# Neuromuscular Deficits Following Anterior Cruciate Ligament Reconstruction Require Increased Duration of Rehabilitation in Collegiate Athletes

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**Introduction**

One in four athletes who have experienced an anterior cruciate ligament (ACL) injury will experience a second ACL rupture within the first year of returning to their sport.[1] Furthermore, one in three athletes experience a general re-injury to the knee within the first two years following anterior cruciate ligament reconstruction.[2] This illustrates the importance of comprehensive and effective rehabilitation and return to sport progression following ACL reconstruction not only for injury prevention, but also for long term health of the athletes. Anterior cruciate ligament (ACL) injuries are prevalent among collegiate athletes and often require surgery and extensive rehabilitation. To our knowledge, no systematic review exists analyzing the relationship between the length of recovery time and reinjury rates attributed to neuromuscular deficits in collegiate athletes who have undergone anterior cruciate ligament reconstruction (ACLR). Despite advancements in surgical techniques and rehabilitation, reinjury rates remain a large concern with a considerable number of these instances attributed to neuromuscular deficits. This paper aims to address the need for comprehensive rehabilitation after ACLR that specifically addresses neuromuscular specific rehabilitation.

*Definitions*

In relation to this paper, the following terms will be used, and their definitions will be as follows. Neuromuscular deficits are impairments to coordination, control, and communication between the nervous system and muscles. Neuromuscular rehabilitation consists of targeted exercises and interventions which assess neuromuscular deficits that resulted from the initial anterior cruciate ligament injury. Neuromuscular reeducation is the retraining of the neuromuscular system to perform movement patterns correctly, as well as enhancing neuromuscular control and proprioception. This term will be used synonymously with neuromuscular reconditioning and neuromuscular retraining. Neuromuscular control is the ability of the nervous system to coordinate muscle activity to produce coordinated movements of the body.

**Methods**

Studies were included that related to neuromuscular recovery and rehabilitation after anterior cruciate ligament repair. Only studies with a publication date between 2019 and 2024 were considered. Some studies were found through the "cited in" tool in older articles, to maintain the publication time criteria. Eight articles were found that matched criteria for the search. The search terms used were "neuromuscular," "anterior cruciate ligament," "reconstruction," "neuromuscular deficit," "anterior cruciate ligament reconstruction," "athletes," and "collegiate athletes."

**Results**

In total, sixteen studies were analyzed for synthesis in this systematic review. Two of these studies were systematic reviews of the literature on neuromuscular control and the risk of ACL reinjury in return to sport. Eight of these studies addressed recommendations for comprehensive rehabilitation and return to sport criteria. Six of these studies were experimental and analyzed with the STROBE scale criteria. All studies passed the STROBE scale criteria (see Table 1 in Appendix).

**Comprehensive Rehabilitation**

The need for comprehensive rehabilitation that addresses all impairments following anterior cruciate ligament reconstruction is a main focus of the current literature. Rehabilitation should begin as soon as possible after ACLR surgery, particularly on the non-injured leg to reduce loss of muscle strength. Thirty percent or more athletes sustain an injury within the first two years of returning to sport; comprehensive rehabilitation is necessary to address this issue.[3] A variety of exercises must be components of the rehabilitation protocol, including strength training, plyometrics, neuromuscular training, and cardiovascular conditioning. Furthermore, quadriceps muscle strength deficits are a larger problem within ACLR patients that needs to be addressed in all stages of rehabilitation to adequately restore the strength.[4-7] Even with the current rehabilitation protocol, strength deficits throughout the leg can be seen up to five years following injury.[8] When quadriceps strength is not adequately restored during rehabilitation, athletes are at a much greater risk of reinjury. This is a major issue that needs to be addressed and investigated to prevent long-term chances of reinjury in athletes. An example of the current protocol from Sanford Health can be seen in Table 2[9] (See Appendix).

*Return to Sport*

Following the early, mid, and late stage of rehabilitation, athletes will progress towards clearance to return to sport, which is the final stage of comprehensive anterior cruciate ligament rehabilitation. However, 35-40 percent of athletes that elect to have anterior cruciate ligament reconstruction do not return to sport after their injury, with 20-25 percent of athletes being completely unable to due to residual pains and injuries.[3] The return to sport progression is recommended to begin with on-field rehabilitation, then progress into return-to-team training, and finally return to competition.[3] There are milestones within each of these progressions that should be met before advancing onto the next stage in order to lower risk of reinjury. Only one study was found proposing a five stage return to sport rehabilitation program that focuses on addressing "impairments associated with neuromuscular performance, movement quality, and sport specific performance" to fully prepare athletes for return to sport and subsequent competition. It is essential for athletes to meet all return to sport criteria before they return to competition, as they are 25 percent more likely to sustain a reinjury to the ACL if they fail to achieve this criteria.[3] This criteria should include assessments of single leg drop biomechanics, rate of force development, single limb stability, isolated strength techniques, torque through full range of motion in the knee, interlimb symmetry, and other various assessments that assist in the decision of return to sport.[1,3,6-7,10-11] Additionally, this criteria should include restoring change of direction ability, bilateral deficits in proprioception that lead to longer time to stabilization, the addition of cognitive demands into tasks, lower limb performance in multiple directions, capacity to cope with demands of the sport both physically and mentally, and further neuromuscular control.[2-4,11-12] Meeting the milestones previously described is essential for an athlete's recovery and improving the chances of returning to sport without reinjury. Another study suggests a different five stage return to sport progression including "resumption of noncontact practice, followed by small sided contact practices, full unrestricted practice, return to competition at a restricted workload, and last, return to competition unrestricted."[5] However, this protocol can be hard to implement without adequate support from healthcare professionals, such as physicians and athletic trainers. The return to sport progression in this study is a longer progression than the previous study, but it progresses the athlete in smaller, more specific steps to help reduce the risk of reinjury upon full return to competition. While there are multiple suggestions for return to sport progression, it remains the most important part of rehabilitation, regardless of the different progressions. There needs to be athlete supervision from a healthcare worker to decide on the progressions through return to sport, which is not addressed in the current protocol.

**Neuromuscular Reeducation**

A two-year recovery period is optimal for neuromuscular re-education to provide adequate time to address the deficits lost following injury and surgical intervention. As of now, the recommended rehabilitation and return to sport timeline is 9-12 months to allow for graft healing.[5] However, this timeline does not allow for sufficient neuromuscular retraining to address the persistent neuromuscular control deficits after ACLR. Athletes are at the greatest risk of reinjury within the first two years, mainly due to the persistence of these deficits.[5] The addition of a neuromuscular training program into rehabilitation shows a reduction in deficits in knee biomechanics which is associated with a lower risk of reinjury to the ACL.[10] This neuromuscular training can restore adequate muscle function and performance. There are multiple areas of neuromuscular deficits that need to be reeducated throughout rehabilitation. Explosive neuromuscular power (strength and power training) and lower limb performance should be tested and addressed in late stage rehabilitation, after the athlete has met the criteria of 80-90 percent limb symmetry.[2-3] Gait alterations stemming from neuromuscular dysfunction are considered to be a part of the neuromuscular issues resulting from ACLR, and need to be addressed in neuromuscular retraining.[2,4] In order for rehabilitation to be comprehensive, it needs to include tasks for restoration of neuromuscular control and performance.[2] To adequately reeducate the neuromuscular processes of the body, neuromuscular control deficits need to be addressed throughout the stages of rehabilitation, and following return to sport. A suggestion for an adequate rehabilitation timeline is presented and compared to the current protocol in Table 3[9] (See Appendix).

**Neuromuscular Rehabilitation**

Neuromuscular rehabilitation needs to be implemented throughout the stages of rehabilitation to accurately prepare an athlete for return to sport. Internal stimuli demands and kinesiophobia need to be considered on an individual basis throughout rehabilitation, so they cannot be generalized into protocol. However, ACL injuries occur most frequently when external stimuli are present in the situation that causes the athlete to fail to maintain neuromuscular control.[3] When these cognitive demands and external stimuli are added, athletes have a much greater risk of reinjuring their ACL. This risk increases substantially due to insufficient recovery of neuromuscular control during rehabilitation.[4,11] Additionally, rehabilitation of sensorimotor control (nerve actions involving both sensory and motor pathways) is essential for movement control during on-field practices and play.[3] Return to sport clearance should not occur until sensorimotor control is reestablished in the body. Furthermore, the current criteria for neuromuscular rehabilitation does not extend past return to sport. Neuromuscular testing needs to be continually addressed, even after the athlete has completed comprehensive rehabilitation and subsequent return to sport to ensure the athlete has retained the beneficial effects of neuromuscular rehabilitation.[5-6,10] The length of time that neuromuscular testing needs to be continually addressed is unknown and is a necessary area for future research. Without this continuation of neuromuscular control testing, athletes become more susceptible to reinjury of the knee joint within the first few years of returning to sport and in the long term.

*Proprioception and Biomechanics*

Proprioception allows the body to sense its movement and location in the environment, illustrating its importance in neuromuscular training. When athletes fail to restore the changes in their proprioception, knee deficits persist after returning to sport, and the athlete becomes 30-40% more likely to sustain a subsequent ACL injury.[10] These subsequent injuries are largely due to the disruptions within the afferent impulses and mechanoreceptor in the ACLR leg that reorganize the central nervous system processes involved in controlling and stabilizing the knee joint, and the proprioceptive impairments in the sagittal and transverse planes.[1,4,6,11-13] Cutting and change of direction athletes work in these planes, illustrating the need for its consideration in neuromuscular rehabilitation. Neuromuscular rehabilitation needs to include restoration of these impairments and control before the athlete returns to sport.

Altered biomechanics after anterior cruciate ligament injury and subsequent reconstruction are a large focus of rehabilitation. The retraining of bodily movements is an essential milestone in neuromuscular rehabilitation to address impairments throughout the kinetic chain. It is important to include practice for relearning various movement coordinations during function tasks in rehabilitation to address the "biomechanical and neuromuscular control deficits" that persist.[1-3,6,13] These biomechanical differences can be seen in both the injured and uninjured limb following ACLR.[13] With this information, it becomes necessary to address altered biomechanics in early stages of rehabilitation to prevent persistent deficits along the entirety of the kinetic chain that may lead to reinjury.

**Limitations**

This study is the first, to our knowledge, that analyzes the relationship between the length of recovery time and reinjury rates attributed to neuromuscular deficits in collegiate athletes who have undergone anterior cruciate ligament reconstruction. Additionally, many of the studies cited in this review are the first study of their topic in the sports medicine literature. This review and many of the included studies do not take gender, graft type, or fatigue into consideration with neuromuscular deficits and their persistence after returning to sport. Future research is needed to address disparities in the reinjury rates related to these factors, including the length of time that neuromuscular testing should continue after athletes return to sport. Furthermore, limitations exist in the research on kinesiophobia in athletes after returning to sport. Athletes not being mentally ready for returning to the demands of their sport can increase their risk of reinjury.

**Conclusion**

Understanding the implications of recovery duration on neuromuscular rehabilitation and reinjury rates is crucial for sports medicine professionals, coaches, and athletes. It is important for developing appropriate rehabilitation strategies and injury prevention protocols for collegiate athletes that have undergone ACLR that address neuromuscular deficits comprehensively, not only for return to sport, but for lifelong function. The alarming statistics in terms of reinjury rates among athletes highlights the need for effective strategies in restoring neuromuscular deficits before returning athletes to sport. Continual assessment of neuromuscular function beyond return to sport is also essential to address persistent deficits and their chances of increasing reinjury risk. Future research is needed to address why the current return to sport testing is failing to restore the variables of the criteria, underlying alterations in biomechanics, and further issues that persist after ACLR that place athletes at an increased risk of reinjury.[3-4,11]

**References**


1. Lanier AS, Knarr BA, Stergiou N, Snyder-Mackler L, Buchanan TS. ACL injury and reconstruction affect control of ground reaction forces produced during a novel task that simulates cutting movements. *Journal of Orthopaedic Research.* 2020;38(8):1746-1752. doi:10.1002/jor.24604

2. Buckthorpe M, Della Villa F. Recommendations for Plyometric Training after ACL Reconstruction - A Clinical Commentary. *Int J Sports Phys Ther.* 2021;16(3):879-895. Published 2021 Jun 1. doi:10.26603/001c.23549

3. Buckthorpe M. Optimising the late-stage rehabilitation and return-to-sport training and testing process after ACL reconstruction. *Sports Medicine.* 2019;49(7):1043-1058. doi:10.1007/s40279-019-01102-z

4. Chou T-Y, Huang Y-L, Leung W, Brown CN, Kaminski TW, Norcross MF. Does prior concussion lead to biomechanical alterations associated with lateral ankle sprain and anterior cruciate ligament injury? *A systematic review and meta-analysis. British Journal of Sports Medicine*. 2023;57(23):1509-1515. doi:10.1136/bjsports-2023-106980

5. Brinlee AW, Dickenson SB, Hunter-Giordano A, Snyder-Mackler L. ACL reconstruction rehabilitation: Clinical Data, biologic healing, and criterion-based milestones to inform a return-to-sport guideline. *Sports Health: A Multidisciplinary Approach.* 2021;14(5):770-779. doi:10.1177/19417381211056873

6. Buckthorpe M, La Rosa G, Villa FD. Restoring knee extensor strength after anterior cruciate ligament reconstruction: A clinical commentary. *Int J Sports Phys Ther.* 2019;14(1):159-172.

7. Hart LM, Izri E, King E, Daniels KA. Angle-specific analysis of knee strength deficits after ACL reconstruction with patellar and hamstring tendon autografts. *Scandinavian Journal of Medicine & Science in Sports.* 2022;32(12):1781-1790. doi:10.1111/sms.14229

8. Bagley MC, Harper SA, McDaniel J, Custer L. Single leg aerobic capacity and strength in individuals with surgically repaired anterior cruciate ligaments. *Phys Ther Sport*. 2020;46:131-136. doi:10.1016/j.ptsp.2020.08.013

9. ACL reconstruction. Accessed March 21, 2024. https://www.sanfordhealth.org/-/media/ org/files/medical-professionals/resources-and-education/acl-reconstruction-guideline.pdf.

10. Nagelli CV, Di Stasi S, Wordeman SC, et al. Knee Biomechanical Deficits During a Single-Leg Landing Task Are Addressed With Neuromuscular Training in Anterior Cruciate Ligament-Reconstructed Athletes. *Clin J Sport Med*. 2021;31(6):e347-e353. doi:10.1097/JSM.0000000000000792

11. Blasimann A, Koenig I, Baert I, Baur H, Vissers D. Which assessments are used to analyze neuromuscular control by electromyography after an anterior cruciate ligament injury to determine readiness to return to sports? A systematic review. *BMC Sports Science, Medicine and Rehabilitation*. 2021;13(1). doi:10.1186/s13102-021-00370-5

12. Calisti M, Mohr M, Federolf P. Bilateral Deficits in Dynamic Postural Stability in Females Persist Years after Unilateral ACL Injury and Are Modulated by the Match between Injury Side and Leg Dominance. *Brain Sci.* 2023;13(12):1721. Published 2023 Dec 16. doi:10.3390/brainsci13121721

13. Alanazi AD, Mitchell K, Roddey T, et al. The effects of a high-intensity exercise bout on landing biomechanics post anterior cruciate ligament reconstruction: a quasi-experimental study. *BMC Sports Sci Med Rehabil.* 2021;13(1):36. Published 2021 Apr 7. doi:10.1186/s13102-021-00263-7

## Appendix

### **Table 1:** STROBE Scale Ratings

| Author (s) | Nagelli et al. | Calisti et al. | Lanier et al. | Hart et al. | Alanazi et al. | Bagley et al. |
|---|---|---|---|---|---|---|
| Participants | 18 ACLR, 10 control; recruited by Department of Sports Medicine | 43 female university students, 23 had previously sustained ACL injury, 20 did not | 47 participants, 10 were active (no previous injury) 10 ACL deficient, 11 ACLR with same activity level were recruited | 409 male multi-directional field sports players who underwent ACLR with various graft. | 18 soccer players in ACLR (8 men, 10 women); control was uninjured and matched to the ACLR group(8 men, 10 women) | 5 males, 3 females with unilateral ACLR |
| Methods | 12 sessions, seven exercise progressions focusing on single leg tasks, bilateral jumping, posterior chain activation, core/trunk strengthening, all with four levels of difficulty. | Five minute warm up, two submaximal bilateral ountermovement jumps, two unilateral CMJs per leg, five successful single leg landings over 30 cm in forward direction. | Participants completed a force control task for two minutes. Four tests completed: right anterior posterior, right limb medial lateral, leg limb AP, leg limb ML | Warm up of a two minute jog and five body weight squats, then testing with jumping and change of direction. Then concentric knee extension and flexion testing. Five repetitions of knee extension and flexion. 60 second rest period, then two maximal effort sets of five reps with 60 second rest. | Warm up protocol of five minutes of cycling, ten half squats, and five continuous vertical countermovement jumps. Three vertical jumps and three long jumps to determine max vertical jump height. Given demonstration o functional tasks and instructed to perform two practice trials. 30 second Wingate anaerobic protocol after a warm up period of two minutes. | Visit one: warmed up on bike for 10 minutes, performed single leg isokinetic strength measures, then single leg aerobic capacity test on contralateral limb. Visit two: participants performed the same activities with outcomes being assessed on opposite limbs. |
| Results | In single leg test, ACLR athletes had greater knee flexion angles, decreased knee abduction angles, increased knee flexion ROM, landed with greater knee flexion angles, knee abduction angles, increased knee flexion ROM, greater knee adduction moments, lower peak vertical GRF. No significant differences in post training besides ACLR athletes landing with greater knee adduction angle than control. | In terms of TTS, the ACL group needed 0.33 +/- 0.11 seconds longer to stabilize the injured leg, 0.59 +/- 0.15 seconds longer to stabilize on ACL-injured dominant leg, 0.47 +/- 0.17 seconds longer to stabilize on healthy non-dominant leg. | LyE values in the ACLR group were higher than controls and high performance athletes (control and high performance did not differ). The ACLR group showed diminished mGRF control and it is affected by direction. The ACLR group had diminished control in AP direction only. | Graft type affected extensor torque at knee angles of 67-85 degrees and flexor torque at knee angles of 27-85 degrees. Angular velocity of 60 degrees per second has been found to identify greatest strength deficits in ACLR patients. Extensor peak torque was higher in HT than BPTB. Flexor peak torque was higher in BPTB than HT. | Specifically, post- exercise landing was characterized by greater hip flexion ( p =0.01), greater knee flexion (p = 0.001), and greater ankle dorsiflexion (p = 0.002) Additionally, post- exercise landing was characterized by significantly greater hip extension moments (p = 0.009), greater knee extension moments (p = 0.012), greater ankle plantarflexion moments (p = 0.003), and decreased quadriceps activity (p = 0.007 regardless of group assignment. | There were no significant differences between the uninjured limb for VO2 max, VT, maximum watts cycled, time to fatigue, maximum heart rate, or RPE. No significant difference between uninjured and injured legs for peak torque, total work, work fatigue, or average power for hamstrings or quad for any velocity. |
| STROBE: | 14/21 | 18/21 | 16/21 | 18/21 | 19/21 | 17/21 |

### **Table 2:** Sanford Health Example Protocol Timeline

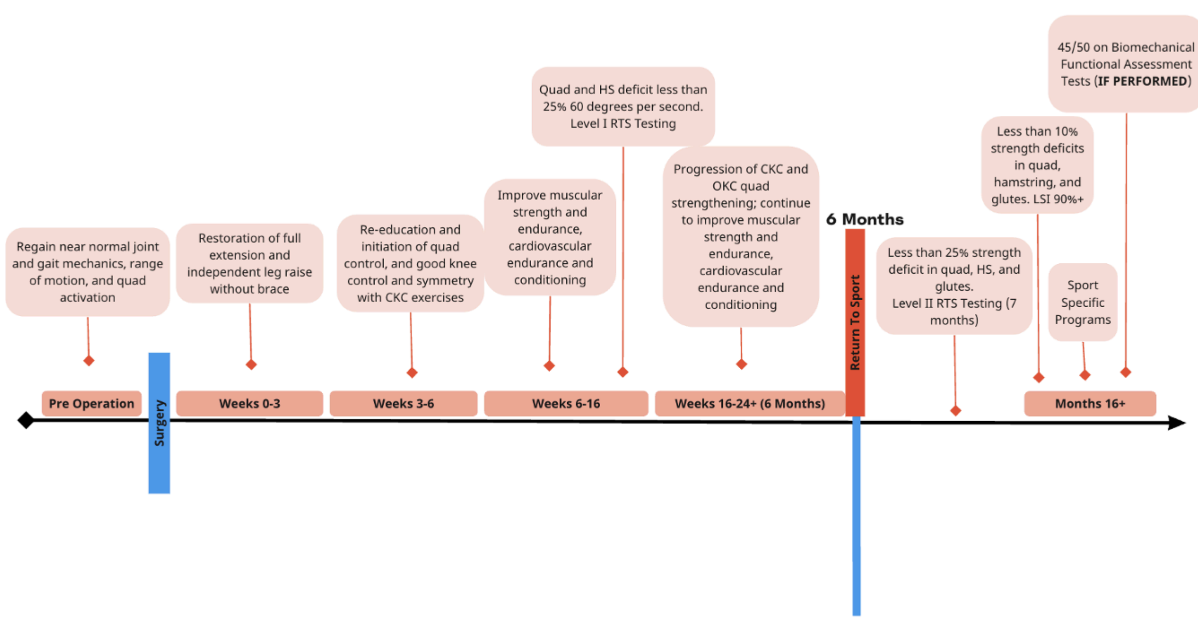

**Table 3:** Comparison of Current ACLR Protocol and Proposed ACLR Protocol with Neuromuscular Considerations