Current Concepts for Injury Prevention in Athletes After Anterior Cruciate Ligament Reconstruction

CME

Timothy E. Hewett,*†‡§ PhD, FACSM, Stephanie L. Di Stasi,†‡ PhD, PT, and Gregory D. Myer,†§||¶# PhD, FACSM, CSCS*D
Investigation performed at The Sports Health and Performance Institute, The Ohio State University

Ligament reconstruction is the current standard of care for active patients with an anterior cruciate ligament (ACL) rupture. Although the majority of ACL reconstruction (ACLR) surgeries successfully restore the mechanical stability of the injured knee, postsurgical outcomes remain widely varied. Less than half of athletes who undergo ACLR return to sport within the first year after surgery, and it is estimated that approximately 1 in 4 to 1 in 5 young, active athletes who undergo ACLR will go on to a second knee injury. The outcomes after a second knee injury and surgery are significantly less favorable than outcomes after primary injuries. As advances in graft reconstruction and fixation techniques have improved to consistently restore passive joint stability to the preinjury level, successful return to sport after ACLR appears to be predicated on numerous postsurgical factors. Importantly, a secondary ACL injury is most strongly related to modifiable postsurgical risk factors. Biomechanical abnormalities and movement asymmetries, which are more prevalent in this cohort than previously hypothesized, can persist despite high levels of functional performance, and also represent biomechanical and neuromuscular control deficits and imbalances that are strongly associated with secondary injury incidence. Decreased neuromuscular control and high-risk movement biomechanics, which appear to be heavily influenced by abnormal trunk and lower extremity movement patterns, not only predict first knee injury risk but also reinjury risk. These seminal findings indicate that abnormal movement biomechanics and neuromuscular control profiles are likely both residual to, and exacerbated by, the initial injury. Evidence-based medicine (EBM) strategies should be used to develop effective, efficacious interventions targeted to these impairments to optimize the safe return to high-risk activity.

In this Current Concepts article, the authors present the latest evidence related to risk factors associated with ligament failure or a secondary (contralateral) injury in athletes who return to sport after ACLR. From these data, they propose an EBM paradigm shift in postoperative rehabilitation and return-to-sport training after ACLR that is focused on the resolution of neuromuscular deficits that commonly persist after surgical reconstruction and standard rehabilitation of athletes.

Keywords: anterior cruciate ligament; anterior cruciate ligament reconstruction; second injury; ACL risk factors; ACL injury prevention

Anterior cruciate ligament (ACL) injuries affect more than 120,000 athletes in the United States every year[28,49] and are 1 of the most common and devastating knee injuries sustained as a result of sports participation. Anterior cruciate ligament injuries often result in joint effusion, muscle weakness, altered movement, and reduced functional performance; few athletes are able to resume sports at the same level without surgery.[14] Anterior cruciate ligament reconstruction (ACLR) continues to be the standard of care for ACL-deficient athletes who aim to return to high-level sporting activities,[50] but outcomes are widely varied[10,20,31,35] and unexpectedly poorer than previously reported.[3,20,35] Less than half of athletes who undergo reconstruction are able to return to sport within the first year after surgery.[3] For those athletes who successfully return to activity, it is estimated that approximately 1 in 4 will go on to a second knee injury.[39,47,74,81] Expectedly, the outcomes after a second ACL injury and subsequent ligament reconstruction are notably less favorable.[84]

Deficits in neuromuscular control during dynamic movements are hypothesized to be the principal culprit in both primary[37,78,94,95] and secondary ACL injury risk.[74,86] Excessive out-of-plane knee loads, particularly increased external knee abduction moments, predict principal ACL injury incidence in young female athletes with high specificity and sensitivity.[37] Frontal-plane displacement of the trunk[94] as well as reduced core proprioception[95] are both predictive of a primary ACL injury in female athletes.[37] Five-year follow-up with this cohort indicated that 44% of ACL-injured patients went on to a secondary ACL injury. Injury risk in athletic populations appears not to be limited to frontal-plane mechanisms alone; athletes who went on to a primary ACL injury also demonstrated significant side-to-side differences in lower extremity biomechanics as well as reduced relative lower extremity flexor activation

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relative to uninjured controls during the drop vertical jump.[37] Similar mechanisms of injury risk have been identified in athletes medically cleared to return to sport after ACLR.[74] Findings from a population of young athletes who underwent ACLR implicated contralateral limb compensations, including abnormal frontal-plane mechanics, combined for a most predictive model of secondary ACL injury risk.[74] These seminal findings indicate that these abnormal and asymmetrical biomechanical and neuromuscular control profiles are likely both residual to, and exacerbated by, the initial injury. The most efficacious intervention strategies should target these modifiable impairments to optimize the safe return to high-risk activity.

Post-ACLR rehabilitation protocols have evolved greatly over the past few decades, shifting from conservative efforts of prolonged immobilization with delayed strengthening[75] to current paradigms that advocate immediate weightbearing, early motion and progressive strengthening, and neuromuscular training. Despite these efforts, muscle weakness,[19,46,70,81] impaired movement,[17,33,34,46,71,77] abnormal neuromuscular control,[74,88,90] and difficulty returning to sports[3,35] are common for many months after ACLR. Importantly, secondary ACL injury risk appears to be strongly related to multiplanar movement asymmetries of the lower extremities.[74] In this Current Concepts article, we present the latest evidence related to risk factors associated with graft failure or secondary (contralateral) injury and our recommendations for a new approach to return-to-sport training after ACLR that is focused on resolution of neuromuscular deficits that are known modifiable risk factors that persist following ACLR and rehabilitation of this highest risk population.

REDUCED FUNCTION AND NEUROMUSCULAR CONTROL AFTER ACLR

Muscle weakness, joint effusion, lack of normal joint range of motion, and impaired function are nearly ubiquitous in the days, weeks, and even months after ACLR. In combination, these impairments can significantly alter neuromuscular control of the reconstructed knee. Recovery of quadriceps function, in particular, has long been advocated as a means to optimize function in the athlete after ACLR.[15,22,40,41,46,82] The persistence of knee extensor weakness is common for several months after surgery[9,11,40,51,93] and is strongly related to the presence of abnormal movements during activities of daily living.[46,54,85] Athletes who underwent ACLR with at least a 20% deficit in quadriceps strength symmetry walk with truncated knee motion and a gait pattern characteristic of acutely injured athletes.[46] However, normal quadriceps strength does not ensure normal neuromuscular movement patterns, even during simple functional tasks. Six months after ACLR, athletes who demonstrate involved limb isometric quadriceps strength recovery (at least 90% of their uninvolved limb) continued to walk with reduced knee motion[34] and altered knee joint moments.[77] While enhancement of quadriceps strength is a necessary component for the optimization of knee function after an injury, restoration of normal neuromuscular control in athletes after ACLR, which can influence the safe return to sport, is clearly multifactorial in nature.

Reports of return-to-sport success after ACLR are highly varied and are likely attributable, in part, to the wide spectrum of criteria upon which "success" is defined. Medical clearance, self-reported return to sport, and achievement of minimum performance criteria to begin sport reintegration are all common barometers of return-to-sport success reported in the literature.[3,35,44,53] However, what is consistent between studies is the absence of ubiquitous functional success after ACLR.[3,10,35] Ardern and colleagues[3] reported that within 1 year after ACLR, two thirds of athletes had not attempted a full return to their previous level of activity. Of the athletes who had not returned to sport within the first postoperative year, less than 50% indicated an intention to return to sport.

Two-year functional outcomes data from the Multicenter Orthopaedic Outcomes Network (MOON) group indicate that less than 50% of athletes after ACLR return to sport.[20] A steady functional decline appears common in the years after ACLR.[2,84] Therefore, resumption of the previous level of activity and continued participation in the desired sport after ACLR are far from guaranteed from ACLR and standardized rehabilitation.

Asymmetrical movement patterns of athletes early after ACLR are well described[17,35,46,54] and understood to persist for several months, and even years, after surgery.[12,16,33,71,74,77] Primarily, postsurgical biomechanical studies on athletes who underwent ACLR have been performed using activities of daily living.[17,34,46,77,86] Truncated motions and reduced joint moments of the involved knee have been identified during level walking up to 2 years after ACLR.[33,34,77,86] More dynamic tasks that replicate sport-specific movements only accentuate the

*Address correspondence to Timothy E. Hewett, PhD, The Sports Health and Performance Institute, The Ohio State University, 2050 Kenny Road, Suite 3100, Columbus, OH 43221 (e-mail: tim.hewett@osumc.edu).

†The Sports Health and Performance Institute, The Ohio State University, Columbus, Ohio.

‡Departments of Physiology and Cell Biology, Orthopaedic Surgery, Family Medicine and Biomedical Engineering, The Ohio State University, Columbus, Ohio.

§The Sports Medicine Biodynamics Center and Human Performance Laboratory, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio.

‖Departments of Pediatrics and Orthopaedic Surgery, College of Medicine, University of Cincinnati, Ohio.

¶Departments of Athletic Training, Sports Orthopaedics, and Pediatric Science, Rocky Mountain University of Health Professions, Provo, Utah.

#Athletic Training Division, School of Allied Medical Professions, The Ohio State University, Columbus, Ohio.

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movement abnormalities of these athletes after ACLR.[69] The drop vertical jump landing task has exposed significant asymmetries in multidimensional kinematics at the hip and knee as well as force generation and attenuation in athletes up to 4 years after ACLR.[12,16,52,71,74]

Abnormal movement patterns after an ACL rupture are not isolated to the injured knee alone. There is mounting evidence of a bilateral neuromuscular response to an ACL injury that persists and may even be exacerbated after reconstruction.[23,33,87] Voluntary activation deficits have been noted in both limbs after an ACL injury, despite improvements after surgery.[87] In a small group of active athletes who underwent ACLR, changes in knee kinematics and kinetics were noted in both limbs 3 months after surgery.[23] Specifically, peak knee angles, moments, and joint powers were higher in the uninvolved limb of athletes after ACLR when compared with controls and to their own uninjured limb. Interestingly, these behaviors are not unlike those in athletes with acute ACL deficiency.[6,17,78,79,86]

Neuromuscular adaptations of the hip on the uninvolved side also appear characteristic of athletes who underwent ACLR.[74,77] A longitudinal gait analysis of 26 noncopers up to 2 years after ACLR revealed contralateral hip adaptations that manifested early after the injury and persisted 6 months after surgery.[77] These athletes demonstrated hip power generation in the involved hip early in weight acceptance, while the uninvolved hip absorbed power.[77] Compensatory strategies of the uninvolved hip were the primary predictor of risk in athletes who went on to a secondary ACL injury within 1 year of returning to sports activity.[74] As 1 of 4 predictive factors in a highly specific and sensitive model for secondary ACL injury risk, the transverse-plane uninvolved hip net moment impulse early during landing independently predicted the risk of a secondary injury with 77% sensitivity and 81% specificity. These data highlight 2 major findings: (1) ACLR alone does not fully abate the neuromuscular deficits and asymmetries incurred as a result of injury, and (2) assessment and treatment of bilateral limb compensations during rehabilitation appear necessary to obtain a comprehensive clinical picture of postoperative movement deficiencies.

RISK FACTORS FOR SECONDARY ACL INJURY

Much like primary ACL injuries, the majority of secondary ACL injuries are caused by noncontact mechanisms,[92] underscoring altered intrinsic neuromuscular control as an important factor in injury risk. The risk of a secondary ACL rupture is, at a minimum, several times greater than that of primary ACL injury risk.[73] As expected, higher levels of postreconstruction activity are associated with a higher incidence of a secondary ACL injury.[81] Reports of the incidence of graft rupture and contralateral limb injury range from 6% to 32%,[4,39,46,74,80,81] and risk level may be sex specific. In a longitudinal study of 180 athletes over a 15-year period, ACL graft rupture was reported to be more likely in men.[47] A prospective cohort study of over 1400 athletes after ACLR found that while graft rupture rates did not differ between sexes, the contralateral injury rate was higher in female than in male athletes.[81] Similarly, in a group of 63 athletes cleared to return to sport after ACLR, 14 of the 42 (33%) female athletes went on to a contralateral ACL rupture within 1 year. Female athletes represented 88% of the documented contralateral limb ACL injuries.[73]

Recent reports have indicated that neuromuscular impairments are also predictive of a secondary ACL injury in athletic youth.[74] Fifty-six athletes after ACLR who were medically cleared for sports participation underwent 3-dimensional biomechanical analyses and postural stability testing and then were prospectively followed for 1 year to document the movement characteristics predictive of secondary ACL injuries.[74] Thirteen of the 56 young athletes sustained a second ACL injury within the year. Regression analyses indicated 4 predictive factors for secondary injury risk with excellent specificity (88%) and sensitivity (92%): uninvolved hip rotation net moment impulse during landing, frontal-plane knee motion during landing, sagittal-plane knee moment asymmetries at initial contact, and deficits in postural stability on the reconstructed limb. The highly predictive model of second injury risk underscores the importance of targeted return-to-sport rehabilitation, as all predictors were modifiable in nature.

Other factors, like age and sex, also appear related to secondary ACL injury risk. Younger athletes have demonstrated the highest reinjury rate[81] and may have an increased risk of a contralateral injury[39,47] when compared with older athletes. Female gender was associated with a lower postsurgical activity level[20,84] and was associated with a decreased likelihood of returning to sport within 1 year after ACLR[3] when compared with their male counterparts. While these nonmodifiable factors may significantly contribute to secondary injury risk and incidence, further research must investigate their influence on identified modifiable factors on the risk profile for athletes who underwent ACLR.

Impairments after ACLR can be profound; however, outcomes after revision ACLR in athletes are reportedly worse. Poor outcomes after ACL revision are documented by several groups on hundreds of athletes and range from poor functional abilities to an increased prevalence of degenerative changes.[5,7,20,30,84,91] However, little data document the return-to-sport success in this population. Revision procedures are associated with a lower activity level[20] and lower self-reported knee-specific outcomes scores.[84] Similar to primary ACLR outcomes, return-to-sport estimates range from 60% to 93% within 4 years of revision.[5,30] Second revision rates are as high as 25% within 6 years of primary ACL revision.[5] While an ACL revision may mitigate significant physical function deficits after graft failure, its effect on improving high-level function and mental health factors may be negligible.[91] In summary, revision ACLR may be viewed as a salvage procedure,[5] and robust and effective strategies to prevent the need for such surgical intervention must be employed.

METHODS TO IDENTIFY POST-ACLR NEUROMUSCULAR IMPAIRMENTS

The importance of early and accurate identification of postsurgical impairments in athletes nearing medical discharge

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has been extensively detailed. Performance on a battery of clinically administered tests has been advocated by many to capture and address residual impairments in strength and function after ACLR.[25,27,48,53,85] The influence of quadriceps strength on function after ACLR is well established.[15,22,46] Therefore, testing quadriceps strength symmetry is an important component of the criteria for rehabilitation progression to sports-specific tasks and eventually for discharge to unrestricted sports activity. While deficits in hamstring strength were unrelated to functional performance tasks in athletes 6 months after ACLR,[41] the ratio of hamstring-to-quadriceps torque production appears to be a key variable in the primary ACL injury risk model.[63] Strength symmetry of at least 85% is now advocated for athletes beginning reintegration into cutting, pivoting, and jumping sports.[25,35,85]

Dynamic single-limb task tests can capture important deficits in function of the reconstructed knee that may be otherwise obscured by double-limb performance tests.[69] Performance on the single-limb hop test for distance on ACL-deficient patients predicted their self-reported function 1 year after ACLR with 71% sensitivity and specificity.[32] A combination of agility and plyometric testing was used to differentiate between the physical performance characteristics of athletes who underwent ACLR and controls.[69] Side-to-side asymmetries in the single-limb hop tests, not the double-limb bilateral tasks, were required to discern between groups. In light of new evidence highlighting the implications of asymmetrical movement patterns after ACLR, reducing limb asymmetries before returning to sport appears imperative for maximized performance and reduction of secondary ACL injury risk.[74]

LATE-PHASE POSTOPERATIVE REHABILITATION: EVIDENCE FOR SPORTS PERFORMANCE SYMMETRY TRAINING

Current postoperative rehabilitation guidelines for athletes after ACLR advocate criterion-based progression through knee range of motion, strengthening, and sport-specific activities.[1,67,68,89] Achievement of symmetrical joint mobility, strength, and functional performance are common criteria for medical discharge to return to sport.[1,35,44,68] However, there is a lack of objective criteria by which adequate dynamic neuromuscular control is defined for athletes who will return to high-velocity, high-load maneuvers.[67] Neuromuscular and movement asymmetries are known to predict primary ACL injury risk[37,58,83] but have only recently been identified as risk factors for a second ACL injury,[74] thus highlighting the potential positive effects of a targeted neuromuscular training program that emphasizes movement symmetry before the return to sport.

Our proposed late postoperative rehabilitation and sports performance symmetry training is based on the findings of the prospective cohort study performed in our laboratory that examined neuromuscular and biomechanical factors related to second injury risk.[74] Four measures of neuromuscular asymmetry, representing all 3 planes of motion, were found to accurately predict second ACL injury

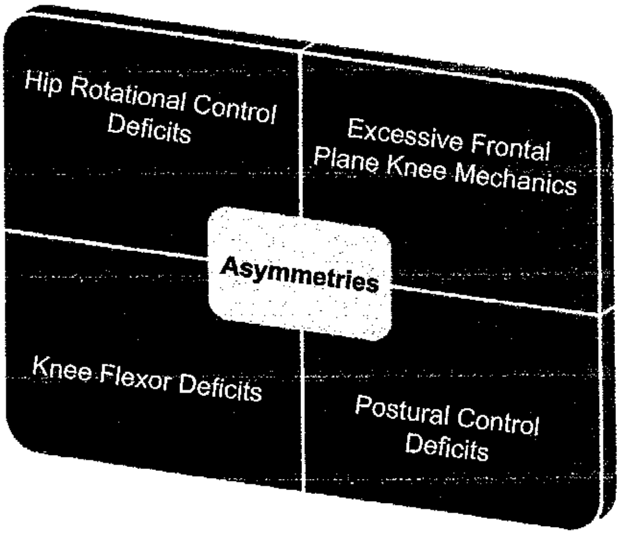

Figure 1. Schematic representation of the 4 measures of neuromuscular asymmetry highly predictive of second injury risk in athletes who underwent anterior cruciate ligament reconstruction.

risk[74] and are represented graphically in Figure 1. Over a dozen therapeutic exercises have been proposed as a novel method for primary ACL injury prevention, all based on data from several epidemiological and interventional studies evaluating primary injury risk.** Based on the current state of the available evidence, we surmise that these exercises may adequately remediate the neuromuscular asymmetries implicated in secondary ACL injury risk.[67,74]

Persistent muscle weakness of the ACL-injured limb is known to influence postsurgical function.[15,21,22,41,46] There appears to be a preferential loss of quadriceps strength,[43] but not hamstring strength,[42] after an ACL injury. Expectedly, recovery of quadriceps strength is important in restoring normal knee function,[46] as persistent weakness of the quadriceps may adversely affect sport-specific function because of their primary role as force attenuators and generators about the knee. While deficits in hamstring strength are characteristic of athletes who go on to their first ACL injury,[58,83] its influence on function after ACLR is not well defined.[41]

The coordinated coactivation of the hamstrings and quadriceps may play a role in mitigating primary injury risk by way of reducing ligament strain[29] and promoting normal landing mechanics.[26] Balanced agonist and antagonist coactivation may also protect the reconstructed knee against second ACL injury risk via similar protective mechanisms. Deficits in the neuromuscular coordination of the hamstrings and quadriceps on the reconstructed limb may manifest as excessive landing contact noise during both double- and single-legged landing tasks.[56] Impairments in hamstrings force steadiness, or the ability of the hamstring muscles to produce force without variation, were observed on isokinetic testing in athletes after ACLR with a semitendinosus-gracilis autograft. Decreased hamstring

**References 36, 38, 55, 57, 59-61, 64, 65, 72.

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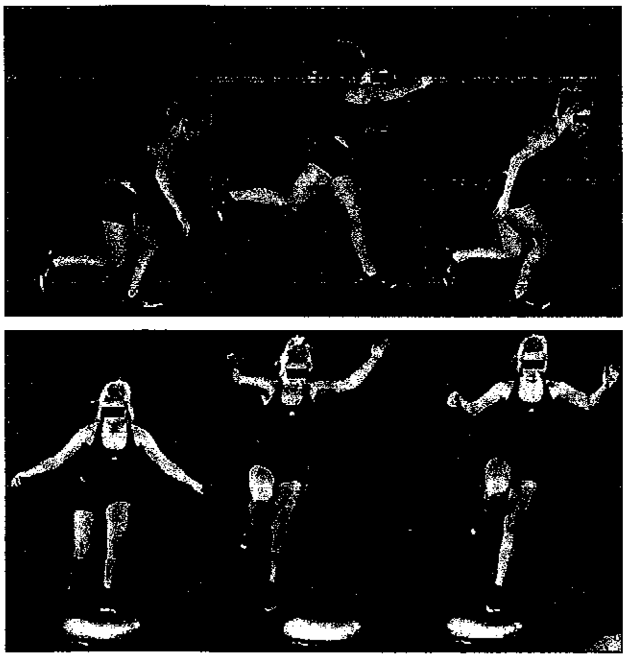

Figure 2. Examples of single-leg anterior (A) and lateral (B) progression activities. These tasks can aid the sports medicine clinician both in identifying and treating clinically important, bilateral neuromuscular dysfunction after anterior cruciate ligament reconstruction.

force steadiness was associated with poorer single-legged hop test performance an average of 14 months after surgery.[8] Therefore, progressive single-limb landing activities, like anterior and lateral jumping progressions (Figure 2), may not only accentuate post-ACLR limb deficits[69] but can also provide an excellent training tool to help athletes avoid quadriceps-dominant landing techniques[56] and achieve the desired level of sports performance symmetry.

Importantly, neuromuscular and biomechanical abnormalities and asymmetries can occur in spite of adequate muscle strength, muscle symmetry,[36,77] and sports activity status[71,74]; these may be evident for years after ACLR.[12,35] Based on current data detailing the increased rate of contralateral injuries in female athletes,[73,81] the prevalence and persistence of asymmetrical movement strategies in the months and years after ACLR, and the accuracy with which limb asymmetries predict second injury risk,[74] restoration of sports performance symmetry may aid significantly in the reduction of second ACL injury risk.[67,68]

Neuromuscular training, in various forms, has been effectively used in the prevention of ACL injuries,[36,38,60] enhancing function[22,24,53] and movement behaviors[13,18] early after the injury, and improving function[76] and movement behaviors after ACLR.[35] The tuck jump (Figure 3) is a dynamic, repeated double-limb jumping task that requires excellent trunk and lower extremity neuromuscular control to perform properly. It not only highlights sports performance asymmetry in all 3 planes of motion[62] but may also be effective in the treatment of movement deficits before the return to sport.[61,67] Force attenuation under high load

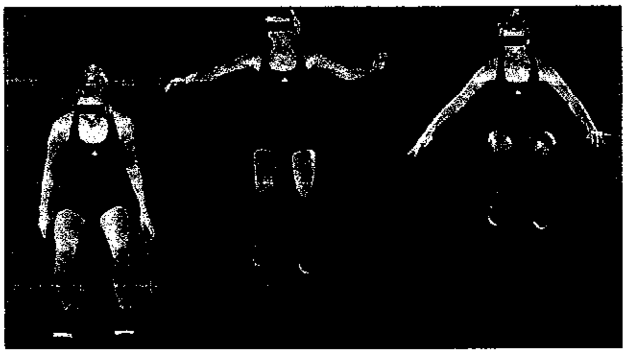

Figure 3. Proper tuck jump technique. The athlete begins in deep hip and knee flexion and swings the arms backward in preparation for the jump. The goal is to minimize frontal-plane motion of the trunk and lower extremities while achieving a thigh position that is parallel to the floor at the height of the jump. The sports medicine clinician should view the athlete during repeated jumps in both the sagittal and frontal planes to identify takeoff and landing asymmetries.

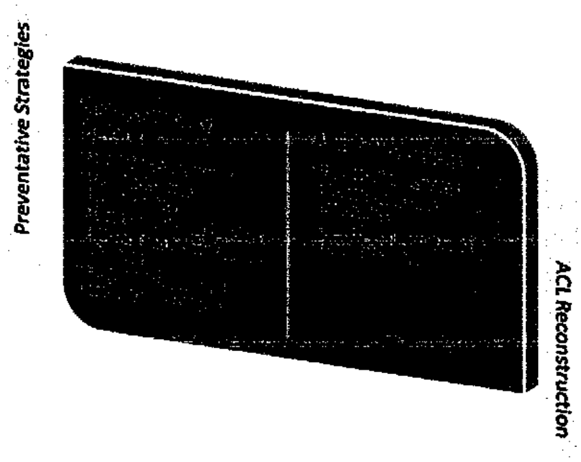

Figure 4. Schematic representation of how anterior cruciate ligament reconstruction can drive postsurgical symmetries and neuromuscular deficits. These impairments are, in turn, minimized with sports symmetry training and preventative multiplane dynamic movement tasks.

conditions is commonly impaired after ACLR[12,71,74] and has meaningful implications for second injury risk.[74] Postoperative and return-to-sport rehabilitation programs that challenge dynamic neuromuscular control, facilitate technique perfection, and enhance limb symmetry may also successfully reduce the movement impairments associated with second injury risk; the effectiveness of these training programs has not yet been evaluated.

While high frontal-plane loading at the knee alone is predictive of a primary ACL injury,[37] it appears that a combination of multiplane neuromuscular patterns is predictive of secondary injury risk.[74] This risk profile highlights the influence of post-ACLR adaptations in both limbs on secondary injury risk and underscores

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evidence indicating the importance of sports performance symmetry before returning to unrestricted activity. Our proposed treatment paradigm (Figure 4) focuses on restoration of symmetrical function during the critically important period when common rehabilitation programs end but many neuromuscular deficits often persist.

RETURN TO SPORT AFTER ACLR: OBJECTIVE ASSESSMENT VERSUS TIME AFTER SURGERY

Historically, return-to-sport clearance was based on time; sports medicine professionals often allowed the return to sport 6 months after surgery.[4,44] In light of emerging evidence that indicates athletes are at increased risk for a second injury within the first 7 months after ACLR,[45] we advocate serial function and strength testing throughout the late rehabilitation phase to identify the neuromuscular strategies that may further increase this risk.[57,74]

Current investigations indicated that young athletes assessed after medical release and return to sport demonstrate measurable functional deficits after ACLR that are independent of the time from surgery.[66] These data further support the current approaches to target functional deficits related to a second injury before reintegration back to sport. In young female athletes, decreased hamstring strength was associated with an increased risk of an ACL injury, while young female athletes with similar hamstring-to-quadriceps ratios to that of male athletes had a reduced risk to go onto an ACL injury.[58] The cumulative data indicate that reduced hamstring strength and recruitment is related to initial and likely secondary injury risk, which supports the use of isokinetic testing in return-to-sport decision making and guidance of interventions to reduce the risk of a second injury.

Prior studies emphasize the need to utilize objective tools that are sensitive to limb-to-limb deficits and to develop rehabilitation protocols that are targeted to eliminate limb asymmetries.[66,67,69,71,74] Use of functional assessments, as opposed to temporally guided or graft-specific decision making, can support a safer return to sport for competitive athletes.[68]

CONCLUSION

To optimize functional and clinical outcomes after ACLR and to prevent a second knee injury, an EBM approach is proposed in this review that directly addresses known, modifiable neuromuscular and biomechanical risk factors for increased risk of second ACL tears.[84] Optimal return to sport after ACLR appears to be predicated on numerous postsurgical factors.[74,92] Second ACL injury risk is most strongly related to modifiable postsurgical factors[74] and is specific to the magnitude of multiplanar limb asymmetries. Inadequate neuromuscular control and biomechanical asymmetries of the trunk and lower extremities predict first knee injury risk.[37,94] Addressing these impairments in athletes after ACLR using targeted rehabilitation may significantly reduce the second injury incidence and subsequent functional disability. The proposed EBM approach will target these highly impactful impairments by way of focused sports symmetry training to optimize the safe return to high-risk activity and increase both the efficiency and efficacy of intervention strategies.

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