands strict exercise. But improper exercise may lead to poor joint function recovery. So patients should incorporate cardiopulmonary rehabilitation into their routine to restore optimal joint function. However, the development of cardiopulmonary rehabilitation faces many challenges. Firstly, the promotional work of medical staff is not sufficient. Some of them even have wrong ideas about cardiopulmonary rehabilitation. For example, they lack a comprehensive understanding and cannot develop suitable rehabilitation plans for patients[44]. Besides, in medical practice, there is no unified standard for cardiopulmonary rehabilitation. Sometimes, it's hard to measure the optimal rehabilitation standard. For instance, in aerobic load training, using muscle force that is either too strong or too weak yields poor skeletal stimulation and growth effects[43].Therefore, it is essential to build a holistic, effective, and individualized rehabilitation system. This enables patients to recognize the significance of cardiopulmonary exercise after bone surgery. It's a fundamental and essential part of the whole rehabilitation process. We need to develop a guiding and cooperative doctor-patient relationship and apply it to pre- and post-surgical evaluations. By doing so, we can develop more precise rehabilitation plans based on individual conditions, thereby improving overall cardiopulmonary function and more effectively relieving post-surgical symptoms[45]. In the future, cardiopulmonary rehabilitation exercise is expected to become a common clinical method for post-orthopedic surgery.

7. Summary and Future Perspectives

Cardiopulmonary rehabilitation following orthopedic surgery is a progressive process that spans the entire recovery period. For instance, during the bedridden phase post-surgery, targeted joint mobilization can enhance local blood circulation, prevent joint stiffness, and reduce the risk of venous thrombosis. Guided by Wolff's law, exercises targeting muscles attached to bones, combined with respiratory rhythm adjustments, facilitate accelerated bone growth. In the ambulatory phase, moderate aerobic exercises can improve cardiorespiratory endurance, mitigate bone loss, and effectively increase bone density. Both clinical observations and animal experiments cited in this review underscore the efficacy of cardiopulmonary rehabilitation and its relevance to post-orthopedic surgical recovery. However, challenges persist due to the lack of standardized metrics for evaluating the impact of cardiopulmonary rehabilitation on postoperative bone recovery, as well as the need to refine and innovate exercise protocols during restricted mobility periods. Future efforts should focus on synthesizing extensive clinical research data to establish evidence-based guidelines. Within the broader rehabilitation framework, integrating cardiopulmonary exercises with traditional Chinese medicine (TCM) and Western medicine approaches could enhance clinical outcomes. By harmonizing the heart-lung-bone relationship across TCM and biomedical paradigms, this integrated strategy may further alleviate postoperative pain, reduce complications, and elevate patients' quality of life. Ultimately, the goal is to develop a comprehensive cardiopulmonary rehabilitation system that integrates interdisciplinary insights, ensuring safer, more effective, and personalized recovery pathways for orthopedic patients.

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