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Epidemiology, Mechanism, and Modern Approaches to Rehabilitation of Anterior Cruciate Ligament Injuries: A Focus on High-Risk Sports

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Abstract. The incidence of Anterior Cruciate Ligament (ACL) injury is a widespread and debilitating sports medicine complication in high-intensity sports and its prevalence is ever-growing. The postoperative reinjury and the threat of premature osteoarthritis are salient, and are one of the long-term dangers of the careers of the athletes. In this paper ACL injury epidemiology, the biomechanical factors, modern approaches to rehabilitation strategies in the high risk sports like basketball are reviewed. These injuries are mainly caused by non-contact ACL injury which is most of the time due to biomechanical imbalances such as dynamic knee valgus collapse and excessive tibial rotation and the prevention of this issue demands incorporation of sport-specific movement pattern interventions. The contemporary system of rehabilitation has become a sequence of several steps, that are standardized, including not only strength and neuromuscular training, but also some new technologies, including wearable sensors and blood flow restriction therapy. Rehabilitation approaches in the future will consider individualization and specialization more carefully, focus on functional performance over mere time-based milestones, and encourage the change of the rehabilitation goal of the medical clearance to sports preparedness. This paper critically evaluates the evidence research that is currently in progress in the fields of epidemiology and clinical significance of ACL injury, biomechanical mechanisms of non-contact injury, purpose and evidence of preoperative prehabilitation and staged postoperative rehabilitation/return-to-sport plans in order to present theoretical foundation and practical recommendations in the prevention, and rehabilitation of ACL injury.

Keywords: Anterior Cruciate Ligament Injuries, Rehabilitation, Sports

1. Introduction

ACL tears are one of the significant issues in sports medicine that occur in large numbers, especially in sporting activities that demand a lot of jumping, cutting, or pivoting. The numbers keep rising, and it is accurate on the primary surgeries and revision surgeries. This is quite noticeable in professional basketball: the cases of surgeries among NBA basketball team doctors are growing, and

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it speaks of the severity of this injury at the highest level and the importance of graft failure and re-injuries concerns [1]. It is very costly to the sportsmen. They have to undergo 9–12 months of rehab, face high healthcare bills, and even risk compromising their career duration and quality. The problem of ACL injury is not unfounded, and it depends on the sport because every sport has its own biomechanics. Incidence rates of soccer, lacrosse, and basketball may be high, though they do not occur in the same way. In basketball, most forms of non-contact injuries are experienced whereas in soccer, there are more direct contact forms of injuries. It means that prevention should be sports-patterned and oriented at motions which take place in course of play [2].

The effects of ACL tear are very serious in the long-term despite the initial injury. Patients are highly exposed to early osteoarthritis and other chronic functional problems even in a successful surgery. In this way, there is no focus on correcting the anatomy only, but they protect the health of the joints during lifetime. When considering the management of a complete ACL tear amongst individuals who remain active, we are inclined to believe in a three part formula, first-stage acute care and surgery and followed by lots of rehab. Surgery usually means the reconstruction of the ligament by autograft or allograft tissue to give back the knee stability.

Nevertheless, on the basis of some recent studies, it seems that the surgery does not suffice. In fact, it is the success of the rehab that will come later, the progression of the rehab, and the extensiveness of the recovery that is done that is the key to success. Modern rehabilitation treatment system is established and is standardized in terms of procedures. It is categorized into several phases, with achievement requirements in each, and not before the stage one achieves them, they can proceed to the next stage. Rehabilitation therapy is made up of strength training, neuromuscular re-education, proprioceptive training and psychological preparation. At the same time, hi-tech methods like wearable sensors to track the gait and blood flow control therapy to help with supplying early stages of strength development are implemented. The macro goal is to return to the sport safely and, additionally, to minimize the risk of a second injury as well as postpone the onset of osteoarthritis. This way, ACL rehab will be a considerable long-term health investment.

2. Biomechanical mechanism of non-contact ACL injuries: high-risk scenario insight

ACL tear, particularly non-contact tear, is a complex, multiplanar sequence of lower extremity biomechanical failure. The video analysis of high-risk sports basketball have been very useful in decomposing this sequence and showing generalities which may be applicable to the majority of the court and field sports. Krosshaug et al.'s archetypal analysis of male professional basketball players demonstrates that the majority of injuries are received during those unopposed, player-controlled motions as opposed to a direct hit; intrinsic biomechanics plays a more important role than the one of external force [3]. This is primarily a dynamic valgus collapse of the knee (hip adduction and internal rotation with knee abduction), and excessive rotation of the tibia, occurring more in the initially extended knee (knee close to less than 30 degrees of flexion) at the initial landfall on the ground. The posture places significant mechanical load on the ACL. Two high-risk situations prevail:

1. Awkward Landing: This type of landing most commonly occurs during a jump, where the athlete maintains an upright trunk, limited knee flexion, and a displaced center of mass.

2. Deceleration/Cutting: It occurs during a sharp change of direction, where the weight-bearing foot experiences substantial rotational and shear forces [3].

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Such patterns signify the lack of the proximal neuromuscular control. It is impossible to stabilize the femur through hip and core stabilizers (gluteus medius and maximus, obliques) hence the risky valgus posture of the knee.

A research study on NBA injuries based on broadcast records discovered that basketball actions that happen in high risk of injury were rebounding, defensive close-outs, and contested layups [4]. These instances can be typically a combination of cognitive load (pressure to make decision), environmental (playing among other players) and biomechanical compromise (off-balance positioning). The combination of these aspects leads to the inability of the athlete to maintain the lower limbs in the optimal position (knee-over-toe position with control of the hips and trunk) under the influence of high-speed, high-load, and even unpredictable factors. This biomechanical results in precarious position such as shallow knee flexion angle, valgus knee moment, flat-footed or supinated foot and forms a stable point of tibial rotation and a laterally flexed trunk. This stance maximizes the anterior tibial shear force, the primary load on the ACL.

Therefore, in all sports, injury prevention interventions are based on overcoming this process: to teach athletes to land and cut with deeper knee and hip flexion, trunk uprightness and control, to strengthen the posterior chain and hip abductors. The basketball experience on the high percentage of the occurrence of such at-risk motions provides a critical point of insight into the prevention of ACL injuries within a wide scale of sport activities.

3. Rehabilitation training before and after reconstruction surgery

3.1. Preoperative prehabilitation

Preoperative neuromuscular impairment and muscle weakness are common. ACL rupture can be accompanied by deficits in neuromuscular function and muscle weakness. This part discusses the application of preoperative rehabilitation (PreHab) in holistic recovery of target groups of people after ACL repair or reconstruction. Several pre-operative functional impairments such as persistent quadriceps inhibition with the presence of muscle strength asymmetry that manifest with poor functional outcomes and slow recovery after surgery are intimately linked with risking the occurrence of ACL re-tear. Over the past few years, the increased interest of adverse consequences arising due to the lack of preoperative injury management has stimulated the establishment of preoperative rehabilitation. The goal of preoperative rehabilitation is to optimize physical preparedness prior to ACL reconstruction and enhance the preoperative outcomes [5,6].

Carter et al. performed a systematic review study to examine the effect of preoperative rehabilitation on postoperative outcomes of anterior cruciate ligament reconstruction (ACLR). As well, the review suggested that preoperative rehabilitation programs that included muscle strengthening, balance training, and perturbation training could have a small positive influence on the knee extensor strength, single-leg jump performance, gait symmetry, and some patient-reported outcomes during the first postoperative months of ACLR (commonly 3 to 6 months postoperative). Nevertheless, out of 738 studies, the number of eligible randomized controlled trials (RCTs) was low, with only 3 possible RCTs identified [5]. There was also major heterogeneity in outcome measures that did not allow researchers to replicate their methods and data, thus lowering the number of studies available. However, the review did not find any evidence that preoperative rehabilitation predisposes or worsens the outcome of surgeries. In spite of the fact that preoperative rehabilitation has not been clearly demonstrated to provide significant gains in strength, functioning, or returning limitations of sports, its capacity to induce minor functional gains during the initial phase with a very low clinical risk has garnered increased attention [5]. The limited effectiveness of

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universally applicable preoperative rehab programs indicates that more targeted interventions, such as quadriceps-specific training, may help improve and better elucidate potential benefits.

The other significant factor contributing to the moderate and persistent benefits that are witnessed with preoperative rehabilitation is that it influences the quadriceps strength after ACL tear. ACL injury is well known to cause muscle weakness that is usually accompanied by arthogenic muscle inhibition, effusion in the joint as well as pain. Even during the post-operative period, severe muscle strength deficits can occur. It is worth noting that the strength of the quadriceps has been found to be one of the most reliable predictors of postoperative functional performance and rehabilitation progress and movement symmetry following ACLR [7], which is why it becomes a main clinical goal of the preoperative stage. According to Grindem et al. in a systematic review preoperative rehabilitation based programs of preoperative exercise are related to the increase in preoperative quadriceps strength, and the maintenance of such strength is followed to the postoperative rehabilitation stage in various studies [7]. The above findings imply that the low efficacy reported in the global applicability of the preoperative rehabilitation interventions could indicate the lack of enough targeting. The unaddressed quadriceps deficiencies in the functioning may have a serious negative effect on the postoperative performance and create the threat of re-injury. Consequently, the preoperative rehabilitation interventions in the context of quadriceps strength are more likely to remedy major functional deficits, and partially explain the initial functional benefit found following ACLR.

Even though quadriceps functional restoration is a major objective of preoperative rehabilitation, strength alone might not be adequate to achieve the complex neuromuscular control and coordination demands following ACLR. ACL tear has been linked to neuromuscular control disorder such as distorted muscle activation patterns, lack of limb symmetry, and lack of motor coordination. And these disorders can go on and result in negative outcomes without any preoperative intervention. The results of preoperative rehabilitation studies that include balance training and perturbation training evidence demonstrate that, even though the overall effect sizes are small, neuromuscular readiness interventions may help produce early gait symmetry and functional performance change [5]. Moreover, Buckthorpe et al. validated that the optimization studies of early rehabilitation have found that people with a higher preoperative motor control and quality of movement are more capable of meeting the demands of the early postoperative rehabilitation [8]. Regardless of the fact that the current evidence is still few and diverse, preoperative rehabilitation has been identified safe and could have slight, yet significant benefits in neuromuscular and functional preparedness [6]. Quick deceleration, change of direction, and coordination control of lower limbs is important in sports that require high performance like basketball. Thus, improvement of neuromuscular function impairments prior to ACL reconstruction is of great clinical relevance, which justifies the further implementation and perfection of preoperative rehabilitation methods.

Overall, the current evidence indicates that even when the quality of evidence is low, and there is a high degree of heterogeneity across different programs, preoperative rehabilitation is a safe intervention that can bring about small yet significant benefits in terms of strength, neuromuscular control and early functional functioning following ACLR. Although broadly based preoperative rehabilitation interventions have small outcomes, more specific interventions targeted at quadriceps strength and neuromuscular preparedness, have greater effect in reducing the lingering preoperative deficit of functional abilities. In particular, basketball, coordinated movements, quick deceleration, and symmetry of limbs are important. Early rehabilitation could be enhanced by preoperative physical preparedness. Consequently, preoperative rehabilitation must be considered as the start-up

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stage of an ongoing recovery process, that has a direct impact on the demands and the results of the early postoperative rehabilitation.

3.2. Postoperative education and rehabilitation schedule

The program developed should be based on the nature of each stage such as the early phase, middle phase, return-to-sport preparation phase and the return-to-sport phase. There are training and rest priorities in each of the phases. Development of the program should be progressive and be based on functional criteria as opposed to strict time points.

Early intervention is crucial to promote tolerance-based recovery of the injured area, with subsequent training tailored to the patient's tolerance and functional recovery progress. The knee instability, functional impairment, and secondary joint degeneration had very close links with a post ACL injury and reconstruction; longterm muscle weakness, and quadriceps weakness. Thus, the quadriceps rehabilitation should be introduced prior to the intense rehabilitation training. Despite the proven data of the high-intensity resistance training being an effective stimuli to improve muscle strength, resistance training in conventional rehabilitation protocol tends to utilise non-functional postures like sitting or supine, which can limit the transfer of the training gains to everyday tasks like walking. As well, because of the issue of graft safety, it is common not to be able to perform adequate resistance training during the initial postoperative phase. Palmelli-Smith et al. investigated whether low-resistance progressive functional resistance training (i.e. when undertaken during walking) would enhance the strength of the thigh muscle in the early postoperative stage. The researchers conducted a single-center, parallel-group randomized controlled study where 30 participants were recruited 6 weeks to 10 weeks after surgery and split in three groups, namely a functional resistance training (FRT) group using custom braces to generate bidirectional knee joint resistance, a functional resistance training (FRT) group using elastic bands to generate unidirectional extension resistance to the ankle joint, and a control group of participants that only performed target trajectory matching training without external resistance [9]. Every participant was taking a treadmill walking training 2-3 times a week during 8 weeks. The assessment of knee isokinetic flexion and extension muscle strength was assessed prior to training, post-training, and 8 weeks following cessation of training. The research findings indicated that the group that had functional resistance training using custom braces was the most significantly improved in terms of muscle strength. Peak torque of the knee extensor on the concerned side in the brace group was much greater as compared to the control group at the conclusion of the intervention and this benefit was still attained 8 weeks following the termination of the intervention. The extensor muscle strength in the brace group induced by the intervention improved by 42 x on average as compared to the baseline and 18 x on average in the control arm. On flexor muscle strength, the brace group also showed a significant difference over the elastic band group and the control group at the conclusion of the intervention, which showed that, the hamstring is strengthened by bidirectional resistance training [9]. These findings verify that the functional resistance training, particularly the training through the use of equipment equipment capable of offering controlled bidirectional resistance of equipment, is a useful addition to the conventional early postoperative rehabilitation of the ACL.

In designing mid-term and late rehabilitation programs, the knee joint taken as intervention should be extended to the proximal hip and core areas to enhance neuromuscular control in impacting the efficiency of lower limb knee chain dynamics. Although the strength of quadriceps and hamstring muscles are relevant, any deficiency in the activity of the core and hip muscles as proximal stabilizers may result in pelvic instability during movements and thereby compensatory abnormal loads on the knee joint with which the likelihood of ACL re-injury is closely linked.

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However, conventional rehabilitation often lacks systematic training to address this aspect. This study aimed to investigate the advantages of pre-regular core stability training on neuromuscular performance by using randomized controlled trial as the research methodology [10]. The researchers split a sample of 26 male athletes that had an ACL reconstruction procedure into two groups. After 8 weeks of core stability exercises, which was performed a series of exercises that were simple, quick and time effective the intervention group went through it before training as a team, and the control group went through their usual training. Cores endurance was assessed with a handheld dynamometer, hip abduction and external rotation muscle strength were measured before and after intervention and single-leg landing kinematics with video motion analysis. Findings revealed that the core training group registered considerable gains in core endurance and hip abduction and hip external rotation strength over the control group. What is more important is that this group had a higher knee flexion angle and lesser valgus angle during the single-leg landing which showed that the group had greater shock absorption capacity and dynamic knee stability. Such findings support the assumption that pre-regular training low-dose core stability training may be used effectively to optimize the neuromuscular activity and biomechanical patterns of athletes due to ACL reconstruction and should be seen as the aspect of the preparation to get back in sports.

Table 1. Summary of key interventions and evidence for Anterior Cruciate Ligament (ACL) injury rehabilitation

Rehabilitation Phase	Core Intervention Measures	Specific Content	Ref.
Preoperative Rehabilitation (PreHab)	Quadriceps Strengthening Training	Specialized training targeting quadriceps inhibition and muscle strength asymmetry following ACL injury	[7]
	Neuromuscular Control Training	Including balance training and perturbation training to improve muscle activation patterns and limb symmetry	[5,8]
Early Postoperative Rehabilitation	Functional Resistance Training (FRT) - Custom Brace Group	Utilizing custom braces to provide bidirectional knee joint resistance combined with treadmill walking training	[9]
	Functional Resistance Training (FRT) - Elastic Band Group	Applying unidirectional extension resistance to the ankle joint using elastic bands combined with treadmill walking training	[9]
	Conventional Rehabilitation Training (Control Group)	Only target trajectory matching training without external resistance intervention	[9]
Mid-to-Late Postoperative Rehabilitation	Core Stability Training	Implementing simple, efficient core stability exercises to enhance core endurance and the strength of hip abductor and external rotator muscles	[10]
	Sport-Specific Training	Simulating competitive scenarios, including neuromuscular explosive power training, correction of abnormal movement patterns under fatigue	[11]

Conclusively, in developing late rehabilitation and return-to-sport interventions, prioritizing should be placed on the restoration of higher-order neuromuscular impairments which influence athletic performance and risk of re-injury, and not just the restoration of basic muscle strength and joint range of motion. Muscle strength symmetry is usually regarded to be one of the crucial indicators that could be used to determine the return to sport; however, the indicator in itself cannot be able to provide the safe entry of athletes to competitions. Without considering explosive power development, supporting the quality of movement under fatigue, and finding answers to sport-specific conditions, the probability of secondary injury will remain high among athletes. As it was identified in a systematic review study by Della Villa et al., four elements that are stunned in most situations are necessary to optimize the late rehabilitation process: entering neuromuscular explosive power, screening and correcting abnormal movement patterns in relation to injury risk, testing and training under fatigue conditions, and sport-specific retraining [11]. In this respect, the authors came up with a new late rehabilitation and return-to-sport training model, which underlines the positive intent that the last stage of the training process should be performed in the environment that is infinity close to the real competition that involves simulating the elements of tactical decision-

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making, the competitive stress, and fatigue acquisition [11]. This model propose the replacement of the medical clearance as the endpoint program of rehabilitation conditions with the sport preparedness, which proposes that decisions arise to return athletes to sports condition must be guided by the resilient functionality shown under challenging dynamic settings and not by idiosyncratic measurements, which can only be obtained in the laboratory settings. These insights advocate for re-conceptualizing late-stage rehabilitation as a highly specialized, performance-oriented training regimen, rather than merely a continuation of basic conventional therapy.

4. Conclusion

The study of the prevention, treatment, and rehabilitation of the Anterior Cruciate Ligament (ACL) injuries has experienced systematic advancement. In high-risk sports with high ACL injury rates, research has deemed non-contact injury as a result of major biomechanical processes such as dynamic knee valgus and insufficient neuromuscular control through video analysis, which lays the foundation for formulating sport-specific prevention initiatives. During the preoperative phase, although the evidence levels are not consistent, the PreHab is a safe intervention proved; with the help of specific quadriceps strengthening and neuromuscular training, PreHab preconditions the formation of the most favorable conditions for surgery and early functional recovery (See table 1). The system of postoperative rehabilitation has transformed into a phase-based scheme, with an orientation towards functional standards: at the very beginning, the techniques of functional resistance training are introduced in order to successfully enhance muscle strength and minimize graft injuries; at intermediate and final stages, the work is focused on more proximal parts of the body, more on kinetics of chain efficiency and the landing situation and is built into acquiring the paradigm shift of a medical clearance to safe return to competition. In the future, technological innovation in this field will be closely linked to digitalization and individualization. As an example, multi-dimensional sports data can undergo analysis performed by artificial intelligence and machine learning to provide early accurate prediction of injury risk and real-time feedback of biomechanical data. The combined presence of wearable sensor technology and extended reality (XR) environments will create an immersive and highly simulated training environment based on the neuromuscular and sport-specific skills and enable rehabilitation to approach real competition conditions within a controlled setting. In the meantime, regenerative medicine and bioengineering technologies (tissue-engineered ligaments and bioactive scaffolds) should have a positive impact on healing quality based on the source of structural repair; when used in conjunction with complex rehabilitation approaches, these technologies will collectively push the ACL injury management to be more pro-active or preventive, more specific and more functional.

Authors' contribution

All the authors contributed equally and their names are listed in alphabetical order.

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