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Individualized Rehabilitation Plan and Clinical Practice after ACLR Surgery

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Abstract. Anterior Cruciate Ligament injuries are common traumatic injuries, which often result in long-term physical limitations and lowered quality. Given the ACL's critical role in stabilizing the knee, effective treatment and rehabilitation are essential for restoring function and return to sport (RTS). This paper summarizes the contemporary progress of ACLR and subsequent rehabilitation, emphasizing the importance and development of personalized and multidisciplinary measures and concepts. The research results emphasize the superiority of autologous transplantation over allogeneic transplantation in terms of lower rupture rate and better prognosis. In addition, rehabilitation shifted to function-based protocols that raise awareness on the neuromuscular control and loading methods, with the three training methods-NMT, VBT, and BFR-gaining rising attention. Preoperative rehabilitation ("prehab") has shown significant benefits in strength recovery, symmetry, and postoperative performance. Besides, psychological factors influence the outcome. Psychological readiness —measured by tools such as the ACL-RSI—has emerged as a key predictor of successful RTS. Clinical depression and anxiety, similarly, have been linked to worse physical outcomes due to a lack of motivation. Cognitive-behavioral therapy, mindfulness practices, and social support interventions are increasingly recognized as essential parts of comprehensive care. This study underscores the importance and benefits of an integrative, individualized, and closely monitored model of ACL rehabilitation, which addresses both physical and psychological factors. By aligning innovative therapies with conventional strength training and individual patient needs, the duration of rehabilitation and the reinjury rate could be significantly reduced.

Keywords: ACL rehabilitation, preoperative rehabilitation, psychology.

1. Introduction

Anterior Cruciate Ligament (ACL) injury is an acute and traumatic musculoskeletal injury, which can be disabling and impose constraints on physical and sports activities. Particularly, for athletes and physically active people, their living quality can be greatly compromised due to the ACL injury. The Anterior Cruciate Ligament is an important stabilizer in the knee joint, attaching from the lower surface of the femur to the upper surface of the tibia through the tibiofemoral articulation, and resisting anterior translation of the tibia. It is frequently injured during cutting, pivoting, landing from a jump, and when receiving a direct collision. The annual incidence of ACL tear for all ages

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and all sexes is 68.8 per 100,000 people per year, with a rate of 2.4-9.5 times higher in females compared to males [1]. Physical examinations, Lachman test for instance, provide a promising certainty for ACL rupture. Magnetic Resonance Imaging (MRI) is used to evaluate and confirm diagnoses. With its high percentage of sensitivity and specificity, giving levels of tear, it is critical in making surgical plans.

Given the significant functional impairment caused by ACL tears, ACL reconstruction (ACLR) surgery is often the preferred treatment for individuals seeking to return to high-demand physical activities. Surgical techniques for ACLR have changed, from extra-articular reconstruction to intra-articular reconstruction and the novel double-bundle reconstruction. Graft fixation evolved over time as a result of more in-depth research on ACLR. However, surgery alone is insufficient for full recovery—rehabilitation is the cornerstone of successful outcomes.

Recent advancements in ACL reconstruction (ACLR) rehabilitation emphasize personalized, innovative, and criterion-based protocols integrating biomechanical, neurological, and psychological strategies. A 2024 review study highlights the novel focus of ACLR rehabilitation, shifting to function-driven rehab, with several objective benchmarks (i.e., limb symmetry ≥90% in the hop test). Also, raising awareness on the influence of psychological readiness on second injury rate and knee function [2]. A 2025 study demonstrates BFR's efficacy in early-phase rehab, showing significantly greater quadriceps strength gains versus a traditional control group [3]. However, optimal pressure parameters remain debated, with Asian studies advocating lower pressures (50–60% arterial occlusion) than Western protocols (~80%) [4]. Psychological readiness is now recognized as critical for return-to-sport (RTS). The ACL-RSI score (≥56) predicts successful RTS with 90% accuracy, yet a large percentage of athletes remain psychologically unready despite physical recovery [5]. Studies highlight the growing importance of preoperative rehabilitation ("prehab") in ACLR recovery. Targeted prehab programs are demonstrated to be capable of significantly enhancing postoperative outcomes by improving muscle strength, joint stability, and psychological readiness. Evidence suggests these preparatory interventions help patients achieve better functional recovery and reduce complications. As prehab becomes increasingly recognized as a valuable component of ACLR treatment, understanding its principles and setting a standardized protocol are essential for optimizing patient care [6,7].

Given the complexity of physical and psychological factors in ACL rehabilitation, a comprehensive approach integrating evidence-based surgical techniques, structured rehabilitation protocols, and psychological support is essential for optimal recovery. Researches in recent years emphasize the importance of personalized rehabilitation strategies—including preoperative conditioning, NMT, and innovative methods like BFR and VDT—to maximally mitigate muscle failure and quicker RTS. As ACL injuries continue to be a global injury, particularly prevalent among young athletes, advancing comprehensive rehab models that take into account both functional recovery and psychological care will be critical to improving long-term outcomes and reducing reinjury rates [8,9].

2. ACLR surgery

2.1. Epidemiology

ACL tear is a common sports injury that can be very traumatic and can affect athletes tremendously, with an overall incidence of 68.6 per 100,000 person-years. Epidemiology studies highlight the difference between age and gender. People ranging from 14-25 have the highest prevalence of ACL tear, especially for those engaged in sports like soccer and basketball [1,10]. Gender disparities are

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also evident, with females facing a higher risk of ACL injury compared to males, particularly in sports involving cutting and pivoting movements. Studies suggest that females face a 2-8 times higher risk of getting an ACL tear due to anatomical, hormonal, and neuromuscular factors, such as wider pelvic angles, smaller ACL in size, greater ligament laxity, and differences in landing mechanics [1,2]. These findings underscore the importance of rehabilitation programs.

2.2. ACLR surgical techniques

The anterior cruciate ligament is a fibrous, inter-articular structure that originates from the posteromedial aspect of the lateral femoral condyle and inserts anterior to the intercondylar eminence of the tibia, serving as a primary restraint for anterior translation of the tibia. The ACL tear is classified into different levels of severity — grade 1, grade 2, and grade 3 — according to the Anterior Cruciate Ligament Injury Severity Scale (ACLISS). The ACLISS scoring system has a mark of 1-12, from mildest to severest (12 for the highest severity). The median value is 4.5, a score below 4 is considered grade 1 injury, scoring between 4 to 7 is classified as grade 2 injury, and a score above 7 is diagnosed as grade 3 tear. Due to the ligament's limited vascular supply from the middle genicular artery and poor intrinsic healing capacity, surgical reconstruction (ACLR) is often required for physically active individuals. Current surgical choices include autografts and allografts. Autografts are chosen more commonly due to their compatibility, resulting in a better recovery outcome. Studies show that people with allografts face an increased risk of rupture, with 22.0% risk and 6.6% risk for a 14-year-old person who undergoes allograft and autograft ACLR, respectively. Modern use of autografts mainly consists of three types of autograft: bone-patellar tendon-bone (BPTP), hamstring tendon (HS or HT), and quadricep tendon (QT). BPTP demonstrates excellent bone-to-bone healing, however may be accompanied by anterior knee pain and risk of patellar fracture. HT can be used on skeletally immature patients and requires a smaller incision. Different from BPTP, patients receiving HT autografts undergo risks of flexion weakness, nerve injuries, and elastic deformation. QT, similarly, can be used on skeletally immature patients and gained attention for its thick collagen structure and minimal harvest site. Drawbacks consist of documented knee flexion weakness and unclear long-term postoperative outcomes.

3. Rehabilitation methods after surgery

3.1. General protocol for ACLR rehabilitation

Postoperative rehabilitation following ACL reconstruction follows a structured, phased approach to ensure optimal recovery while minimizing complications. Phase 1, ranging from 0-4 weeks, focuses on reducing swelling, pain, and inflammation, using ice, compression, elevation and anti-inflammatory medicines if needed. Patellar mobilization is critical in the initial phase of rehabilitation, as well as the knee extension angle (0 degrees). Weight bearing should be avoided, then progressive, with crutches and a locked brace when walking. Strengthening activities aim to activate muscles, particularly the quadriceps. Straight leg raise and ankle pumps are recommended, and neuromuscular electrical stimulation can be used to enhance the activation. For restoring knee flexion angle, 90-120 degrees flexion should be achieved while avoiding radical motion to prevent deformation and damage to both the reconstructed ligament and the patella. Phase 2 (4-10 weeks) targets to maintain full ROM, improve muscle strength, while protecting the graft and reducing swelling. More muscle groups are trained compared to phase 1, including the quadriceps, hamstrings, hip flexors, gluteals, and the calf. Clam, side-lying hip abduction, single limb deadlift,

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step-up, calf raises, and lunges are suggested. If patients have access to machines and equipment, the hamstring curl machine, hip abductor and adductor machine, seated calf machine, and stationary bicycle are beneficial and convenient for enhancing strength. Phase 3 (3 months to 6 months) continues the goal of phase 2, but with more intense training and full weight bearing. Apart from muscle activation and strength building according to individual deficit, an agility and plyometric program can be applied. From 6 months and above, phase 4 concentrates on return-to-sport rehabilitation. Patients should be educated about the limitations and safety awareness. Performance, including hard cutting, intensive running, and pivoting, should be progressive and carried out carefully [11,12]. All patients ought to consult doctors and physical therapists periodically to actively monitor and assess their knee conditions and accurately set up a personalized training program.

3.2. Novel approaches for ACLR rehabilitation

Recent advancements in ACL reconstruction (ACLR) rehabilitation have introduced innovative strategies that integrate technology and personalized medicine to optimize recovery. Velocity-based training (VBT) monitors the intensity by tracking the velocity of the movements, giving real-time feedback. The larger the weight used, the slower the velocity, and it continues as the velocity reaches a minimum (1RM). Using an individualized submaximal load facilitates accurate training while reducing the risk of muscle failure. The VBT is beneficial for ACLR rehabilitation, especially in the mid to late stage. Amyotrophy is inevitable post ACLR, with decreased forces produced by the muscle; thus, restoring muscle function without putting too much stress, causing fatigue, is critical throughout the rehabilitation. Applying VBT with 60-80% of 1RM and 15-30% VL gives an optimal outcome for muscle growth. Higher VL may result in neuromuscular fatigue and require longer recovery time. However, the VBT should not be considered as the sole training for ACLR rehabilitation. Training sessions should integrate the traditional strength-based rehabilitation and the VBT with periodization to minimize the risk of injury. The efficacy of VBT in the early stage of ACLR rehabilitation remains unclear, with little research data [10].

Neuromuscular training (NMT) continues to be a cornerstone of ACL rehabilitation, focusing on dynamic stability, proprioception, and movement retraining. Neuroplasticity is a brain re-wiring process that could play a negative role in ACLR recovery if not corrected, leading to a flexed knee when walking, for instance. NMT's unique value lies in correcting arthrogenic muscle inhibition and impaired proprioception through progressive exercises including perturbation training, dynamic balance drills, and sport-specific agility work, which collectively help restore optimal movement patterns and neuromuscular control. The application of NMT follows a phased approach: early rehabilitation (0–6 weeks) focuses on basic proprioception and quadriceps reactivation; the intermediate phase (6–12 weeks) introduces dynamic stability challenges; while later stages (3–6 months) incorporate high-intensity agility drills before progressing to sport-specific simulations with cognitive-motor dual tasks in the return-to-sport phase (6+ months). Clinicians must acknowledge the multifaceted demands for returning to sport, as applying either solely physical strength training or NMT would be insufficient for the rehabilitation, especially for athletes who require a high level of body condition [13,14].

Blood Flow Restriction training (BFR) has emerged as a valuable method for ACLR rehabilitation, particularly for addressing the post-operative atrophy and muscle strength deficit. The primary advantage of BFR lies in its ability to stimulate muscle hypertrophy and enhance strength using low-load resistance (20-40% of 1RM), which minimizes stress to protect the healing graft

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while promoting physiological adaptations [3]. BFR applies controlled vascular occlusion, which creates an anaerobic environment that enhances muscle protein

synthesis and recruits type II muscles to mitigate atrophy. Nevertheless, patients should be well informed and assessed for medical history and chronic diseases before receiving BFR. Contraindications include the following: poor circulatory system, hypertension, sickle cell anemia, arterial calcification, diabetes, thrombosis, and other vascular diseases. Despite the restraints, BFR presents an alternative for traditional strength training, giving a viable method for post ACLR patients to reduce muscle failure in the early rehabilitation stage when weight-bearing is forbidden [3,4].

4. Factors influencing postoperative rehabilitation outcome

4.1. Preoperative rehabilitation's effect on postoperative rehabilitation outcome

The term preoperative rehabilitation is regarded as the rehabilitation activities done between the time after being diagnosed for ACL tear and before the ACLR. A growing body of evidence demonstrates that structured prehab programs can significantly enhance post-operative functional outcomes, reduce complications, and accelerate return to sport timelines. Recommended preoperative rehabilitation exercises include the open- and closed-chain exercises, neuromuscular stimulation, proprioceptive exercises, balance, and quadricep-focused muscle training [5,6]. According to the research, receiving 10 sessions of preoperative rehabilitation before the operation can increase the knee function score by 12% to 15%. Another study by Giesche et al. found that the group with preoperative rehabilitation had a greater increase in the single-leg hop score, with 13.5% in contrast to the control group of 9%. Shaarani et al. discovered a lower reduction of the baseline limb symmetry index for quadriceps in the prehab group (-20.3%). Similarly, Kim et al. reported a greater increase in the limb symmetry index of 75.1% to 85.3% for the prehab group. Despite the significant positive effect on the postoperative outcome, the implementation protocol for the prehab remains debatable. Most studies suggest 4-6 weeks, while some evidence argues that even a longer period (8-12 weeks) may return better outcomes, particularly for athletes aiming for high-level competition. Additionally, the effect on the hamstring is inconspicuous. Overall, patients are encouraged to have a few weeks of rehabilitation sessions before the operation.

4.2. Psychological aspect and impact on the rehabilitation outcome

Clinical depression and anxiety post-ACLR have not been taken into account for rehabilitation until recent years. The symptoms of depression and anxiety are not unique to ACLR but rather relevant in orthopaedic post-operation patients. Garcia et al. reported that 27 out of 64 patients (42%) are classified as MDD (major depressive disorder). In addition, Crichlow et al. discovered that up to 45% of orthopaedic patients suffer from clinical depression, for which 26% of them experience severe symptoms (assessed without somatic element). Interestingly, the MDD group was scored significantly lower for the IKDC, and 4 of them reported complications, while the non-MDD group had no relevant reports. The ACL depression syndrome is mainly attributed to poor mobility, disconnection from people, social withdrawal, frustration with a prolonged recovery period, sudden loss of athletic identity, and lack of self-worth due to the inability to perform at the pre-injury level. Among the ACLR patients, athletes are prone to develop anger and depression, 7 times higher than the baseline. The psychological depression could lead to physical drawbacks, manifesting in the immunologic and musculoskeletal system, as well as the hormone levels. Specifically, bone

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formation is negatively affected, the inflammatory markers increase, and the HPA axis is more activated, producing cortisol (stress hormone). Besides, pain catastrophizing — a lowered pain threshold — may occur, meaning that the patient's perception of pain is more sensitive and potentially being exacerbated subjectively. This could interfere with the rehabilitation sessions as the length, the tedium and fatigue during recovery, and other unpleasant factors collectively amplify the agitation.

Psychological readiness—a composite of confidence, motivation, and emotional stability—has emerged as a strong indicator of successful return to sport (RTS), and is valued in parallel to physical metrics. Patients with a low sense of readiness tend to avoid physical activities and struggle with plyometrics and high-intensity training. Studies discovered an inversely proportional relationship between the second injury rate and with level of psychological readiness. However, to specify, it is only significant for the younger year group, and the readiness level seems to be irrelevant to the re-injury rate for the older year group. With the measure of self-reported readiness level, patients with kinesiophobia are 17% less likely to RTS [5].

When observing signs of depression and anxiety, patients should actively turn to psychiatrists for help and professional treatment. Other interventions like cognitive-behavioral therapy (CBT) and goal-setting strategies integrated into rehab programs can mitigate these effects. ACT (Acceptance and Commitment Therapy) can be introduced to patients to help them overcome difficult emotions while committing to valued actions. This is often used on chronic pain patients, and brings a similar effect on ACLR patients. Furthermore, having 10 minutes of guided meditation every day yields benefits for patients, including relaxation, which reduces inflammatory markers. Meditation is believed to improve sleeping quality, which is equally crucial for muscle recovery and growth as strength training. As aforementioned, the depression could be caused by the lack of connection to people and social circle. Thus, patients may join to ACLR recovery group or other support groups, where sharing experiences and exchanging ideas enhances mental wellbeing for all the members. Apart from psychological approaches, low-impact activities can boost endorphin release without putting stress on the joint and damaging the graft. For instance, swimming with moderate intensity and walking in water are sustainable and suitable for people with varied cardiovascular health. Gradual reintroduction to activity helps ACL patients regain trust in their bodies and combat kinesiophobia.

5. Conclusion

This paper concludes a holistic approach to ACLR rehabilitation, consisting of physical, neuromuscular and psychological strategies. Study highlights the efficacy of BFR in early rehabilitation, NMT for detailed and controlled movement retraining, VBT for late stages to restore muscle strength and function and preoperative rehabilitation for enhancing outcomes. Psychological readiness and timely management of depression and anxiety are now recognized equally vital as physical recovery, which strongly influences RTS and reinjury rates. However, further studies and a wider sample size are needed to standardize rehab duration and validate VBT efficacy during earlier stages of rehab and clearer indications of depression signs.

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