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Mechanisms of Anterior Cruciate Ligament Injury and the Impact of Integrated Neuromuscular Training on Rehabilitation

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Abstract

The anterior cruciate ligament (ACL) plays a vital role in maintaining anterior stability of the knee joint. ACL injuries are among the most common cases in sports medicine and often result in significant impairment of athletic performance and overall quality of life. Such injuries not only cause knee dysfunction but also increase the long-term risk of complications such as osteoarthritis. The mechanisms of injury are influenced by anatomical factors, high-risk movement patterns, and deficits in neuromuscular control, making ACL rehabilitation a crucial issue in both medical and athletic fields. This study aims to provide a comprehensive examination of ACL injury mechanisms and to evaluate the effectiveness of Integrated Neuromuscular Training (INT) as a rehabilitation strategy. INT, rooted in neuromuscular control principles, is designed to restore knee and lower-limb function more effectively through a systematic and multidimensional approach. The methodology of this study is based on a literature review and theoretical analysis of prior research addressing ACL injury mechanisms, rehabilitation interventions, and the clinical as well as athletic application of INT. The findings indicate that INT is effective in enhancing knee joint stability, correcting faulty movement patterns, and reducing the risk of re-injury. Furthermore, INT contributes to improved functional performance and accelerates recovery in athletes undergoing ACL rehabilitation. The implications of this study suggest that INT can be applied not only in clinical rehabilitation settings but also in preventive training programs for athletes at high risk of ACL injury. The study provides theoretical insights for refining exercise intervention frameworks and offers practical guidance for clinicians and sports practitioners in both injury prevention and treatment.

Keywords: *Anterior cruciate ligament injury, Biomechanics, Integrated neuromuscular training, Mechanism of action, Rehabilitation.*

A. Introduction

With the widespread adoption of national fitness programs in China, participation in various sports activities has surged annually. Consequently, the incidence of sports-related injuries has also risen, with anterior cruciate ligament (ACL) injuries being particularly prominent (Bai et al., 2022). The ACL is a critical structure for maintaining anteroposterior stability of the knee joint, functioning to stabilize the tibia and prevent excessive anterior tibial translation and internal tibial rotation (Kohn, Rembäck, & Rauch, 2020).

During high-intensity, high-impact sports (e.g., basketball, soccer, tennis, skiing), athletes frequently perform demanding maneuvers such as rapid deceleration, abrupt directional changes (cutting), and jumping. These actions subject the ACL to excessive mechanical loads, significantly increasing the risk of injury (Zhong & Ouyang, 2025). Professional athletes, engaged in prolonged high-intensity training and competition, exhibit a substantially higher ACL injury incidence compared to the general population. ACL injuries often necessitate

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prolonged absence from sport, lead to reduced athletic performance, pose a serious threat to athletic careers, and may even force premature retirement.

The current gold-standard treatment following ACL injury is anterior cruciate ligament reconstruction (ACLR) (Zhao, Liu, & Zhuang, 2024). However, ACLR does not guarantee full restoration of knee joint function or reduction in secondary injury risk. Only approximately 50% of ACLR patients successfully return to their pre-injury competitive sport level (RTS). Notably, among young athletes, the re-rupture rate can reach up to 20% within the first year of returning to sport (Zhong & Ouyang, 2025; Beard et al., 2022). ACL injury management involves lengthy rehabilitation and carries significant risk of post-traumatic sequelae. Chronic or recurrent knee joint instability is common, contributing to reduced quality of life, diminished athletic capacity, and an elevated risk of developing secondary knee osteoarthritis (Jenkins et al., 2022). This imposes a substantial physical and psychological burden on patients.

Advancements in understanding knee joint anatomy and sports injury mechanisms, coupled with refinements in ACLR techniques, have heightened interest in the role of exercise interventions for ACL rehabilitation and prevention. Integrated Neuromuscular Training (INT) has emerged as a novel and promising rehabilitation and prevention strategy. INT transcends the limitations of traditional isolated training approaches by systematically integrating multiple components, including muscular strength training, balance training, agility training, and proprioceptive training (Yin et al., 2021). Operating from the fundamental principles of neuromuscular control, INT aims to comprehensively restore movement function of the knee joint and the entire lower extremity (Peng, 2020). This training paradigm also enhances athletes' proprioception and somatosensory awareness during competition (He, Dong, & Jiang, 2017).

The functional impairment resulting from ACL injury extends beyond mere ligamentous disruption; it encompasses dysfunction within the lower limb neuromuscular control system and aberrant biomechanics (Zhong & Ouyang, 2025). Post-surgical recovery relying solely on the repair, without adequate rehabilitation, often leads to complications such as residual knee instability, muscle atrophy, and restricted joint range of motion (ROM), severely hindering comprehensive functional restoration. INT not only strengthens muscles, enhancing the knee's load-bearing capacity during complex movements, but also optimizes neuromuscular synergy, improves dynamic joint stability, and enhances overall motor coordination (He et al., 2017). This facilitates the anticipation and mitigation of potential injury risks.

Therefore, a thorough investigation into the therapeutic and prophylactic efficacy of INT for ACL injuries holds significant promise. It offers a scientifically grounded, efficient, and forward-looking rehabilitation pathway for ACL-injured patients while providing a robust preventive strategy for high-risk populations. This research direction carries substantial theoretical innovation and practical significance within the fields of sports medicine and rehabilitation science.

B. Methods

This study adopts a qualitative research design in the form of a systematic literature review and theoretical analysis. The focus is to synthesize existing empirical and conceptual studies on anterior cruciate ligament (ACL) injury mechanisms and evaluate the impact of Integrated Neuromuscular Training (INT) on rehabilitation. By examining peer-reviewed journals, clinical reports, and experimental studies, this design enables the identification of key injury mechanisms and the assessment of INT as an effective intervention strategy.

The research procedure was conducted in several stages. First, relevant academic databases such as PubMed, ScienceDirect, SpringerLink, and Google Scholar were systematically searched using keywords including "ACL injury," "neuromuscular training," "rehabilitation," and "biomechanics." Second, studies published between 2000 and 2025 were screened for relevance to ACL injury mechanisms or INT-based interventions. Third, selected studies were categorized into two main themes: (1) mechanisms of ACL injury and (2) rehabilitation strategies using INT. Finally, a comparative synthesis was carried out to evaluate the theoretical and practical contributions of INT to rehabilitation and prevention.

Data were collected through documentary analysis of scientific articles, clinical trials, systematic reviews, and sports medicine guidelines. Inclusion criteria focused on studies involving ACL injury rehabilitation, biomechanical analyses, and neuromuscular interventions. Exclusion criteria involved articles lacking empirical evidence or unrelated to the rehabilitation context. Data points extracted included intervention methods, outcomes, recovery duration, and injury recurrence rates.

The data analysis employed qualitative content analysis to identify recurring patterns, theoretical frameworks, and empirical findings. A thematic coding approach was applied to classify injury mechanisms, rehabilitation outcomes, and the effectiveness of INT. The results were synthesized into a narrative framework, highlighting the advantages, limitations, and future potential of INT in ACL rehabilitation. This approach allowed the formulation of evidence-based insights that bridge theory and practice in sports medicine and rehabilitation science.

C. Results and Discussion

1. Intrinsic Mechanisms of ACL Injury

The anterior cruciate ligament (ACL) is an intra-articular ligament within the knee joint. Its primary functions are to restrain anterior tibial translation, limit excessive rotational movements, and maintain knee joint stability. Embedded with proprioceptive receptors, the ACL contributes to neuromuscular control, dissipates external forces, and restricts relative rotation between the femur and tibia. ACL rupture leads to knee joint instability and impaired athletic performance. The mechanisms underlying ACL injury are multifactorial, encompassing anatomical factors, neuromuscular function, sex differences, age, and genetic predispositions, among others (Wang, 2024).

Anatomical Factors

The knee joint is one of the most complex and heavily loaded joints in the human body. Understanding ACL injury mechanisms necessitates focused examination of key anatomical parameters: the medial tibial posterior slope (often referred to as the tibial plateau anterior inclination angle in Chinese literature), the femoral intercondylar notch index, and lower limb alignment (Li et al., 2017; Zhong & Ouyang, 2025).

The ACL serves as the primary restraint against anterior tibial translation, yet its position and function are constrained by the morphology of the femoral intercondylar notch, specifically its width and depth characteristics (Wang, n.d.). An increased medial tibial posterior slope alters the sagittal plane relationship between the tibia and femur. This biomechanical change results in a heightened tendency for anterior tibial translation during knee flexion and extension (Li et al., 2017). Consequently, an excessively steep posterior slope subjects the ACL to sustained excessive tensile loads during daily activities and sports, progressively compromising its mechanical integrity.

The femoral intercondylar notch index quantifies the ratio of notch width to depth. A smaller index indicates a relatively narrower and shallower notch morphology, which restricts the space available for the ACL and increases the risk of impingement during dynamic movements (Wang, 2024).

Lower limb alignment, defined as the mechanical axis of the lower extremity during weight-bearing, directly governs load distribution across the knee joint. Deviations from normal alignment are consequently strongly associated with ACL injury risk (Zhao et al., 2024; Zhong & Ouyang, 2025). Genu varum (commonly termed "bow-leggedness" or "O-shaped legs") represents a classic manifestation of malalignment. In this posture, the mechanical axis shifts medially, leading to excessive compressive loads concentrated on the medial compartment, significantly exceeding physiological levels. Conversely, genu valgum ("knock-kneed" or "X-shaped legs") involves a lateral deviation of the mechanical axis. Under valgus conditions, the vector of tensile forces acting upon the ACL is altered. Furthermore, widening of the lateral joint space compromises the control of tibial rotation relative to the femur. This combination renders the ACL highly vulnerable to fatigue failure and injury when resisting abnormal rotational forces.

In summary, an increased medial tibial posterior slope, a decreased femoral intercondylar notch index, and pathological lower limb alignment collectively constitute significant anatomical risk factors predisposing individuals to ACL injury.

Sport-Specific Factors

Sports participation is a leading cause of ACL injuries and a significant contributor to post-traumatic knee osteoarthritis. Different sports disciplines, characterized by their distinct movement patterns and technical demands, exert markedly divergent influences on ACL injury risk. Collision/contact team sports, including rugby, basketball, soccer, wrestling, and track and field (particularly events involving cutting/pivoting), demonstrate the highest incidence rates and overall injury burden (Zhang, 2018).

These sports necessitate frequent high-intensity deceleration, abrupt directional changes (cutting maneuvers), and pivoting actions, subjecting the athlete's knee joint to substantial torsional and shear forces within milliseconds. Additionally, the inherent risk of body contact and collisions significantly contributes to contact ACL injury mechanisms (Zhang & Jiang, 2016).

Using basketball as an exemplar, during fast-break transitions and dribble penetration phases of gameplay, athletes execute rapid directional changes. In these scenarios, the ACL—serving as the primary restraint against anterior tibial translation and rotation—is highly vulnerable to injury when forces exceed its load-bearing capacity (Cai, 2017). When an athlete attempts to evade a defender with a sharp body rotation, the knee often undergoes excessive internal rotation combined with valgus angulation. This places asymmetric tensile loads on the ACL, significantly elevating the risk of rupture (Zhao & He, 2018). This risk is further amplified during high-velocity deceleration coupled with directional changes. Under these conditions, the periatricular musculature may be unable to achieve optimal, coordinated contraction rapidly enough to provide dynamic stabilization and protect the ACL, thereby exacerbating injury susceptibility. Epidemiological data consistently ranks basketball among the sports with the highest ACL injury incidence rates, with professional leagues reporting numerous season-ending ACL injuries among players each season (Zhao & He, 2018).

Furthermore, training/match intensity and frequency constitute another critical dimension influencing ACL injury risk. High-intensity activities inherently involve greater muscular force output, faster movement velocities, and more extreme joint excursions, imposing substantial mechanical loads on the ACL. If the musculotendinous structures surrounding the knee joint are denied sufficient recovery time between bouts of intense activity, cumulative fatigue ensues. This fatigue manifests as delayed neuromuscular response times and imbalances in muscular contraction forces and coordination, progressively compromising the dynamic protective mechanisms crucial for ACL integrity (Liang et al., 2022).

Proprioception and Neuromuscular Control Factors

Proprioception, defined as the sensory capability to perceive limb position, movement state, and joint loading, plays a fundamental role in maintaining joint stability and enabling precise motor control (Wang, 2019). The periarticular tissues of the knee are densely populated with proprioceptive receptors, including muscle spindles and Golgi tendon organs. These receptors continuously monitor joint angle changes, muscle length, and tension variations, transmitting this afferent information rapidly to the central nervous system (CNS). This feedback loop facilitates the neuromuscular adjustments necessary for smooth and stable joint motion.

Following knee joint injuries (e.g., sprains, contusions) or prolonged periods of overuse or immobilization, damage may occur to these proprioceptive receptors and their afferent neural pathways. This results in impaired joint position sense (JPS) and kinesthesia, leaving the individual unable to accurately perceive the knee's real-time kinematic state (Li & Zhang, 2020). For instance, when walking on uneven terrain, intact proprioception enables anticipatory fine-tuning of periarticular musculature to adapt to ground irregularities and maintain balance. In individuals with proprioceptive deficits, however, delayed muscle activation occurs, predisposing the knee to excessive varus, valgus, or rotational displacements.

Within sports rehabilitation, robust evidence demonstrates that ACL-reconstructed patients with inadequate proprioceptive recovery exhibit a significantly higher risk of re-injury compared to those with restored proprioceptive function. This underscores the critical importance of proprioception in both ACL injury prevention and rehabilitation protocols (Wang, 2019; Zhao & Liu, 2021).

Deficient neuromuscular control constitutes a major risk factor for ACL injury. When neuromuscular control is compromised, dynamic knee joint stability is impaired, rendering the knee more vulnerable to injury during athletic activities. For example, during jumping and landing maneuvers, insufficient neuromuscular control hinders the ability to rapidly adjust knee joint position and alignment. This failure synergistically amplifies the risk associated with underlying anatomical predispositions and sport-specific movement demands, potentially leading to excessive ACL strain or rupture (Chen & Li, 2015; Zhou, 2017).

Specifically, during the landing phase, the quadriceps muscles contract forcefully to absorb impact forces, generating substantial anterior tibial shear force. If the hamstring muscles lack sufficient strength or fail to co-contract effectively to counteract this shear force, the ACL is subjected to excessive loading. Furthermore, muscle force imbalances impair the generation of balanced centripetal forces and rotational control moments. This significantly compromises the knee's ability to resist complex external loads, rendering the ACL highly susceptible to injury and posing a severe threat to knee joint health and athletic performance.

2. Mechanisms Underlying INT Intervention for ACL Injury

Therapeutic approaches for anterior cruciate ligament (ACL) injuries are broadly categorized into surgical management and non-surgical management (Zhang, 2018). Surgical management primarily refers to arthroscopic ACL reconstruction (ACLR). This procedure utilizes arthroscopic techniques to reconstruct the injured ACL using either autografts (typically tendons harvested from the patient) or allografts/synthetic ligaments, aiming to restore knee joint stability. ACLR remains the most prevalent surgical intervention for ACL injuries (Zhang, 2018).

Non-surgical management encompasses physical therapy and pharmacotherapy (Liu & Chen, 2019). Crucially, sports rehabilitation training must be integrated during the later stages of treatment to restore normal knee joint function.

Integrated Neuromuscular Training (INT) operates from the fundamental principles of neuromuscular control to comprehensively restore movement function of the knee joint and the entire lower extremity (Chen & Li, 2015). It is designed to enhance the practitioner's proprioception and somatosensory awareness (Zhou, 2017). INT incorporates multiple foundational components, including muscular strength training, proprioceptive training, speed and agility training, dynamic stability training, plyometric training (rapid stretch-shortening cycle exercises), and fatigue resistance training (Wang, 2020; Zhao & Liu, 2021). Synthesis and critical analysis of existing research suggest that the primary mechanisms through which INT mitigates ACL injury risk involve enhancing muscular strength, fortifying core stability, improving proprioception and neuromuscular control, optimizing movement patterns, and correcting aberrant lower limb biomechanics (Sun & Yang, 2022; Xu, 2023).

Enhancing Muscular Strength and Fortifying Core Stability

Integrated Neuromuscular Training (INT) employs specific exercises and stimuli to activate a greater number of motor units and enhance the neural recruitment capacity of the nervous system. During training, the brain continuously dispatches stronger and more precise neural signals to the muscles, leading to increased motor unit activation. This results in the generation of more coordinated and powerful muscle contractions (Chen & Li, 2015; Zhou, 2017; Huang, 2021). INT includes targeted training for various lower limb muscle groups, effectively augmenting muscular strength and promoting inter-muscular force balance.

The muscular strength training component of INT focuses on both core musculature and major/minor muscle groups. Eccentric training is incorporated to enhance rapid force-generating capacity and optimize the strength balance between knee flexors and extensors (Liu et al., 2020). Appropriate muscle synergist and antagonist coordination can reduce stress on the ACL. For instance, during a basketball player's jump shot after a rapid deceleration or a soccer player's powerful instep kick, robust muscular protection is rapidly engaged around the knee, effectively mitigating abnormal stresses on the ACL and preventing injury. Enhanced core muscular strength and endurance better maintain spinal stability, providing a solid foundation for all bodily movements. Core stability is intrinsically linked to the kinetic chain. INT emphasizes inter-segmental coordination throughout the body, optimizing inter-muscular coordination and contraction sequencing, thereby minimizing force dissipation and maximizing overall force output. Training the coordinated action between the core and limb muscles facilitates efficient force transmission and dynamic balance.

Enhancing Proprioception and Neuromuscular Control Systems

Proprioception dynamically regulates the stability of the spine and limbs to achieve movement goals, underscoring its critical role in executing precise movements and maintaining joint stability (Zhang & Luo, 2015). Research indicates that the proprioceptive training component of Integrated Neuromuscular Training (INT) effectively prevents proprioceptive dysfunction during athletic activities. This effect is largely attributable to improvements in postural stability, joint position sense (JPS), and dynamic neuromuscular control (Kowalczyk et al., 2019). Training performed on unstable surfaces (e.g., Bosu balls, foam pads) or through multidirectional movement drills increases variability in joint and muscle loading, thereby stimulating proprioceptive receptors to more actively perceive body position and motion. With consistent training, the nervous system develops greater acuity in perceiving limb position, movement direction, and velocity, ultimately refining proprioceptive function. Even in complex, dynamic scenarios—such as high-speed turns in skiing or rapid directional changes during tennis strokes—the knee joint can anticipate limb position and movement trajectories, enabling muscles to initiate precise pre-activation (Scarborough et al., 2019). This allows for timely correction of aberrant joint motions, safeguarding the ACL and other knee ligaments from excessive tensile, torsional, and shear forces, thereby maintaining joint stability.

Following ACL injury, the communication between the nervous system and muscular tissues becomes disrupted. Damage to muscle spindles, tendon organs, and joint capsule mechanoreceptors results in proprioceptive deficits that rarely recover spontaneously, leading to knee joint instability, muscle atrophy, and additional sequelae. INT incorporates diverse exercises—such as agility ladder drills and single-leg balance on unstable surfaces combined with ball-catching and throwing—that demand the nervous system to rapidly and accurately recruit specific muscle groups in a coordinated manner (Zhai et al., 2022). Research has demonstrated that the hamstrings act to restrain excessive anterior tibial translation and internal tibial rotation, while the quadriceps function as antagonists. Appropriate synergistic and antagonistic co-activation between these muscle groups reduces strain on the ACL (Zhai et al., 2022). Moreover, balance training activates the gluteal muscles and hamstrings, thereby enhancing the co-contraction capacity of the posterior thigh muscles (Correia et al., 2020; Sabet et al., 2019), which in turn improves knee joint stability. Through balance training, proprioceptive exercises, and other modalities, INT improves knee joint range of motion (ROM) and balance capacity, alleviates knee pain (Domínguez-Navarro et al., 2018), and enhances central nervous system control over muscles via plyometric training (Zhao & Li, 2021). Collectively, these adaptations enable the knee joint to maintain superior stability during athletic maneuvers (Liu & Wan, 2022; Benis et al., 2016).

Optimizing Movement Patterns and Improving Lower Limb Biomechanics

Integrated Neuromuscular Training (INT) incorporates exercises that specifically target the mobility of lower limb joints—namely the hip, knee, and ankle—thereby increasing joint range of motion (ROM) and enhancing flexibility. This optimizes the kinematic chain of the lower limb, ensuring that joints function within normal biomechanical limits and reducing the risk of joint wear and injury. Anterior cruciate ligament (ACL) injuries are frequently associated with neuromuscular control deficits that lead to aberrant lower limb biomechanics, particularly increased knee valgus angles and external rotation moments, which place excessive stress on the ACL (Montalvo et al., 2018).

A 10-week INT intervention involving 14 high school female volleyball players demonstrated an approximate 15% increase in isokinetic hip abduction strength, while knee abduction and flexion strength remained unchanged (Myer et al., 2005). Improvements in hip abduction strength enhanced lower limb control, reduced stress on the knee joint, and consequently increased knee joint stability (Zhou et al., 2020). Numerous international studies have observed varying degrees of knee valgus during landing tasks among athletes (Schmidt et al., 2019). Notably, Hewett et al. (2005), using three-dimensional motion analysis and force plates to assess 205 female athletes in soccer, basketball, and volleyball, reported that the nine athletes who sustained ACL injuries demonstrated significantly greater knee valgus angles, valgus moments, and ground reaction forces compared to uninjured athletes. Evidence further shows that INT interventions can significantly reduce these valgus angles and moments (Faigenbaum et al., 2009), thereby optimizing knee joint biomechanics and lowering the risk of ACL injury.

The plyometric component of INT contributes to mitigating injury risks in the sagittal plane during jumping tasks, while balance training specifically reduces injury risk at the moment of landing (Sugimoto et al., 2016). Additionally, core stability training within INT strengthens the gluteal muscles, which actively counteract knee valgus forces and improve knee joint stability. Importantly, patients who undergo INT following ACL reconstruction (ACLR) show significant improvements in knee joint ROM and gait parameters, thereby facilitating a safer and more effective return to activities of daily living (ADLs) and sports participation (Arundale et al., 2018).

3. Application Research on the Rehabilitation Efficacy of INT for ACL Injuries

From the perspective of enhancing sport-specific performance, Integrated Neuromuscular Training (INT) places greater emphasis than traditional training methods on developing lower limb power, agility, speed, neuromuscular recruitment capacity, and proprioceptive control (Faigenbaum et al., 2009). Numerous studies have validated INT's significant efficacy in improving athletes' performance and movement quality (Myer et al., 2013).

Using tennis as an example, INT programs tailored for the sport must address specific demands such as rapid torso rotation at ball impact, sudden deceleration and acceleration, and frequent lateral movements. Such programs often integrate tennis-specific footwork drills with balance training. Athletes practice in simulated court environments, performing rapid lateral shuffles and crossover steps—sometimes while holding a racket to maintain balance control. This enables athletes to adjust their body position quickly after movement and execute stable strokes. Such training strengthens the periarticular musculature of the knee, enhances proprioceptive acuity for joint positioning, and improves the ability to generate precise force during high-intensity rallies. Consequently, it reduces the likelihood of ACL overload due to loss of body control, thereby mitigating injury risk.

The rehabilitation outcomes of INT for ACL recovery can be evaluated across multiple domains, including knee functional scores, muscular strength, and kinesthetic proprioception. As a comprehensive training methodology, INT seeks to establish efficient movement patterns, improve neuromuscular control, enhance muscular strength and coordination, and ultimately increase knee joint stability (Arundale et al., 2018; Sugimoto et al., 2016). The overarching aim is to restore athletic performance while preventing or minimizing the risk of reinjury (Montalvo et al., 2018). Critical analysis of existing research indicates that INT facilitates ACL injury rehabilitation and sport performance recovery primarily by enhancing muscular strength, fortifying core stability, improving proprioception and neuromuscular control, optimizing movement patterns, and correcting aberrant lower limb biomechanics.

Within INT studies, isokinetic dynamometry provides valuable insights into the progression of knee flexor and extensor strength. For example, research on ACL rehabilitation in soccer players revealed that after eight weeks of INT, athletes demonstrated significant increases in peak torque for both knee flexors and extensors across different angular velocities (de Villarreal et al., 2015). These findings suggest effective muscular strengthening, which enhances mechanical support for high-intensity competition and lowers the risk of reinjury.

The INT training framework extensively employs unstable surface training, balance exercises, and sport-specific movement simulations (Herrington et al., 2013; Pfile et al., 2016). These modalities reactivate periarticular proprioceptive receptors and remodel neural feedback loops. Evidence confirms that following INT intervention, patients demonstrate significantly fewer errors in joint position sense (JPS) tests, reflecting improved proprioceptive acuity and the ability to anticipate joint state changes during movement (Sugimoto et al., 2016). This enables more timely coordination of muscle contractions, preventing abnormal stresses on the ACL and enhancing joint stability. Agility ladder drills with directional changes and rapid cutting maneuvers further challenge the proprioceptive system to quickly and accurately perceive joint motion in high-speed scenarios, facilitating precise neuromuscular adjustments (Herrington et al., 2013; Dingenen et al., 2015). Additional studies also report that post-ACLR patients undergoing INT exhibit significant improvements in knee ROM and gait parameters, which contribute to more effective return to activities of daily living (ADLs) and sports participation (Arundale et al., 2018).

Traditional injury rehabilitation protocols often emphasize muscular strength development as the primary means of reducing injury risk. However, they frequently overlook compensatory movement patterns arising from neuromuscular control deficits, which may paradoxically increase vulnerability to injury (Benjaminse et al., 2015). Compared to conventional functional training, INT not only emphasizes muscular conditioning but also prioritizes the nervous system's regulation of muscular activity. Because dynamic athletic performance requires the synchronized effort of multiple muscle groups, INT's integrated, multimodal approach elicits superior improvements in lower limb strength, neuromuscular control, and overall function compared to isolated strength training (Zouita et al., 2016).

D. Conclusion

In summary, Integrated Neuromuscular Training (INT) demonstrates significant efficacy in both the rehabilitation and prevention of anterior cruciate ligament (ACL) injuries. INT circumvents limitations inherent in conventional exercise interventions—such as isolated training modalities—while offering a holistic approach to developing diverse physical capacities. The mechanisms underpinning INT's therapeutic and prophylactic effects for ACL injuries encompass enhanced muscular strength, fortified core stability, improved proprioception and neuromuscular control, optimized movement patterns, and corrected aberrant lower limb biomechanics. Despite substantial progress in current research, significant avenues for exploration persist regarding INT's application in ACL injury management. Current understanding of INT's precise mechanisms of action and optimal training protocols remains insufficiently developed. Future research should integrate advanced methodologies including sports biomechanics instrumentation, neuroelectrophysiological assessments, and dynamic three-dimensional motion capture systems to enable real-time, precise quantification of dynamic changes in neuromuscular function and joint biomechanics during INT. This objective data will provide a robust foundation for protocol optimization and outcome assessment, thereby enhancing scientific rigor and precision. Furthermore, future studies must prioritize evaluating INT efficacy across diverse populations stratified by age, sex, sport discipline, and injury severity, alongside optimizing and personalizing INT protocols to maximize its potential in ACL injury rehabilitation and prevention and its application to other sports-related injuries.

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