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Progress in Rehabilitation Treatment of Anterior Cruciate Ligament Rupture in Sports Injuries

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ABSTRACT

Anterior cruciate ligament (ACL) rupture is a high incidence of injury in sports medicine, especially in soccer, basketball and other sports requiring sudden stop and change of direction. The annual incidence rate of high-risk sports population is higher, and the risk of female football players is more prominent due to physiological characteristics. Although surgical techniques continue to mature, the quality of postoperative rehabilitation directly determines the effectiveness of joint function recovery and the success rate of returning to exercise. This article systematically reviews the latest developments in the rehabilitation treatment of ACL rupture, with a focus on the innovation of precision assessment systems, the updating of early rehabilitation concepts, the application of advanced technologies, individualized strategies for special populations, and the development of interdisciplinary collaboration models. Research has found that the dynamic evaluation of integrated vertical jumping tests can effectively identify "pseudo rehabilitation", the integrated medical and nursing technology model can significantly shorten the recovery time of joint range of motion, and the combination of virtual reality and isokinetic training can significantly improve muscle strength and functional scores. These advances are driving the transformation of ACL rehabilitation from a traditional experiential model to a more precise, personalized, and multidimensional direction. This transformation significantly improves the postoperative functional recovery rate and significantly reduces the risk of secondary injury. This article provides evidence-based support for clinical rehabilitation practice, helping to optimize rehabilitation plans and improve patient outcomes.

KEYWORDS

Anterior cruciate ligament rupture; Sports injury; Rehabilitation treatment; Neuromuscular control; Multidisciplinary collaboration; Functional reconstruction

1. INTRODUCTION

The anterior cruciate ligament, as the core structure that maintains knee joint stability, is often damaged during non-contact movements such as single leg deceleration, jumping, and landing. Most injuries are related to sudden mechanical changes during exercise. ACL rupture not only leads to knee joint instability and motor dysfunction, but also causes neuromuscular control defects, significantly increasing the risk of long-term osteoarthritis and seriously affecting the patient's exercise life and quality of life. Although arthroscopic reconstruction surgery has become the standard treatment method, traditional rehabilitation models suffer from problems such as one-sided evaluation, lagging intervention, and insufficient individualization, resulting in unsatisfactory postoperative return to exercise and a high risk of re injury.

In recent years, with the cross integration of biomechanics, sports medicine, and rehabilitation engineering, there have been many breakthroughs in the field of ACL rehabilitation. Accurate evaluation technology has broken through the limitations of traditional muscle strength and activity detection, and can identify potential functional defects in compensatory exercise modes; The early

rehabilitation concept has shifted from "braking protection" to "active intervention" to accelerate tissue healing and functional recovery; The application of rehabilitation robots, virtual reality and other technologies has achieved precise reconstruction of motor functions[1]; Individualized programs for special groups such as teenagers and female athletes are constantly being improved; The multidisciplinary collaboration model integrates multidimensional resources such as healthcare, rehabilitation, and nutrition.

This article is based on recent clinical research and authoritative guidelines, systematically elaborating on the latest progress of ACL rupture rehabilitation treatment from five dimensions: evaluation system, early intervention, advanced technology, special population management, and multidisciplinary collaboration. It analyzes the limitations of traditional models and the advantages of modern rehabilitation, providing scientific references for clinical practice and promoting the standardization and precision development of ACL rehabilitation treatment.

2. INNOVATION AND CLINICAL APPLICATION OF PRECISE EVALUATION SYSTEM

Traditional ACL rehabilitation assessment mainly relies on muscle strength testing and joint range of motion measurement, which often leads to misjudgment of "pseudo rehabilitation" due to neglecting dynamic function and neural control defects, becoming an important cause of re injury. In recent years, the precision evaluation system has developed towards a multidimensional direction of "static+dynamic", "subjective+objective", and "local+overall", significantly enhancing the sensitivity and specificity of evaluation.

In terms of biomechanical evaluation, the application of gait analysis technology has achieved quantitative interpretation of motor function. Related studies have found through a professional gait analysis system that there is a significant change in the ground reaction force on the affected side in the early stage after ACL surgery. This indicator reflects improvement in weight-bearing capacity earlier than muscle strength recovery and can be used as a sensitive indicator for early rehabilitation monitoring. Isokinetic muscle strength testing can accurately capture muscle strength asymmetry. Professional tests have shown that the increase in peak torque of the quadriceps muscle during postoperative recovery can reduce muscle strength defects, and the normalization of the hamstring/quadriceps (H/Q) ratio is a key threshold for preventing secondary injuries.

The innovation of dynamic functional evaluation is particularly crucial. The study in the British Journal of Sports Medicine confirms that the Single Leg Vertical Jump Test (SLJ/SLDJ) can effectively identify functional deficiencies missed by traditional tests - even if the patient's horizontal jump symmetry is good, there may still be deficiencies in the vertical jump height and knee joint work on the affected side. The proposed Jump Height Symmetry Index (LSI) and Reaction Strength Index (RSI) in this study have been incorporated into the Return to Exercise (RTS) evaluation system, which can effectively avoid misjudgments of "pseudo rehabilitation". Integrating Vicon motion capture technology and surface electromyography technology for comprehensive evaluation can clearly identify and present compensatory patterns such as insufficient activation of the soleus muscle, providing clear targeted directions for precise clinical intervention.

Another core breakthrough in the evaluation system is the organic integration of subjective and objective indicators. The subjective score of the Lysholm Knee Function Scale is combined with objective data such as isokinetic muscle strength test results and gait analysis parameters to achieve a three-dimensional evaluation of the patient's functional status. Research has confirmed that when the difference in quadriceps strength between the affected and healthy sides is reduced to a specific range and the hamstring/quadriceps (H/Q) ratio reaches the ideal standard, the risk of re injury in the occupational population after returning to work is significantly reduced. This key standard is defined as the "muscle strength defect threshold", providing a quantitative reference for individualized

rehabilitation goal setting [2]. The series of innovations in the above evaluation techniques have laid a solid theoretical and practical foundation for the precise formulation and dynamic adjustment of rehabilitation plans.

3. UPDATING THE CONCEPT OF EARLY POSTOPERATIVE REHABILITATION AND OPTIMIZING THE IMPLEMENTATION PLAN

Early rehabilitation after ACL surgery has long followed the principle of "braking protection", leading to a high incidence of complications such as joint adhesion and muscle atrophy. In recent years, early intervention models based on the concept of Enhanced Recovery Surgery (ERAS) have gradually replaced traditional approaches, achieving a dual improvement in rehabilitation efficiency and safety through the core strategy of "controlling inflammation+early activity+precise protection". The core breakthrough of early rehabilitation lies in the advancement of intervention timing and the precision of the plan. In recent years, clinical guidelines have clearly stated that initiating standardized rehabilitation within one week after surgery can significantly improve the recovery rate of joint function. Related studies have shown that the integrated medical and nursing technology accelerated rehabilitation model can significantly shorten the recovery time of knee joint range of motion (ROM), and the Lysholm score at 3 months after surgery is significantly higher than that of the traditional group. Early rehabilitation is not blind activity, but a staged intervention based on the law of injury repair: 0-2 weeks after surgery, the core is to control swelling and pain, promote circulation through ankle pump exercise, prevent atrophy through isometric contraction of the quadriceps femoris muscle, and cooperate with 24-hour support fixation and three daily ice packs; Gradually carry out knee joint flexion and extension training for 3-6 weeks, gradually increase the flexion angle with the help of heel sliders, and push towards the 90 ° target 4 weeks after surgery. The refinement of pain and inflammation management is an important guarantee for early rehabilitation. Research has confirmed that pain after training should be controlled within a range that does not affect subsequent recovery. If continuous swelling of the knee joint or joint clicking symptoms are observed clinically, the current rehabilitation intervention measures should be immediately discontinued. In addition to traditional ice pack therapy, the application scope of physical factor therapy continues to expand in this stage: low-intensity pulsed ultrasound can promote the formation of orderly arranged structures of tendon collagen fibers, while fluid shear force simulators assist in the cartilage repair process through dynamic activity training, providing biomechanical support for early tissue repair.The importance of individualized program adjustment in early rehabilitation process is increasingly prominent in clinical practice. For patients undergoing combined meniscus repair surgery, it is necessary to extend the duration of some weight-bearing stages appropriately; For patients who use autologous tendon grafts and allogeneic tendon grafts, the timing of initiating closed chain training for both should also be differentiated based on the characteristics of the grafts. At the same time, the closed-loop regulation of oxidative stress indicators based on near-infrared spectroscopy technology can optimize the microenvironment of tissue repair and further improve the healing effect [3]. These concept updates and program optimizations have completely changed the clinical pathway of ACL postoperative rehabilitation, providing scientific support for rapid functional recovery.

4. BREAKTHROUGH OF ADVANCED REHABILITATION TECHNOLOGY IN MOTOR FUNCTION RECONSTRUCTION

The core goal of the advanced rehabilitation stage (3 months after surgery) is to rebuild motor function and neuromuscular control, laying the foundation for returning to exercise. In recent years, the integration of rehabilitation engineering technology and neuroscience has shifted the intervention from "empirical training" to "precise regulation", significantly improving the quality of functional recovery. The deepening of neuromuscular control training is an important progress. After ACL

injury, delayed activation of the quadriceps and dysregulation of the hamstring muscles are prone to occur, and even with ligament reconstruction, neuromuscular control defects may still persist for a long time. Research has shown that integrating neurocognitive training programs can improve proprioceptive deficits and motor control disorders, significantly reducing joint position perception errors through stimuli such as closed eye joint movements and balance board training. Training based on surface electromyography feedback can correct the pattern of excessive dependence on hip joint compensation on the affected side and improve the contribution of knee joint work during the advancement period. In addition, training such as stability exercises for falling and jumping can enhance the knee joint's adaptability to dynamic loads and significantly reduce the risk of re injury. Rehabilitation robots and virtual reality (VR) technology achieve precise and efficient training. The six degree of freedom rehabilitation robot achieves step-by-step reinforcement from isometric contraction to explosive force training through adjustable loads, and accurately controls the knee joint flexion angle through three-dimensional motion capture, which conforms to the principle of load increment in sports medicine. The combination of VR and isokinetic muscle strength training has significant advantages. Relevant studies have shown that the observation group had higher Lysholm scores and knee joint flexion and extension peak torque than the control group at 16 weeks after surgery, thanks to the VR scene improving exercise learning efficiency. A robot system based on brain computer interface can achieve dynamic matching between electromyographic signals and training intensity, synchronously promoting neural recovery and functional training. Physical factors such as shock waves and low-intensity pulsed ultrasound are important aids for functional reconstruction. Research has confirmed that low-frequency pulse vibration can activate fibroblasts to synthesize type II collagen, accelerating graft healing; Applying extracorporeal shock waves after strength training can promote the proliferation of muscle satellite cells and accelerate muscle strength recovery[4]. These technologies collaborate with active training to build a multidimensional functional reconstruction system, providing strong support for returning to sports.

5. PROGRESS IN INDIVIDUALIZED REHABILITATION STRATEGIES FOR ACL RUPTURE IN SPECIAL POPULATIONS

There are significant differences in physiological characteristics, exercise needs, and injury risks among different populations, and the traditional "one size fits all" rehabilitation model is difficult to meet clinical needs. In recent years, personalized rehabilitation strategies for special groups such as teenagers, female athletes, and professionals have been continuously improved, significantly enhancing the pertinence and effectiveness of rehabilitation. The focus of rehabilitation for adolescent ACL rupture is to balance functional recovery with growth and development protection. The epiphyseal plates of children and adolescents are not closed, and excessive weight-bearing and high-intensity training may affect bone development. Rehabilitation programs should follow the principle of "gradual and dynamic adjustment". The relevant rehabilitation guidelines suggest that adolescents should undergo regular muscle strength and function tests after surgery, and undergo pre adaptation training such as using crutches and wearing braces before surgery. In the early postoperative period, equal length contraction should be the main method to avoid high-intensity resistance training across joints. For adolescents at high risk of epiphyseal injury, "bilateral symmetrical training" is used instead of unilateral reinforcement, which enhances the stability of the core and hip joint through movements such as clamshell opening and closing and hip bridge, indirectly improving knee joint control ability; At the same time, by designing gamified training scenarios, we aim to enhance adolescent rehabilitation compliance. The core of rehabilitation for female athletes is to reduce the risk of re injury. Women have a relatively higher risk of ACL injury and re injury due to factors such as anatomical structure and hormone levels[5]. Research has shown that female athletes need to strengthen hip abductor muscle group and core stability training for rehabilitation, and correct incorrect patterns of knee joint adduction through movements such as lateral plank support and lateral sliding. The Expert Consensus on ACL Rehabilitation for Competitive Sports Athletes recommends

that women should undergo extended neuromuscular control training and regular single leg vertical jumping tests after surgery to meet the standards before returning to the field; At the same time, the training intensity can be adjusted according to the menstrual cycle to reduce the risk of sports injuries. The rehabilitation strategy for occupational groups needs to balance functional recovery and the need for resuming work. Heavy manual laborers need to achieve higher levels of muscle strength, while office workers pay more attention to joint flexibility and gait symmetry. Related studies suggest that the rehabilitation of occupational populations needs to be included in the "resumption of work ability assessment system", and training plans should be developed through gait analysis and muscle strength testing. After achieving functional standards, work related activities should be gradually resumed to adapt to the work needs of different professions.

6. THE INTEGRATED DEVELOPMENT OF INTERDISCIPLINARY COLLABORATION AND LONG-TERM MANAGEMENT MODELS

ACL rehabilitation is a systematic engineering involving multiple dimensions such as medical treatment, rehabilitation, nutrition, and psychology, and single disciplinary intervention is difficult to achieve overall rehabilitation goals. In recent years, the establishment of multidisciplinary collaboration (MDT) models and long-term management systems has promoted the transformation of rehabilitation from "stage based treatment" to "full cycle management". The MDT model of integrated medical and nursing technology significantly improves rehabilitation efficiency and quality. This model is centered around sports medicine doctors, rehabilitation therapists, and nurses, integrating multidisciplinary resources to achieve full collaboration from preoperative evaluation to postoperative rehabilitation. Related studies have shown that patients using MDT mode have significantly better early postoperative knee joint range of motion than the traditional group, and the incidence of complications is significantly reduced. In addition, the MDT model operates based on a precise division of labor mechanism and a dynamic communication mechanism: clinical doctors are responsible for developing surgical plans and monitoring postoperative complications; Rehabilitation therapists focus on developing individualized rehabilitation training plans; Nursing staff carry out home rehabilitation guidance for patients; Clinical nutritionists provide nutritional support services centered around protein supplementation. Organize weekly case discussions and monthly functional assessments to ensure that rehabilitation plans are dynamically adjusted as patients recover, helping to improve their quality of life. The organic integration of psychological intervention and nutritional support has become a new intervention dimension in the field of ACL rehabilitation. After ACL injury, patients are prone to negative psychological states such as anxiety and fear, which affect rehabilitation compliance. Scientific psychological intervention can effectively improve this condition. The use of cognitive-behavioral therapy combined with group rehabilitation training can enhance rehabilitation compliance and improve postoperative return to exercise outcomes[6]. Nutritional intervention provides a material basis for tissue repair, and supplementing high-quality protein, Omega-3 fatty acids, vitamin D, and calcium can reduce joint effusion and prevent bone density decline. The construction and implementation of a long-term management system can effectively reduce the risk of long-term complications after ACL surgery. The risk of long-term osteoarthritis after ACL surgery is high, and it is closely related to muscle strength imbalance and abnormal exercise patterns. The core of long-term management is to maintain muscle balance and optimize exercise patterns. Clinically, it is recommended to regularly conduct isokinetic muscle strength testing and gait analysis after surgery. Rehabilitation effects can be consolidated through exercises such as wall squatting and single leg heel lifting. Low impact exercise and dietary regulation can also be used to control weight, avoid knee injury behavior, regularly maintain joint range of motion, and delay the process of joint degeneration.

7. CONCLUSION

The rehabilitation of anterior cruciate ligament rupture in the field of sports injuries has shifted from traditional experiential models to precise, individualized, and multidimensional models, with significant achievements in the construction of evaluation systems, early intervention implementation, technological application innovation, management of special populations, and establishment of integrated models. The precise evaluation system integrates biomechanical analysis and dynamic functional testing, breaking through the limitations of traditional evaluation and accurately identifying "pseudo rehabilitation" and compensatory exercise patterns, providing scientific basis for the development of rehabilitation plans. The early rehabilitation concept has shifted from "brake protection" to "active intervention", and the integrated medical and nursing technology model accelerates joint function recovery and reduces the risk of postoperative complications. Advanced technologies such as rehabilitation robots and virtual reality, combined with neuromuscular control training, achieve efficient reconstruction of motor function. Individualized strategies for special populations such as adolescents and female athletes can balance functional recovery needs and physiological characteristics. The construction of a multidisciplinary collaboration mechanism and long-term management system promotes the extension of rehabilitation intervention from stage based treatment to full cycle health maintenance. These advances significantly improve the rehabilitation effect of ACL, improve postoperative joint function recovery, secondary injury risk control, and return to exercise rate. However, current rehabilitation practices still face problems such as insufficient popularization of technology in grassroots institutions, incomplete standardization of rehabilitation standards for different populations, and the need to improve remote rehabilitation systems. Future research should focus on the application of artificial intelligence in rehabilitation assessment and program generation, develop more targeted personalized rehabilitation technologies, build a three-level rehabilitation network of "hospital community family", and further optimize interdisciplinary collaboration mechanisms. The rehabilitation treatment of anterior cruciate ligament rupture is a continuously developing field. With the deep integration of biomedical engineering, sports science, and information technology, rehabilitation treatment will become more precise, efficient, and convenient. In clinical practice, evidence-based medicine should be used as a guide, and the latest developments should be integrated based on the individual characteristics of patients to achieve comprehensive goals from injury repair to functional reconstruction, from short-term rehabilitation to long-term maintenance, and to maximize the recovery of patients' motor ability and quality of life.

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