Neuromuscular Training to Target Deficits Associated With Second Anterior Cruciate Ligament Injury

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Anterior cruciate ligament (ACL) rupture is one of the most physically, financially, and emotionally devastating sport-related knee injuries.[24,34,49,141] Return to activity is highly desired and expected for many athletes following ACL reconstruction (ACLR) and postsurgical rehabilitation, but reported success rates range from 43% to 93%.[4,17,19,76,88,138] Unfortunately, for those who do resume their previous level of activity, the risk of a second ACL injury may range from 6% to as high as 30% [65,79,126,133,136,160] and can be associated with several factors, including surgical technique,[16,65,79,84] age,[65,84,136,150] activity level,[16,133] sex,[125,136] time since surgery,[75,133,150] and biomechanical adaptations during dynamic tasks.[126] Although several of these factors are nonmodifiable, the biomechanical components of second–ACL injury risk may be effectively addressed with targeted neuromuscular training prior to unrestricted sports participation.

Aberrant neuromuscular and biomechanical patterns are commonly seen up to 2 years after ACLR[54,55,108,123,126,130] and may help explain the high rate of second ACL injury. Deficits

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in the neuromuscular control of both lower extremities following ACLR have been directly implicated in the risk for second ACL injury[126] and may not only be a result of the initial knee injury and subsequent surgery,[23,131,132] but may also characterize the athlete's preinjury movement patterns.[61,161,162] Therefore, identification and subsequent targeted treatment of aberrant post-ACLR movement patterns are critical not only to maximize functional recovery but also to reduce the risk for a second ACL injury. Though neuromuscular training programs can effectively reduce primary–ACL injury prevalence by between 43.8% and 73.4%,[145] the efficacy of similar programs for reduction of second–ACL injury risk has not been examined. To date, there is no validated rehabilitation program that addresses not only the residual neuromuscular impairments following ACL injury and reconstruction, but also the known risk factors for second ACL injury. The purpose of this paper is to build on the theoretical framework for second–ACL injury prevention set forth previously[58] and to (1) summarize the neuromuscular deficits that precede primary injury and persist following injury, ACLR, and return to activity; (2) provide the evidence for risk factors related to second ACL injury and their link to previous neuromuscular impairments; (3) detail a method to assess neuromuscular impairments following ACLR; and (4) propose a method of intervention to address common neuromuscular deficits in this population.

ACL INJURY RISK FACTORS

Neuromuscular Deficits Prior to Primary ACL Injury

PRIMARY-INJURY RISK FACTORS PROvide an important window into the underlying neuromuscular deficits that may persist in athletes following injury and ACLR. Active stabilization of the knee joint during vigorous sporting tasks depends largely on the coordinated coactivation and force generation of the adjacent musculature,[82,86,143] and variance in these dynamic joint-loading strategies between sexes is theorized to explain the differences in their relative risk for ACL rupture.[50,51,60,63,96,121] Female athletes, who are several times more likely to sustain a primary ACL tear compared to their equally active male counterparts,[2,5] have long been the cohort of scientific interest to evaluate the mechanisms of ACL injury risk. In healthy adult volunteers, women demonstrated reduced dynamic knee joint stiffness during both non–weight-bearing[51] and weight-bearing tasks.[50,121] Specifically, reduced stiffness values in women were identified despite higher levels of lower extremity muscle activity when compared to men,[51,121] highlighting the likely role of sex-specific differences in neuromuscular strategies in primary–ACL injury risk.

Deficits in thigh muscle strength may also be a key variable in the primary–ACL injury risk model of young female athletes.[96,100,101] In a prospective, matched-control study of 132 healthy athletes, only the female athletes who went on to sustain an ACL injury demonstrated lower hamstrings strength when compared to uninjured male controls.[96] A low hamstrings-to-quadriceps strength ratio is 1 of 5 clinically based measures that combine to accurately predict high knee abduction moment (KAM) status in healthy adolescent female athletes.[101] Importantly, a high KAM during 3-D analysis of a drop-vertical jump task was the most accurate predictor of future ACL injury in a cohort of 205 adolescent female athletes.[61] The clinical prediction model for high KAM, which includes a low hamstrings-

quadriceps strength ratio,[101] has since been validated against 3-D motion analysis techniques.[100]

Sex-specific differences in kinematics and kinetics during sport-related tasks provide additional insight into the mechanisms of risk for primary ACL injury.[21,46,61,67,70,92,161] Uninjured females demonstrate altered peak hip and knee flexion angles,[21,61,70] increased frontal plane motion of the hip and knee,[46,61,70] and larger ground reaction forces[61,70] during athletic tasks compared to their male counterparts. Differences in temporal components of dynamic movement between high-level male and female athletes may partially explain the relative sex disparity in primary–injury risk.[67] Peak hip adduction, dynamic knee valgus, and ankle eversion occurred earlier in women than in men during a drop-jump landing task.[67] In the same cohort of 10 male and female Division I college athletes, the females demonstrated knee valgus angular velocities that were nearly twice as high as those of the males.[67]

To date, only 1 prospective study has measured and identified biomechanical variables predictive of primary–ACL injury status.[61] In this study,[61] 205 uninjured adolescent female soccer, basketball, and volleyball players underwent preseason biomechanical assessment of a drop-vertical jump task to determine potential factors predictive of future ACL rupture. At the termination of the team's injury-surveillance period more than 1 year later, 9 athletes had sustained an ACL injury. Peak knee abduction angles and external joint moments, as well as initial contact values, significantly predicted ACL injury status. Independently, the magnitude of the external KAM predicted ACL injury status with 73% specificity and 78% sensitivity.[61] In the same prospective sample, smaller peak knee flexion angles and larger vertical ground reaction forces and external hip flexion moments were also identified in those who went on to sustain an ACL injury, further highlighting the multidimensional risk profile for primary ACL injury.[61]

Risk for primary ACL injury is not solely related to neuromuscular deficits of the lower extremities,[161,162] as impairments in the proprioception and neuromuscular control of the trunk may also increase primary–ACL injury risk, particularly in female athletes.[161] A cohort of 277 healthy college athletes were prospectively examined to determine whether excessive trunk motion, errors in repositioning accuracy, and history of injury could predict knee injury status over a 3-year period.[161,162] Sex-specific knee injury prediction models were identified both by assessment of the neuromuscular response of the trunk during a seated active trunk-repositioning task and a kneeling sudden force-release task.[161] Error in the active repositioning of the trunk predicted knee ligament or meniscal injury status with 86% sensitivity and 61% specificity only in female athletes.[161,162] Deficits in neuromuscular control, as quantified by lateral, extension, and flexion displacements of the trunk during the kneeling sudden force-release task, provided the most accurate prediction model for ACL injury in female athletes, whereas history of low back pain was the strongest predictor of future knee ligament injury in male athletes.[161] So, while the magnitude of external frontal plane loading at the knee is a critical modulator of peak ACL strain at the time of failure,[77,159] there is strong evidence that poor neuromuscular control of trunk position may also increase the risk for ACL injury.[61,64,135,162]

Neuromuscular Deficits Following ACL Injury

Abnormal neuromuscular patterns and significant physical impairments characterize the acute postinjury phase. Joint effusion, limited range of motion, and reduced quadriceps strength are all common impairments following ACL injury. Episodes of giving way (knee joint subluxations) are not uncommon in many of these acutely injured athletes[36,132] and may be related to reduced dynamic knee joint control,[131,132] decreased thigh muscle force,[48] and abnormal joint loading.[47] Though some athletes are capable of return to sport in the short term following specific neuromuscular retraining,[44,45] the majority of athletes continue to experience recurrent instability and significant functional limitations,[36,132] and are often advised to undergo ligament reconstruction.[87] Left untreated prior to surgery, these acute postinjury impairments can have significant negative implications for postoperative outcomes.[37,57,80]

Rehabilitation programs administered early following ACL injury have the potential for significant positive effects on immediate[39,45] and midterm nonsurgical outcomes in this population.[38,90] In a study by Eitzen et al,[38] performance on functional tests following 10 physical therapy sessions, in addition to age, activity level, and episodes of giving way, explained a significant proportion of the variance in the prediction of those athletes who later underwent ACLR. In a different study,[90] it was demonstrated that with prolonged nonsurgical rehabilitation (approximately 6 months), athletes initially classified as noncopers on the basis of poor function and knee instability during a screening examination were just as likely to return to their previous level of sports activity as those athletes who had initially been classified as potential copers. While it is apparent that the neuromuscular systems of athletes following ACL injury are adaptable to rehabilitation, the optimal rehabilitation program to restore high-level function in these athletes without surgery is unknown.

Common Neuromuscular Deficits After ACLR

Muscle Weakness—Muscle weakness,[33,78,120,134] impaired dynamic joint motion,[30,31,54,55,78,130] abnormal neuromuscular control,[116,126,148,154] and difficulty returning to sports[3,4] are all common deficiencies in the months and years following ACLR, and often persist in spite of formal rehabilitation.[31,55,56,130] Strength symmetry with the uninjured contralateral limb, in particular, is proposed as one of several important indicators of return-to-sport readiness and, eventually, for discharge to unrestricted sports activity following ACLR.[56,107,146,151] Quadriceps strength is strongly related to measurements of knee function and neuromuscular control in athletes following ACL injury and those who have undergone ACLR.[25,37,68,69,78,91,134,137] While hamstrings strength alone may not show a significant effect on knee function following ACL injury and reconstruction,[18,69] hamstrings activation may be an important component in neuromuscular control of the reconstructed knee.[18] Deficits in the hamstrings-quadriceps torque production ratio also appear to be a key variable in the primary–ACL injury risk model,[96,100] but the relationship to second–ACL injury risk has not yet been assessed. Prior to the resumption of high-level, high-risk sports activity, many groups advise that symmetry in quadriceps and hamstrings strength, compared to the contralateral limb, be at least 85%.[1,56,107,146] The relationships between muscle weakness, neuromuscular control deficits, and risk for reinjury are still

under investigation, but an understanding of the interplay may be critical to the development of effective, patient-specific rehabilitation programs and reduction of second-injury risk.

Impaired Neuromuscular Control—Recovery of normal strength symmetry after ACLR unfortunately does not ubiquitously translate to appropriate neuromuscular control.[31,55] This concept is also evident in healthy athletic females who demonstrate high-risk biomechanical features despite adequate leg-to-leg strength symmetry.[61] Good neuromuscular control is achieved by the intricate balance of adequate strength and mobility, kinesthetic awareness, efficient joint mechanics, and a sufficiently adaptive motor control system. Even after athletes have undergone ACLR and been cleared to return to activity, deficits in neuromuscular control are evident.[31,108,123,126] In tasks as basic as walking, athletes who fail functional return-to-sport criteria demonstrate more kinematic and kinetic asymmetries of the knee and hip compared with those who pass these criteria.[31] During sport-related jumping tasks, alterations in force-attenuation and force-generation strategies, as well as multidimensional kinematic and kinetic asymmetries of the hips and knees, have been identified up to 4 years after ACLR.[20,26,89,123,126]

Importantly, deficits in the neuromuscular control of both lower extremities following ACLR are highly predictive of the risk for second ACL injury.[126] Paterno and colleagues[126] prospectively examined 56 athletes following ACLR who were medically cleared for sports participation to document the movement characteristics predictive of second ACL injuries. One year following baseline testing, 13 athletes had sustained a second ACL injury, from which 4 predictive biomechanical factors for second-injury risk were identified: (1) a net internal rotator moment of the uninvolved hip upon landing, (2) increased frontal plane knee motion during landing, (3) sagittal plane knee moment asymmetries at initial contact, and (4) deficits in postural stability.[126] This model was shown to predict injury risk with excellent specificity (88%) and sensitivity (92%),[126] and was the first study of its kind to link deficient movement patterns to second–ACL injury risk in athletic individuals.

Deficits in High-Level, Sports-Related Function—Recent prospective, longitudinal data sets highlight the varied return-to-sport success rate of highly active individuals.[3,88,138] Within the first year following surgery, two thirds of athletes post-ACLR who had been cleared for participation had not returned to their competitive sport.[3] A recent systematic review found that only 44% of athletes successfully returned to sport after an average of 41.5 months following ACLR.[4] The low return-to-activity rates may be explained, in part, by the persistence of physical impairments even after formal rehabilitation. When significant quadriceps weakness persists, athletes who have undergone ACLR demonstrate poorer functional-hop performance scores than their stronger counterparts.[134] Less than 50% of high school–level and collegiate-level athletes indicated that they were able to perform at their pre–ACL injury level.[88] Therefore, focused neuromuscular re-education and sports-related training should represent a significant component of postsurgical rehabilitation programs.[1,58,107]

Linking Presurgical and Postsurgical Neuromuscular Impairments With Second–ACL Injury Risk—Several modifiable and nonmodifiable factors have been reported to increase an athlete's risk for a second ACL injury. Nonmodifiable factors,

including surgical technique, sex, and age of the patient, can significantly impact second-injury risk.[15,65,83,125,136,149] Specifically, graft inclination angles less than 17°[65] and use of allografts (odds ratio = 5.56)[16] significantly increase an individual's risk for graft rupture, whereas the use of patellar tendon grafts may significantly increase the risk for contralateral ACL rupture (odds ratio = 2.6).[79] Graft size also appears to influence second-injury risk; within 4 years of ACLR, the odds ratio for graft rupture in athletic individuals with a smaller graft size was 2.2, and revision was performed significantly more often in those athletes with a graft diameter of 7 mm or less.[84] Age[65,84,136,150] and sex[125,136] also play a significant role in second-injury risk. Young, active female athletes, in particular, have a significantly increased risk for a second[17] and contralateral injury when compared to young, athletic males.[125,136] The incidence rate of a second ACL injury in young female athletes is 16 times greater when compared to primary–ACL injury incidence in the same population, and 4 times greater than second-injury rates in young male athletes.[125] Interestingly, after ACLR, the risk for contralateral ACL rupture may be at least twice that of graft rupture, regardless of sex, and may be indicative of residual and magnified asymmetries in neuromuscular control.[125,160]

One of the most significant modifiable predictors of a second ACL injury is the athlete's activity level.[16,133] Return to higher levels of activity that require cutting, pivoting, and jumping may substantially increase the risk of a second ACL injury between 5-fold[16] and 10-fold.[133] Though time since surgery may not dictate functional performance following ACLR,[105] an earlier time since surgery appears to be significantly related to higher second-injury risk.[75,133,150] As the first several months following ACLR are also characterized by compensatory movement patterns and asymmetries,[31,54,55,112,130] attention must be given to the role of modifiable neuromuscular deficits in second–ACL injury risk.[126] In a study by Paterno et al,[126] multiplanar neuromuscular impairments found in both the ACL-reconstructed and uninjured limbs combined to predict second ACL rupture with 92% sensitivity and 88% specificity. Interestingly, knee abduction motion appears to be a key factor in both primary–[61] and second–ACL injury[126] risk models. Although the efficacy of neuromuscular training in reducing second–ACL injury risk has not been empirically tested, reduction of primary-injury incidence using similar methods has proven effective.[110,145]

Targeted neuromuscular training and re-education may have the greatest effect on the modification of the neuromuscular components of second-injury risk. Neuromuscular dysfunction characterizes the preinjury, postinjury, and postsurgical status of athletes with a history of ACL injury (**FIGURE**). Epidemiological data highlight the biomechanical factors related to second–ACL injury risk[126] and the overlapping profile with primary-injury risk,[61] suggesting that there may be negative, additive effects of these neuromuscular deficits on second-injury risk. In addition, there is growing evidence for altered contralateral-limb loading post-ACLR during sports-related activities,[20,26,123,126] which may explain, in part, the increased rate of contralateral-limb ACL rupture in young, active individuals.[17,79,125,160] The influence of trunk position and control on second–ACL injury incidence has not been empirically tested but may also be considered a plausible risk factor, as increased knee abduction loading appears to be directly influenced by trunk positioning during athletic maneuvers.[29,66] While excessive knee abduction loading specifically was not identified as a

predictive component of the second–ACL injury risk model, increased knee abduction motion was a significant predictive variable[126] and is an important component in the calculation of external knee abduction loads. Taken together, these data indicate that neuromuscular deficits of the lower extremities and trunk leading up to and following ACL rupture may be critical modifiable factors of second-injury risk. Further, the use of symmetry measures alone to capture important bilateral physical performance deficiencies compared to matched, uninjured athletes may be inadequate.

PROPOSED ASSESSMENT OF IMPAIRMENTS POST-ACLR

Current evidence-based standards for postoperative rehabilitation include exercises and neuromuscular training to restore full and pain-free range of motion, maximize strength, and achieve preinjury function.[1,107] Targeted rehabilitation programs are likely most effective when tailored to patient-specific neuromuscular deficits, but methods of assessing these deficits can vary widely.[8] The proposed late-phase rehabilitation program described herein incorporates progressively more challenging tasks; therefore, objective criteria should be used to enter patients safely into this program. To perform the proposed clinical testing battery, it is advised that all patients demonstrate full and pain-free knee range of motion equal to that of the contralateral limb,[139] minimal joint effusion,[1] at least 70% strength symmetry,[1] and the ability to hop in place without pain or apprehension.

Time since surgery alone does not adequately identify readiness for return to sport,[105] nor should it determine the course of progression through each phase of rehabilitation.[1,107] Use of a battery of clinical tests and measures, including objective measures of strength, dynamic knee function, and self-reported measures of knee function, is advocated at multiple points throughout the late phase of rehabilitation to document progress toward functional goals and to determine return-to-sport readiness.[7,8,58,81,105,146,151] Quadriceps strength deficits in athletes following ACLR are related to restricted knee motion during gait,[78] lower limb-symmetry values on single-leg hop tests,[134] and poorer self-reported function.[134] Midterm knee function as measured by single-leg hop tests 6 months after surgery demonstrated excellent accuracy for prediction of athletes who will have normal knee function 1 year following ACLR.[80] In a longitudinal outcomes study of 79 athletes following ACLR, those who reported knee function within normal ranges on the International Knee Documentation Committee 2000 Subjective Knee Evaluation Form 1 year after surgery had significantly higher limb-symmetry values on the crossover test and timed 6-meter hop test when tested 6 months after surgery.[80] Thus, serial clinical testing can be an excellent source of information for treating clinicians as they progress their athletes through the phases of rehabilitation and back into their sports activity.

Identification and subsequent treatment of aberrant post-ACLR movement patterns may be critical to maximizing functional recovery following surgery and reducing risk for a second ACL injury.[58] While poor control of aberrant motion is a predictor of both primary–[61,161,162] and second–ACL injury risk,[126] it is not assessed within the scope of the previously described functional tests. Thigh muscle strength assessment and single-hop testing identify quantitative performance asymmetries but do not measure important deficits in the quality of movement. Therefore, the use of easily administered qualitative tests that

can capture pertinent deficits in neuromuscular control is warranted. The drop-vertical jump can provide valuable information on the frontal and sagittal plane motion of both limbs, and has been used as part of a clinical nomogram to predict external knee abduction loads.[101] The tuck jump assessment is another dynamic jumping test that is responsive to improvements following neuromuscular training, and is also linked to important reductions in frontal plane knee motion.[109] Among the 10 criteria for a successful tuck jump assessment, points are deducted from the total score for movement asymmetry; increased frontal plane motion of the trunk, hips, and knees; and a decline in technique.[94,99] Both tests incorporate aspects of symmetry and quality of movement in the assessment, thus capturing neuromuscular impairments that may be present in both limbs, regardless of whether symmetry is present. These tests also require minimal time, limited space, and standard 2-dimensional video-capture technology. In combination with strength assessments, hop testing, and self-reported outcome measures, the addition of clinical tests to assess quality of movement may allow clinicians to identify neuromuscular impairments of the trunk and both limbs that reduce sport-related function and increase second–ACL injury risk (**TABLE 1**).

PROPOSED INTERVENTION TO PREVENT SECOND ACL INJURY

Persistent deficits in neuromuscular control postsurgery are a key component of increased second-injury risk following ACLR.[126] Applying the theories of motor learning,[43] previous findings from our laboratory,[98,102,103,109] and the work of others,[6,9,52,115,116] a late-phase, targeted neuromuscular rehabilitation program is presented that aims to address all modifiable components of the second–ACL injury risk profile, as well as common residual preinjury and postinjury movement deficits.[58,95,106] The use of programs that enhance control of 3-D body positions[9,52,98,102,103,109,113-116] is substantiated by literature that has evaluated ACL injury risk, mechanisms, and joint loading considering multiplanar factors.[61,110,145,152,161]

Programs that have been shown to successfully reduce primary-injury risk and incidence of ACL injuries have incorporated 3-D movement retraining of progressively greater speed and difficulty, while emphasizing proper jump-landing[59,71,74,85,119,127,145,152] and balancing techniques.[71,74,111,119,127,142] The exercises outlined in this manuscript were selected for 3 specific reasons: (1) they activate the muscles hypothesized to be deficient at the time of return to sport, (2) they utilize surfaces and movements that elicit muscle coactivation capable of modifying mechanics theorized to be related to injury risk, and (3) they elicit movements that may replicate conditions experienced during sport (**TABLE 2**). These exercises, in varying combinations, have been evaluated for their efficacy in reducing factors related to primary–ACL injury risk and have been summarized in detail previously.[95,124] Because leg-to-leg asymmetries greatly increase the risk of second ACL injury,[126] and asymmetries in athletes following ACLR appear to be the product of bilateral limb adaptations,[42,54,126,130] this rehabilitation protocol incorporates bilateral training to address neuromuscular deficits that may exist in both limbs. Neuromuscular re-education of the trunk is also emphasized, with the goal of optimal control and movement symmetry. For example, greater torso lean and trunk rotation toward the support leg are related to increasing external knee abduction loads[28]; thus, controlled activities that elicit trunk motion

toward the support leg may help athletes learn better control of these risky knee loads, which may not be completely avoidable during high-level sports activities.

To elicit the desired movement strategies with progressively more advanced tasks, this program has been divided into 4 phases, each with a specific goal (**TABLE 3**). Progression to the next phase is dependent on the correct execution of each task in the prior phase, and may vary based on the individual abilities of each athlete. Each task or activity is evaluated in isolation, so that an athlete may progress more quickly through one task compared to another and continue to be challenged at an appropriate level, given the specific skill set in each task. Ultimately, the goal for this late-phase rehabilitation program is successful completion of each of the 4 phases. To determine return-to-sport readiness, however, comprehensive functional testing should be implemented.[1,31,53,105,107,146] To help guide the rehabilitation specialist in devising a patient-specific neuromuscular training program, the following section describes evidence-based exercises that may effectively target each of the 4 modifiable predictors of second–ACL injury risk.[58,95,106,109,126]

Exercises to Address the Net Hip Internal Rotator Moment Upon Landing

Poor neuromuscular function of the posterior and lateral hip musculature may affect generation of the optimal net hip joint moments required to control hip motion upon landing. Therefore, exercises that require large hip extension and external rotation moments, by way of large hip flexion angles and avoidance of out-of-sagittal-plane hip motion, should elicit powerful contractions of the target musculature, that is, hip extensors, abductors, and external rotators. Although weakness of the hip external rotators, abductors, and extensors may not be strongly related to frontal plane hip and knee mechanics,[155,158] recent evidence links muscle activation deficits to poor control of the lower extremities.[156,157] Further investigation of the influence of hip muscle strength and activation deficits on lower extremity mechanics is warranted; in the interim, however, interventions targeted at these deficits are indicated. Furthermore, pilot work using the proposed training protocol has successfully improved dynamic hip strength[93] and reduced some of the neuromuscular deficits proposed to be related to second-injury risk.[109,144]

Single-leg activities necessitate adequate trunk and lower extremity control to minimize frontal and transverse plane segmental motion. The goal of the anterior (**APPENDIX A**, online) and lateral (**APPENDIX B**, online) single-leg exercise progressions is to induce knee and hip joint torques of increasing magnitude during controlled movements, with the emphasis on the deep–knee hold position. The goal of the deep–knee flexion and –hip flexion position during the lunge progression is to demand adequate force generation and attenuation of the proximal musculature to control out-of-plane moments at the hip (**APPENDIX C**, online). Tuck jump landings (**APPENDIX D**, online) replicate the extended lower-limb posture known to induce valgus loading in athletes with neuromuscular deficiency. As the technique is perfected through the early phases and the athlete learns to minimize non–sagittal plane motion, repetitive plyometric movements are used to introduce high loading conditions at progressively greater velocities.

Exercises to Address Increased Frontal Plane Knee Motion During Landing

Anterior (**APPENDIX A**) and lateral (**APPENDIX B**) single-leg exercise progressions, as well as the lateral jumping (**APPENDIX E**, online) exercise progression, demand control of the frontal plane to execute proper technique. The lunge progression (**APPENDIX C**) demands proximal muscle control by way of a narrow base of support, and also produces large sagittal plane moments about the knee if the athlete utilizes the desired deep–knee flexion positioning of the lead limb. Lack of control in the anterior and lateral single-leg progressions may be manifested by excessive frontal plane motion at the knee. Ligament dominance, quadriceps dominance, trunk dominance, and leg dominance, as previously described, are associated with dynamic knee instability and can be assessed using the tuck jump.[97,106] Proper form on the tuck jump progression, particularly in the late phases, may be indicative of superior neuromuscular control.[109] In a previous study examining the effectiveness of neuromuscular training on high-risk biomechanics, feedback provided to athletes during the tuck jump improved frontal plane knee mechanics on the drop-vertical jump task,[109] indicating an effective transfer of neuromuscular strategy that may have a direct influence on ACL injury risk.[61,126] Biofeedback and instruction provided during progressive training using the tuck jump (**APPENDIX D**) may also reduce excessive frontal plane motion in athletes following ACLR.

Adequate trunk and hip strength may be necessary for proper lower extremity mechanics during dynamic tasks. Lateral (**APPENDIX F**, online), prone (**APPENDIX G**, online), and kneeling trunk (**APPENDIX H**, online) stability training may be effective for the enhancement of trunk proprioception and control of excessive trunk motion known to increase ACL injury risk.[161,162] Hamstrings strength training may also provide better frontal plane control at the knee during dynamic activities[101] and improve its role as an ACL agonist. Low hamstrings-to-quadriceps strength ratios are characteristic of young female athletes at risk for ACL injury and are a component of a highly sensitive and specific prediction model for large knee abduction loads.[101] Enhancement of hamstrings and gluteal strength by way of a progressive, weight-bearing protocol (**APPENDICES I** and **J**, online)[40] may also contribute to lowering second–ACL injury risk. Cumulatively, the current evidence indicates that both plyometric and dynamic stabilization tasks such as those proposed may be necessary to target frontal plane deficits associated with both primary–[61] and second–ACL injury[126] risk.

Exercises to Address Sagittal Plane Knee Moment Asymmetries at Initial Contact

Low knee flexion angles during dynamic tasks have been identified as a plausible mechanism for ACL injury.[41] Asymmetrical sagittal plane knee joint torques are also characteristic of athletes following injury and surgery[30,31,55,123,126,130] and predict second–ACL injury risk with an odds ratio of 3.3.[126] Exercises that encourage greater and symmetrical knee flexion, while controlling frontal and transverse plane motions of the lower extremities and trunk, may help normalize landing mechanics and thus mitigate second-injury risk. Increased flexion of the trunk leads to an increase in hip and knee flexion movement,[12,13] reduces vertical ground reaction forces,[13,140] and increases knee and decreases hip extensor moments.[140] Encouraging more upright trunk posture, however, may be more functional in terms of sports-specific tasks but may keep athletes from transferring

joint moment demands from the knee to the ipsilateral ankle and hip.[117,118] The challenge is to employ exercises that not only elicit a functional upright trunk position but also encourage knee extensor moment symmetry early after initial contact. Activities like the lunge (**APPENDIX C**) and lunge jumping (**APPENDIX K**, online) progression exercises introduce deep–knee flexion holds as a way to introduce large joint torques to the reconstructed knee and can promote improved lower extremity side-to-side strength symmetry[22,103] while maintaining a functional upright posture. Similarly, squat jumps also require deep–knee flexion holds and should be incorporated into the rehabilitation program to increase the athlete's power and recruitment of the posterior thigh and hip musculature. A combination of slight trunk flexion, with emphasis on concomitant hip and knee flexion, and soft landings should address each theorized risk factor for second ACL injury. Slower, precise completion of these earlyphase landing tasks will help promote the continued use of a strategy of increased knee flexion and force attenuation and generation as the activities become increasingly more dynamic and complex with the later phases of each exercise progression.

Deficits in the hamstrings-to-quadriceps torque ratio[96] contribute to primary–ACL injury risk but may also influence second-injury risk. Single-leg dead lifts demonstrate some of the highest hamstrings-to-quadriceps activation ratios.[10] Dynamic hamstrings strengthening (**APPENDIX J**) may help these muscles resist anterior tibial translation under conditions of forceful quadriceps contraction, providing dynamic control and increased force attenuation abilities with increasing knee flexion. Transitions to more dynamic movements that incorporate deep-hold requirements (**APPENDIX E**) have been successful for improvement of relative hamstrings strength,[102] as well as side-to-side asymmetry in force dissipation.[102,103] Quadriceps dominance, as is common in young female athletes during maturation,[60,62] may be addressed using tuck jump training (**APPENDIX D**) with concentrated feedback to guide the athlete in controlling frontal plane motion at the knee.[144]

Exercises to Address Deficits in Postural Stability

Postural deficits that contributed to the prediction of second-injury risk in young athletes were identified during a quasi-static task,[126] and are modifiable with neuromuscular training.[124] Single-limb exercises, like anterior (**APPENDIX A**) and lateral jumping (**APPENDIX B**) progressions, require prolonged single-leg holds while controlling lower extremity loads and position and avoiding loss of balance. Specifically, excessive trunk movement that affects the location of the body's center of mass may impact loads on the knee. Postural stability may be improved by advancement of quasi-static balance exercises (**APPENDIX J**), dynamic trunk strengthening, and neuromuscular re-education with the prone trunk (**APPENDIX G**) and kneeling trunk (**APPENDIX H**) progressions. As athletes advance through mid-level and high-level phases of each protocol, power generation and attenuation are emphasized and sport-specific tasks may be added. Specifically, end-phase training movements, such as hop and hold exercises, may be employed to try to reduce second-injury risk by enhancement of dynamic lower extremity stabilization[102,103] and improvement of single-limb postural control.[124]

DISCUSSION

Symmetry

Dᴜᴇ ᴛᴏ ᴛʜᴇ ᴋɴᴏᴡɴ ɪɴꜰʟᴜᴇɴᴄᴇ ᴏꜰ side-to-side limb asymmetry on second–ACL injury risk,[126] and that several batteries of tests to determine return-to-sport readiness continue to emphasize limb symmetry,[146] rehabilitation protocols should be tailored to address deficits identified in both limbs. This is especially important as we begin to better understand the implications of asymmetry as well as deficits in athletes following ACL injury compared to those in healthy controls, not only for shortterm functional performance but also for reinjury rates and future function. Athletes recovering from ACLR should not be considered fully rehabilitated purely in the absence of asymmetry. Consideration of the sport-specific and position-specific demands of each athlete, combined with residual bilateral neuromuscular deficits, will allow clinicians to tailor return-to-sport recommendations to fit individual needs. Our proposed methods to treat neuromuscular deficits following ACLR are based on the assumption that the restoration of limb symmetry and normal movement patterns will not only maximize functional performance but also mitigate future injury risk. While there is strong evidence for the effectiveness of neuromuscular training in modifying risky neuromuscular patterns in healthy athletes[93,97,98,102,103,109] and athletes who are ACL deficient,[32,39,45] far less is known about the ability of athletes who have undergone ACLR to improve aberrant movement strategies via similar programs. Specifically, the effectiveness of this proposed strategy in achieving functional symmetry, maximizing sport performance, and minimizing abnormal movement strategies must be prospectively examined in athletes following ACLR.

Return to Sport

Clinicians must consider the specific needs of each athlete to tailor the late-phase rehabilitation and preparatory return-to-activity program. The goal of this paper was to provide evidence-based guidelines for the late-phase postoperative care of these athletes in preparation for a safe return to sports activity. Specific return-to-sport training was not the focus of this paper but may be an important component of return-to-activity preparation[27,88] and should be implemented based on the needs of each athlete and the demands of the sport, as previously published for sports like soccer, basketball, and downhill skiing.[11,72,153] To date, the effectiveness of the exercise components described has not been empirically tested on athletes following ACLR; however, recent reports indicate that the addition of on-field rehabilitation helps to address lingering deficits in the return-to-sport phase.[11,27,72,153] Future studies should focus on randomized controlled trials of specific, targeted neuromuscular interventions.

Limitations

The overall purpose of this clinical commentary was to detail a paradigm for late-phase post-ACLR rehabilitation that can address the multifactorial nature of second–ACL injury risk in young, highly active individuals. Much of the literature on the effects of neuromuscular training on primary-injury risk has been focused on young, highly active adolescent females and may not be directly translatable to an older, male cohort following ACLR. As this program was derived from data describing the neuromuscular risk factors for

ACL injury in a predominantly adolescent female athletic population, generalizability to other populations may be limited at this time. Furthermore, though the primary–ACL injury biomechanical risk profile has some overlap with the second–ACL injury risk profile,[61,126] these 2 profiles are not exactly the same; thus, similar exercises may not result in all of the desired adaptations. The exercises are intentionally similar, however, because they have a known effect on the muscles that are deficient following ACLR and hypothesized to modify abnormal lower extremity and trunk movement. Neuromuscular training is proposed as an important component of both presurgical[32] and postsurgical care[1,103]; therefore, if these exercises are incorporated early on, the additive benefits of continued, progressive, and individualized neuromuscular training as outlined within this manuscript may be adequate to elicit the desired effects. This program, as is currently proposed, is meant to augment current perioperative rehabilitation efforts, but will likely not be a substitute for traditional strength training, preseason fitness and skill preparation, or on-field sport reintegration. It is unknown whether the outlined dosage is sufficient to yield both short- and long-term effects on risky body mechanics or neuromuscular performance. The effect of this program on modifying second–ACL injury risk and second–ACL injury incidence is unknown and should be the goal of future investigations. Additional modifications to this program should be based on emerging evidence from studies evaluating the efficacy of this program in the target population.

CONCLUSION

THE GOAL OF THIS REVIEW WAS TO describe the neuromuscular characteristics associated with second-injury risk factors and to provide sports health practitioners with evidence-based information regarding late-phase ACLR rehabilitation. Achievement of optimal function and sports performance after ACLR is likely dependent on a number of both modifiable and nonmodifiable factors.[35,126,160] Neuromuscular control deficiencies are, at this time, the only known modifiable factors predictive of second–ACL injury risk.[126] Targeted interventions aimed at these movement impairments may significantly reduce reinjury risk in athletes who have undergone ACLR.[58] The long-term benefits of an effective rehabilitation program may also be realized, both by the full restoration of functional performance and by the improved ability of these individuals to maintain lifetime activity participation without disabling knee symptoms. The evidence outlined in this review provides a platform on which evidence-based treatment approaches can be developed. Future research studies should focus on randomized controlled trials of specific, targeted neuromuscular interventions.
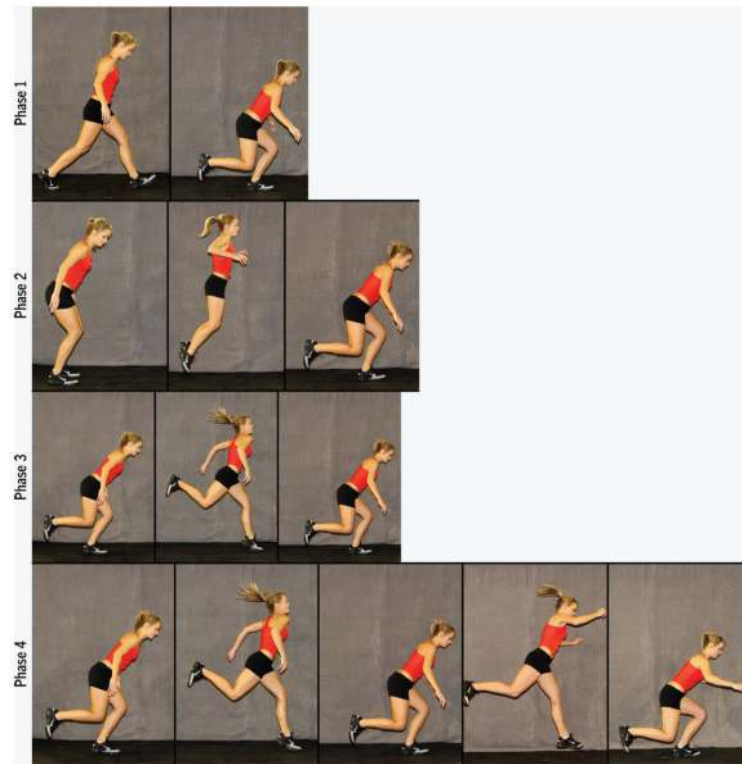
## Acknowledgments

Appendix A

Single-Leg Anterior Progression

The clinician instructs the athlete to descend into a deep–knee flexion hold upon each take-off and landing, avoiding excessive non–sagittal plane motion of the lower extremities and trunk. Phase 1 focuses on symmetry during take-off and landing, and the clinician should encourage jumping farther once the athlete has mastered the basic technique. Progression to phase 2 should occur only after the athlete can demonstrate proper technique during phase 1. Single-leg jumping for distance with proper take-off and landing is the focus of phase 3, prior to repeated anterior jumps in phase 4 (phases 1-4: 3 × 10 repetitions bilaterally).

APPENDIX B

Single-Leg Lateral Progression
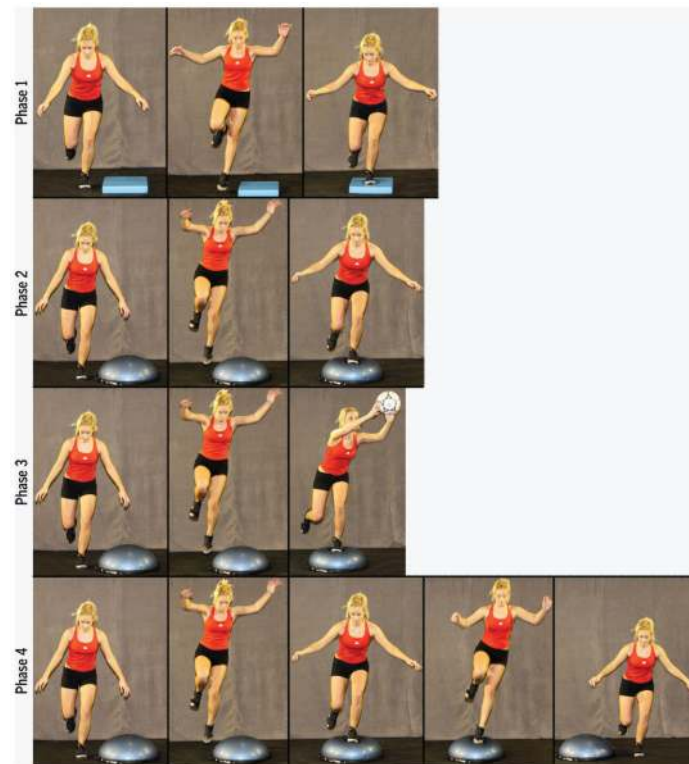
The clinician instructs the athlete to begin and end each hop hold with deep knee flexion, avoiding excessive non–sagittal plane motion of the lower extremities and trunk during take-off and landing. In the later phases, the athlete should also be instructed to minimize the amount of rebound (or reverberation) of the BOSU under the foot. Phase 4 should incorporate lateral and medial jumping (phases 1-4: 3×10 repetitions bilaterally).

APPENDIX C

Lunge Progression
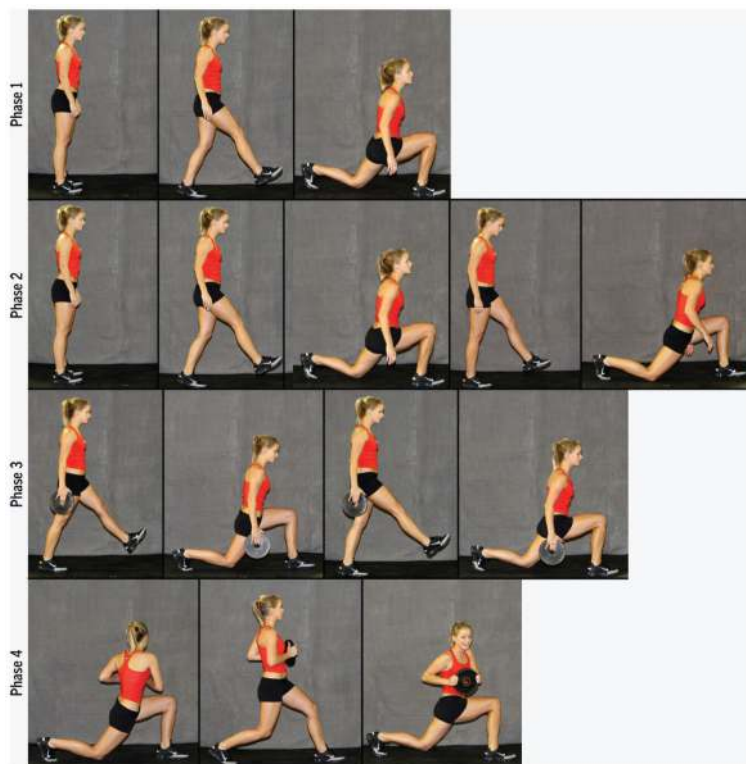
The clinician instructs the athlete to maintain most of the weight on the lead leg as they lunge forward into a deep knee flexion, avoiding hyperextension of the trunk. A slight forward lean is acceptable, as this will assist the patient to drive off the lead leg. The athlete's knee should never advance beyond the ankle during the exercise. The clinician should also cue the athlete to avoid pausing between the lunge and upright portions of the task (phase 1: 3 × 10 repetitions bilaterally; phases 2-4: 10 m × 2 sets).

APPENDIX D

Tuck Jump Progression
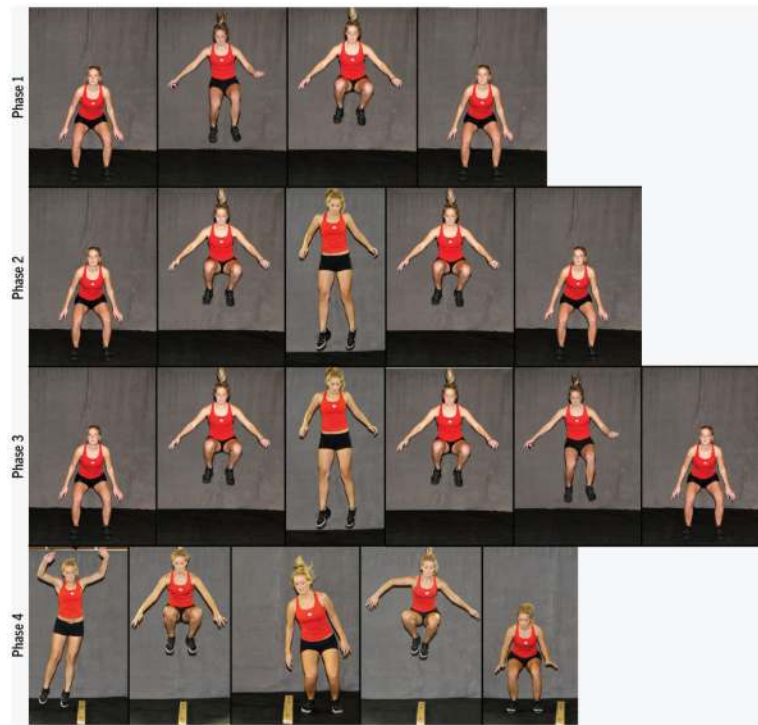
The clinician instructs the athlete on the proper countermovement preparation (slight crouch downward, extending arms behind body) prior to the vertical jump. The vertical jump begins as the athlete vigorously swings the arms forward as they jump straight up, pulling their knees up as high as possible. The goal is to achieve a parallel position of both thighs in relation to the floor, and to use a toe-to-midfoot rocker landing upon descent into a deep–knee flexion hold. As the athlete progresses from 2 consecutive jumps (phase 2) with proper technique to multiple consecutive jumps (phase 3), the clinician instructs the athlete to avoid excessive non–sagittal plane motion of the lower extremities and trunk, and to try to take off and land in the same footprint in which the task started. Tuck jumps performed over an object should be completed only if the athlete completes repeated phase 3 jumps with proper technique (phases 1-2: 2 × 10 repetitions; phases 3-4: 2 × 10 seconds).

APPENDIX E

Lateral Jump Progression
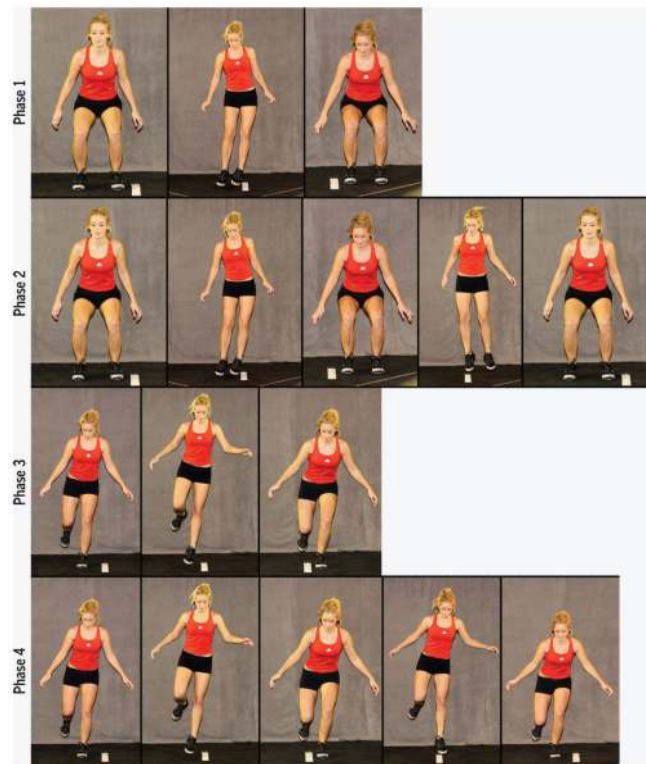
The goal of this exercise is to focus on minimizing the frontal plane motion of the trunk and lower extremities during lateral jumping. The height of the jump is not the focus; rather, increasing speed with good technique is the criterion by which the athlete will be progressed to the next phase. A deep–knee flexion position is emphasized upon each take-off and landing, regardless of phase. The clinician should encourage the athlete to jump "close to the line" in preparation for quicker lateral movements. This exercise is progressed from double leg (phases 1 and 2) to single leg (phases 3 and 4) once the athlete can demonstrate symmetrical timing and proper alignment with single- (phase 1) and then repeated double-leg landing (phase 2) (phases 1-2: 2 × 10 repetitions; phase 3: 2 × 10 repetitions bilaterally; phase 4: 2 × 10 seconds bilaterally).

APPENDIX F

Lateral Trunk Progression
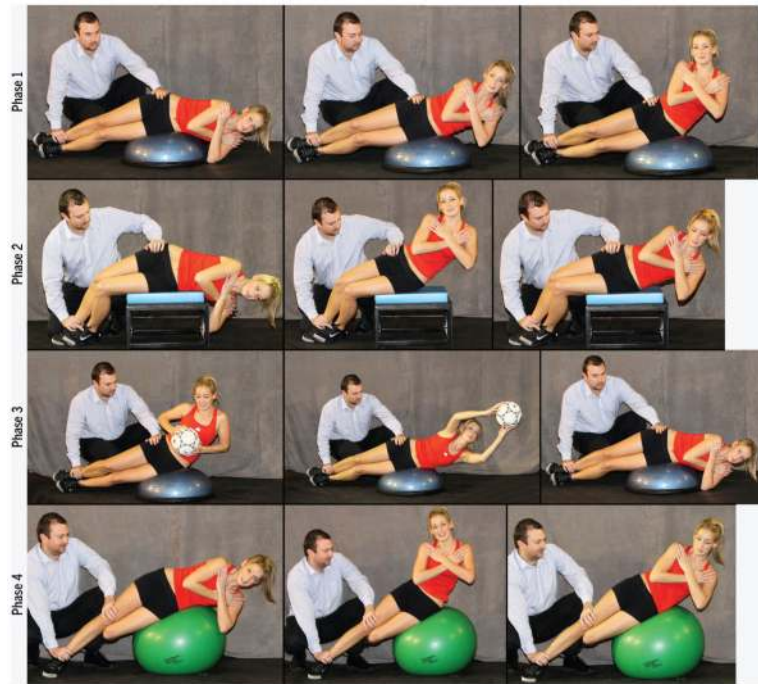
The clinician provides stabilization at the pelvis and lower extremities throughout the phases. The clinician instructs the athlete to bend laterally at the waist during the crunch movement and avoid non–frontal plane motion of the trunk. The athlete should also maintain the arms in a crossed position over the chest, except when involved in a partner toss-and-catch activity. Progression should be implemented when the athlete can complete the current phase with proper form and full trunk motion (phases 1-4: 3×10 repetitions bilaterally).

APPENDIX G

Prone Trunk Stability
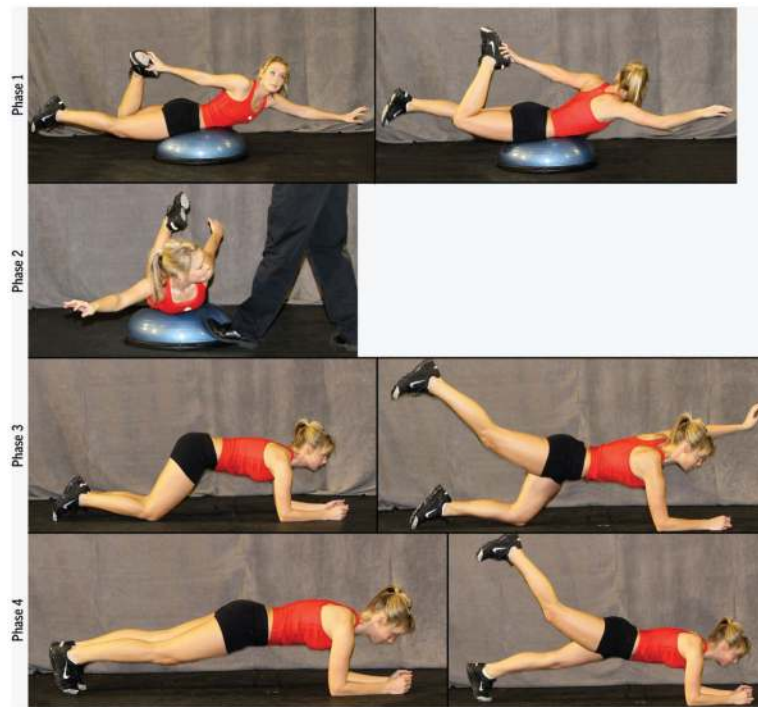
The clinician instructs the athlete to minimize the amount of rebound (or reverberation) of the BOSU under the trunk, especially during partner perturbations. As the athlete progresses to the prone bridge position (phases 3 and 4), the 2 to 3 contact points away from the center of mass further destabilize the athlete as they alternate extremity limb positions. The goal is to avoid excessive trunk rotation and flexion or hyperextension as they lift their limbs (phases 1-4: 3 × 10 repetitions bilaterally).

APPENDIX H

Kneeling Trunk Stability

The clinician instructs the athlete to maintain slight hip flexion throughout the different phases. Excessive trunk flexion and upper extremity strategy (flailing of arms) should be avoided, especially when the clinician is providing perturbations to the support surface (phase 4). The clinician should avoid administering a subsequent destabilizing perturbation prior to the athlete restoring their equilibrium (phases 1, 3, and 4: 3 × 20 seconds; phase 2: 3 × 20 seconds bilaterally).

APPENDIX I

Posterior Chain Progression
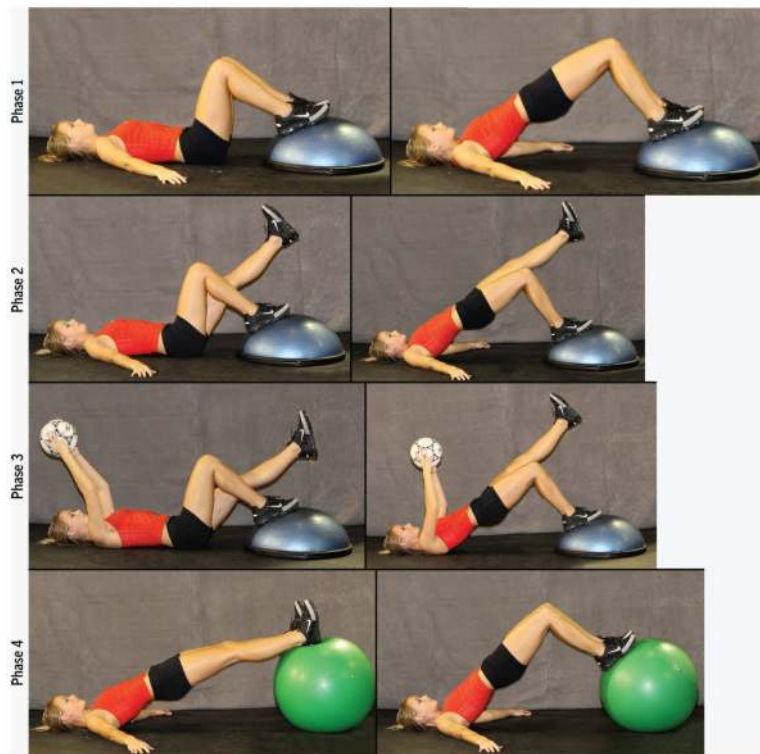
The clinician instructs the athlete to avoid lumbar hyperextension during the bridging-task phases. Manual and verbal cues may be necessary to acclimate the athlete to a neutral pelvic position during this exercise, avoiding contralateral hip drop. As the athlete advances through stages, the goal is to perform full, uncompensated motion. Phase 3 is designed to narrow the base of support and the number of contact points to increase the diffculty of the task. In phase 4, the athlete should be instructed to minimize motion of the ball under their feet while achieving controlled hip flexion and extension (phases 1-4: 3 × 10 repetitions).

APPENDIX J

Romanian Dead Lift Progression

The key component to this exercise progression is the ability of the athlete to minimize trunk deviation in the frontal and transverse planes while avoiding excessive cocontraction of the muscles of the lower extremities. The clinician instructs the athlete to keep the muscles of the standing leg relaxed, with the knee slightly flexed and toes and foot relaxed. Hip hinging with an erect spine should be emphasized throughout the phases (phases 1-4: 3 × 10 repetitions bilaterally).

APPENDIX K

Lunge Jump Progression
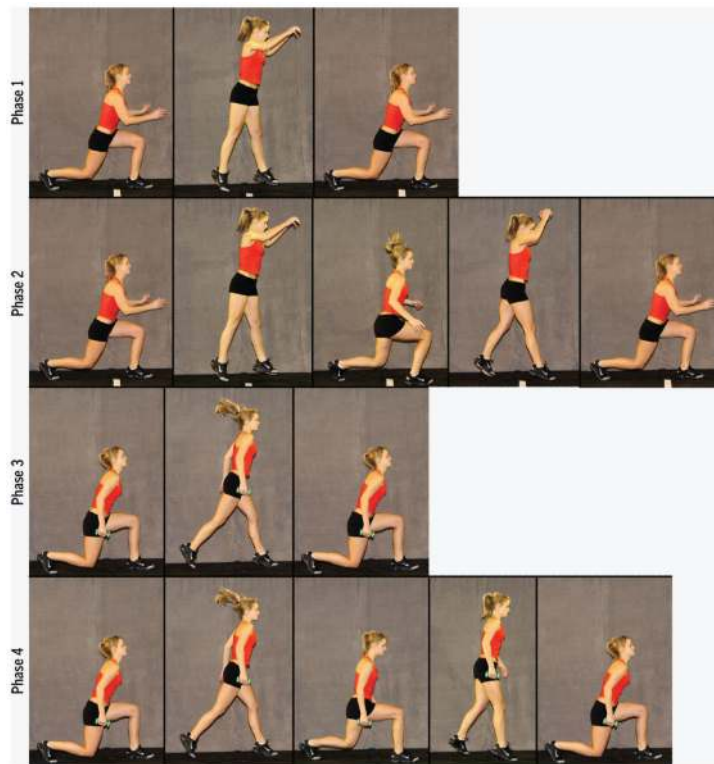
This is a plyometric advancement of the lunge progression in **APPENDIX C**, and the same emphasis should be placed on the mechanics of the lead leg and trail leg, as well as the trunk. The clinician instructs the athlete to maintain more weight toward the lead limb to generate adequate power for the jump and maintain balance. The clinician instructs the athlete to descend into a deep–knee flexion hold upon each jump take-off and landing, avoiding excessive non–sagittal plane motion of the lower extremities and trunk (phases 1 and 3: 3×10 repetitions bilaterally; phases 2 and 4: 3×20 seconds).

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SYNOPSIS

Successful return to previous level of activity following anterior cruciate ligament (ACL) reconstruction is not guaranteed, and the prevalence of second ACL injury may be as high as 30%. In particular, younger athletes who return to sports activities within the first several months after ACL reconstruction may be at significantly greater risk of a second ACL rupture compared to older, less active individuals. Significant neuromuscular deficits and functional limitations are commonly identified in athletes following ACL reconstruction, and these abnormal movement and neuromuscular control profiles may be both residual of deficits existing prior to the initial injury and exacerbated by the injury and subsequent ACL reconstruction surgery. Following ACL reconstruction, neuromuscular deficits are present in both the surgical and nonsurgical limbs, and accurately predict second–ACL injury risk in adolescent athletes. While second ACL injury in highly active individuals may be predicated on a number of modifiable and nonmodifiable factors, clinicians have the greatest potential to address the modifiable postsurgical risk factors through targeted neuromuscular interventions. This manuscript will (1) summarize the neuromuscular deficits commonly identified at medical discharge to return to sport, (2) provide the evidence underlying second–ACL injury risk factors, (3) propose a method to assess the modifiable deficits related to second–ACL injury risk, and (4) outline a method of intervention to prevent second ACL injury. The program described in this clinical commentary was developed with consideration for the modifiable factors related to second-injury risk, the principles of motor learning, and careful selection of the exercises that may most effectively modify aberrant neuromuscular patterns. Future validation of this evidence-based, late-phase rehabilitation program may be a critical factor in maximizing return-to-activity success and reduction of second-injury risk in highly active individuals.
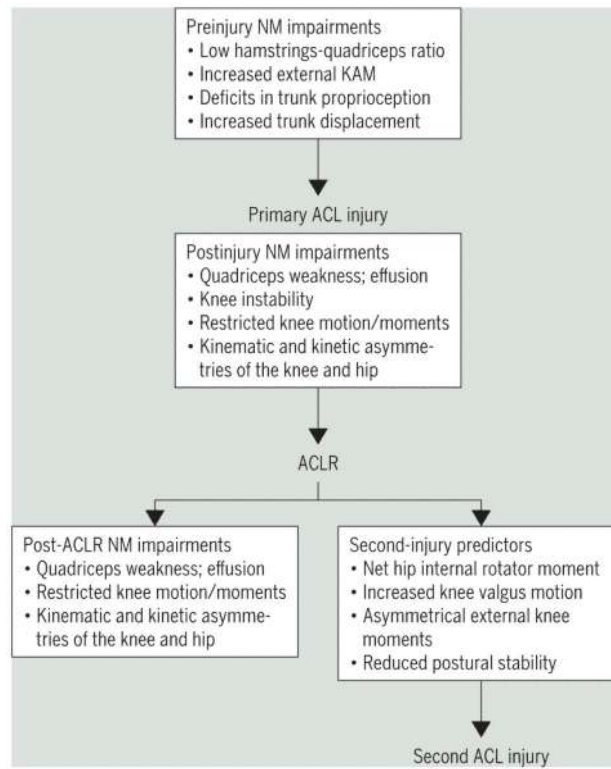
FIGURE.

Neuromuscular impairments leading to primary and secondary ACL injury. Abbreviations: ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; KAM, knee abduction moment; NM, neuromuscular.

TABLE 1

Proposed Methods to Assess Neuromuscular Impairments After ACLR

Assessment Method	Impairments Assessed	Clinically Important Cutoff Criteria	Evidence for Clinical Applicability	
Thigh muscle dynamometry	Quadriceps and hamstrings side-to-side symmetry; hamstrings-quadriceps ratio	90% or greater[1, 134]	1	Athletes who underwent ACLR and had at least 90% quadriceps strength index (side-to-side symmetry) demonstrated functional performance similar to uninjured control subjects[134]
			2	Female athletes who went on to sustain a primary ACL rupture had decreased hamstrings-quadriceps ratios compared to male controls[96]
Single-leg hop tests	Dynamic, sports-related knee function side-to-side symmetry	90% or greater[1, 147]	1	Limb-symmetry indexes on single-leg hop for distance, triple hop for distance, and crossover hop for distance differed between controls and athletes who had ACLR[108]
			2	Symmetry on the triple hop for distance was the most strongly correlated to self-reported function of the 4 hop tests[128]
Tuck jump	Trunk and lower extremity asymmetry and quality of mechanics	Perfect score of 80 points (no asymmetries or abnormalities)[107]	1	Feedback provided on tuck jump technique reduces knee abduction motion during the drop-vertical jump[109]
Drop-vertical jump	Sagittal and frontal plane knee mechanics	Greater than 60% normalized knee separation distance[7]	1	Sagittal and frontal plane knee motion during a drop-vertical jump is part of a clinical algorithm that accurately predicts high external knee abduction loads[101]
Patient-reported outcomes	Patient perception of function, symptoms, sport-related disability	90% or greater[1]	1	IKDC scores were lower in athletes who underwent ACLR compared to controls, and lowest in the athletes with strength asymmetries greater than 15%[134]
			2	Use of self-reported outcomes is advised as part of a battery of tests to determine functional status following acute ACL injury[36, 44] and readiness to return to sport following ACLR[1]

Abbreviations: ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; IKDC, International Knee Documentation Committee Subjective Knee Evaluation Form.

TABLE 2

Evidence for Selected Exercises

Exercise/Task	Key Muscles Targeted	Key Motions/ Elements Targeted	Direct Evidence for Targeted Effect		Indirect Evidence for Targeted Effect	
Single-leg anterior progression	Gluteals; quadriceps and hamstrings	Sagittal plane trunk and LE joint motion; plyometric	1	Single-leg squat activated gluteus medius and maximus similarly and elicited greatest gluteus maximus activation[40]	1	Athletes with ACL deficiency shifted moments away from knee during hopping and their center of mass was more anterior versus controls[117]
Single-leg lateral progression	Gluteals; trunk musculature; quadriceps and hamstrings	Frontal plane trunk and LE joint motion; unstable surface; plyometric	1	Single-leg squat activated gluteus medius and maximus similarly and elicited greatest gluteus maximus activation[40]	1	Athletes with ACL deficiency shifted moments away from knee during hopping versus controls[117]
			2	High hamstrings-quadriceps co-activation ratios occurred with lateral hopping[10]	2	Healthy athletes with increased knee valgus demonstrated higher hip adductor, gastrocnemius, and tibialis anterior activation[122]
					3	Unstable surface shifted joint moments proximally[14]
Lunge progression	Gluteals; quadriceps and hamstrings	3-D trunk and LE joint motion; plyometric	1	Forward lunge elicited high hamstrings-quadriceps coactivation ratios[10]	1	Quadriceps strength was significantly correlated with external sagittal plane knee moments[117] and dynamic knee function in athletes following ACLR[57, 78, 80]
			2	Lunge elicited greater than 75% vastus medialis muscle activity[40]		
Tuck jump progression	Gluteals; trunk musculature	Symmetry of LE movement; frontal plane trunk and LE joint motion; plyometric	1	Female athletes who received feedback on their tuck jump mechanics demonstrated a 38% (up to 6.9°) reduction in the peak frontal plane angle on the drop-vertical jump task[109]	None	
Lateral jumping progression	Gluteals; quadriceps and hamstrings	3-D LE joint motion; plyometric	1	High hamstrings-quadriceps coactivation ratios occurred with lateral hopping[10]	1	Athletes with ACL deficiency shifted moments away from knee during hopping versus controls[117]
					2	Increased lateral trunk motion increased external knee abduction moments[66]

Exercise/Task	Key Muscles Targeted	Key Motions/ Elements Targeted	Direct Evidence for Targeted Effect		Indirect Evidence for Targeted Effect	
Lateral trunk progression	Trunk musculature	Frontal and transverse plane trunk motion	1	External obliques demonstrated high levels of muscle activity in sidelying flexion exercises[73]	1	Increased early lateral trunk displacement with secured lower extremities predicted knee ligament injury[162]
					2	Maximum lateral trunk displacement with secured lower extremities predicted ligament injury in females only[162]
Prone trunk stability	Gluteals; trunk musculature	Sagittal and transverse plane trunk motion	1	Prone bridge elicited high abdominal muscle activity[40]	None	
			2	Trunk extension combined with hip extension elicited trunk extensor activation up to 50%[73]		
Kneeling trunk stability	Gluteals; trunk musculature	3-D trunk motion; unstable surface	None		1	Unstable surface shifted joint moments proximally[14]
					2	Increased lateral trunk motion increased external knee abduction moments[66]
					3	Increased early lateral trunk displacement with secured lower extremities predicted knee ligament injury[162]
					4	Maximum lateral trunk displacement with secured lower extremities predicted ligament injury in females only[162]
Posterior chain progression	Gluteals; trunk muscula-ture; hamstrings	Transverse plane trunk and hip motion	1	Single-leg bridge elicited high gluteus medius, hamstrings, longissimus thoracis, and multifidi activity[40]	None	
Single-leg dead lift progression	Gluteals; trunk muscula-ture; hamstrings	3-D trunk and LE joint motion; unstable surface	1	Single-leg dead lift activated gluteus medius and maximus similarly and elicited greatest gluteus maximus activation[40]	1	Unstable surface shifted joint moments proximally[129]
			2	2. High hamstrings-quadriceps activation ratios with Romanian dead lift[10]		

Exercise/Task	Key Muscles Targeted	Key Motions/Elements Targeted	Direct Evidence for Targeted Effect		Indirect Evidence for Targeted Effect	
Lunge jump progression	Gluteals; trunk musculature; quadriceps and hamstrings	3-D trunk and LE joint motion; plyometric	1	Forward lunge elicited low hamstrings-quadriceps coactivation ratios[10]	1	Long-axis neuromuscular training increased propulsive jumping forces, reduced joint velocities during landing phase, and early stabilization[116]
			2	Lunge elicited greater than 75% vastus medialis muscle activity[40]	2	Long-axis neuromuscular training increased knee flexion, increased gluteal muscle efficiency, changed timing of frontal plane peaks[116]
					3	Athletes with ACL deficiency shifted moments away from knee during hopping versus controls[118]
					4	Quadriceps strength was significantly correlated with external sagittal plane knee moments[117] and dynamic knee function in athletes following ACLR[57, 78, 80]

Abbreviations: ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; LE, lower extremity.

TABLE 3

Phase	Common Task Components	Goal
1	Usually a 2-legged task or a unidirectional single-leg task	Master basic component technique; control out-of-plane motions of extremities and trunk
2	Double- to single-leg transition; decreasing stability of support surface; narrowing base of support	Integrate additional component of task without compromise of technique
3	Introduction of second perturbation to the athlete's neuromuscular system (ie, Airex plus ball catch)	Athlete is able to avoid loss of balance or form under perturbed conditions
4	Multidirectional tasks that demand explosive movements and quick repetition; unstable surfaces and destabilizing perturbations	Quick, explosive, precise movements with rapid response to perturbations and without feedback from instructor