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Research-Based and Clinical Considerations for Effective Neuromuscular Training to Prevent Second Anterior Cruciate Ligament Injury

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The second anterior cruciate ligament (ACL) injury after ACL reconstruction occurs at reported rates, ranging from 5-20 times greater than that of the primary injury, and results in significantly poorer patient outcomes. In athletes, most of the second ACL injuries occur within the first 2 years of return to sport. Significant functional impairments and deficits in neuromuscular control are frequently reported up to 2 years postreconstruction. Neuromuscular deficit-targeted neuromuscular training (NMT) alters high-risk biomechanics and reduces rates of primary ACL injury. Its efficacy in ACL-injured subjects is currently unknown. External loads during dynamic motion, specifically knee abduction moment, internal tibial rotation moment, and proximal anterior tibial shear force, especially in the lateral compartment, increase ACL strain. These factors are reportedly influenced by modifiable and nonmodifiable factors. ACL reconstruction subjects pose a unique challenge to clinicians and researchers due to the numerous confounding factors in identifying and addressing their risk of reinjury. However, they also may provide clinicians and researchers with a great deal of accessible, highly pertinent clinical, anatomical, and biomechanical information in the forms of medical images, charts, and rehabilitation notes. Thorough determination of postoperative biomechanical impairments, modifiable and nonmodifiable risk factors, and the effects of NMT on these factors aids in eventual reduction of second ACL injury rates. A properly structured and executed large-scale, multicenter trial to evaluate the biomechanical efficacy of NMT in the context of these factors would be invaluable both clinically and academically.
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Introduction

Anterior cruciate ligament (ACL) injury is a devastating event with severe short-term and long-term consequences for the injured athlete. Risk of second ACL injury is 5-20 fold greater than risk of primary injury, with as many as 1 in 4 patients suffering a second injury within the first year of return to sport (RTS), even after formal physical rehabilitation.[1,2] Long-term patient outcomes after second injury are also significantly worse than after primary injury. Approximately 70% of ACL injuries occur through a noncontact mechanism (ie, without a direct blow to the knee) during cutting, landing, and jumping, and are believed to be preventable.[3] Neuromuscular training (NMT) effectively retrains movement patterns and reduces neuromuscular deficits, decreasing primary

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ACL injury incidence by 50%-70% in randomized controlled trials.[4-6] However, there are currently no validated NMT protocols for reducing risk of second injury.[7,8] The current review outlines critical techniques and considerations for both clinicians and researchers for implementation of NMT in ACL reconstruction (ACLR) subjects on a large scale.

Significance of Second ACL Injury Prevention

Short-term to medium-term outcomes for patients recovering from primary ACL injury are generally considered good.[9] However, the same cannot be said for patients who suffer a second ACL injury. Several studies have documented significantly poorer outcomes in subjects who required a revision surgery or suffered a tear to the contralateral limb. Keivit et al[10] compared 27 subjects who had undergone a primary ACLR 5.1 years before to 25 patients who required allograft revision 5.3 years before. Compared to primary ACL-injured subjects with a median score of 1, subjects who underwent revision demonstrated median radiographic International Knee Documentation Committee scores of 4, indicating significantly greater progression toward osteoarthritis (OA).[10] Revision patients also reported significantly poorer outcomes on several Knee injury and Osteoarthritis Outcome Score subscales (reported median for revision vs median for primary) including sport (50 of 100 vs 85 of 100), symptom (86 of 100 vs 96 of 100), and quality of life (56 of 100 vs 81 of 100).[10] Gifstad et al reported similar results on the Knee injury and Osteoarthritis Outcome Score subscale at approximately 7.5 years postrevision, and also report significant deficits in affected knee extension and flexion peak torque and work during isokinetic (60°/s) dynamometry in the revision group.[11] Only peak extension torque was significantly lower in the affected limb of subjects who required only primary ACLR. A mere 13%-27% of patients who require a revision surgery successfully return to the same or higher activity levels as they participated in before injury.[11]

Given the gravity of the situation for the at-risk patient, clinicians and researchers alike should feel compelled to approach secondary NMT with an evidence-based understanding of the problem they seek to prevent. Although it is currently clear that the problem of second injury involves numerous anatomical, biomechanical, and neuromuscular factors, there is little-to-no mechanistic understanding of the differences between primary and secondary injury. The current paradigm considered by our group and outlined in the context of the rest of the review postulates that primary and secondary ACL injury mechanisms are in many ways similar, whereas the factors to consider for primary prevention comprise a crucial subset of the risk factors for secondary prevention.

Mechanisms of Noncontact ACL Injury

Approximately 70% of primary ACL injuries occur during a "noncontact" mechanism, or without a direct blow to the knee.[3,12] Most often, these injuries occur during sports while the subject is landing, cutting, or twisting their leg during change of direction. Understanding noncontact ACL injury mechanism(s) is a critical step toward the development and validation of NMT to prevent second injury. Research into the most plausible mechanism(s) of noncontact-ACL injury demonstrates that 3 types of loading at the knee joint induce strain in the ACL: (1) anterior tibial shear force (ATS), especially in the lateral compartment of the knee, (2) external knee abduction moment (KAM), and (3) internal tibial rotation (ITR) moment.[13-16] Although the type(s) and magnitude(s) of these loads that most frequently result in noncontact ACL injury remain somewhat controversial, there are several systematic analyses of video recordings of noncontact injuries in the literature. These studies demonstrate markedly similar knee kinematics between individuals during ACL injury, though the capability to characterize detailed biomechanics from video is limited, video analyses clearly demonstrate a multiplanar mechanism of injury.[17-21]

At the time of contact with the ground, most individuals land with their knee near full extension, with slight external tibial rotation and a neutral frontal plane alignment. Within the first 100 milliseconds of initial contact, the time frame in which injury most likely occurs, the tibia moves from slight external rotation to internal rotation, and knee abduction angle increases dramatically.[17,18,20,21] This movement is frequently described as "valgus collapse" of the knee.[22] Our group recently demonstrated in cadaveric studies that triplanar loading of the knee joint (ie, combined KAM, ITR, and ATS) generates significantly greater strain in the ACL than the medial collateral ligament.[15,23] Furthermore, this cadaveric model reproduced ACL rupture in nearly 90% of specimens and led to similar kinematics as observed in video analyses.[15,23]

Successful implementation of NMT for second injury prevention requires detailed attention to this mechanism, and understanding of the factors that contribute to and detract from high-risk biomechanics. Biomechanical assessment of ACLR subjects is a crucial part of the screening process, and should permit clinicians and researchers to identify the most prominent functional deficits a patient exhibits to address them most effectively. Reduction of KAM, ITR, and ATS through NMT may be an effective means to reduce risk of second injury. Understanding the underlying contributors to these 3 types of loading at the knee is equally crucial to their targeted reduction.[5] Because there are modifiable and nonmodifiable contributors to each type of high-risk loading, targeted reduction of modifiable contributors may be sufficient to mitigate overall risk of second ACL injury, even when nonmodifiable risk factors are present.

Risk Factors for Primary and Secondary ACL Injury

Risk factors for ACL injury are broadly categorized as being either modifiable or nonmodifiable.[24-29] Modifiable factors include biomechanical and neuromuscular control patterns, knee and hip muscle strength, and physical activity level,