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Original Research

# Changes in Dynamic Postural Stability After ACL Reconstruction: Results Over 2 Years of Follow-up

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**Background:** The anterior cruciate ligament (ACL) is crucial for knee proprioception and postural stability. While ACL reconstruction (ACLR) and rehabilitation improve postural stability, the timing in improvement of dynamic postural stability after ACLR remains relatively unknown.

**Purpose:** To evaluate changes in dynamic postural stability after ACLR out to 24 months postoperatively.

**Study Design:** Case series; Level of evidence, 4.

**Methods:** Patients undergoing ACLR were prospectively enrolled, and dynamic postural stability was assessed within 2 days before surgery, at 3-month intervals postoperatively to 18 months, then at 24 months. Measurements were made on a multidirectional platform tracking the patient's center of mass based on pelvic motion. The amount of time the patient was able to stay on the platform was recorded, and a dynamic motion analysis score, reflecting the patient's ability to maintain one's center of mass, was generated overall and in 6 independent planes of motion.

**Results:** A total of 44 patients with a mean age of 19.7 ± 6.2 years completed the study protocol. Overall mean dynamic postural stability improved significantly at 3, 6, 9, and 12 months after surgery, with continued improvement out to 24 months. Notable improvements occurred in medial/lateral and anterior/posterior stability from baseline to 6 months postoperatively, while internal/external rotation and flexion/extension stability declined initially after surgery from baseline to 3 months postoperatively before stabilizing to the end of the study period.

**Conclusion:** Overall dynamic postural stability significantly improved up to 12 months after ACLR. Improvement in postural stability occurred primarily in the medial/lateral and anterior/posterior planes of motion, with initial decreases in the flexion/extension and internal/external rotational planes of motion.

**Keywords:** postural stability; ACL reconstruction; proprioception

The anterior cruciate ligament (ACL) represents the most commonly injured ligament in the knee, occurring at a high incidence especially in young, active individuals.[15,38] The intact ACL is crucial in providing static and dynamic stability to the knee, as well as proprioceptive regulation of the knee joint.[7,17,33] Proprioception is a component of the somatosensory system, serving to provide information on joint position, movement, sensation, and posture[35,37] and regulated via mechanoreceptors (Ruffian endings, Pacinian corpuscles, Golgi tendon organs, and free nerve endings), which make up approximately 1% to 2% of the total volume of the ACL.[2,16,23] Injuries to the ACL cause disruption of these mechanoreceptors, resulting in deficits in proprioceptive feedback and sensorimotor function,[5,27,35] abnormal movement patterns, and the loss of postural stability,[6,12,22,29] increasing the risk for subsequent meniscal and chondral injury.[18,29]

ACL reconstruction (ACLR) is often recommended to restore knee stability, followed by a graduated rehabilitation program aimed at reestablishing knee stability[30] in order to facilitate functional recovery. While ACLR has been shown to improve postural stability when compared with preoperative values, deficits in knee proprioception and postural stability have been reported to persist up to 2 years after ACLR when compared with contralateral limbs.[8,42,46] Because of the influence of postural coordination on movement and activity, regaining proprioceptive and neuromuscular control of the knee after ACLR minimizes the risk of graft failure or contralateral ACL injury.[36]

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Prior investigations evaluating deficits in postural function after ACLR have been limited in their applicability to functional status, utilizing passive movements in primarily nonweightbearing positions.[27,35] The purpose of this study was to quantify the trend in dynamic postural stability within 2 days after ACLR compared with values obtained at 3-month intervals out to 18 months and at 24 months postoperatively. We hypothesized that overall and plane-specific dynamic postural stability would improve with successive testing.

## METHODS

The investigative protocol was preapproved by the institutional review board of the study institution. All participants provided informed consent prior to study enrollment. Skeletally mature patients, based on the presence of closed distal femoral and proximal tibial physes as assessed by the treating surgeon, sustaining acute, complete ACL ruptures indicated for primary ACLR were prospectively enrolled. All study patients were treated with ACLR by 1 of 3 fellowship-trained orthopaedic sport surgeons (R.H.B., M.J.M., R.W.W.) using either hamstring or bone–patellar tendon–bone autograft over a 41-month period. Patients then underwent a graduated, standardized rehabilitation protocol after surgery, focused on controlling effusion and regaining full range of motion, followed by incorporation of closed-chain exercises to rebuild strength, coordination, and neuromuscular balance, with progression to agility, plyometric, running, and sport-specific activities as tolerated.

Exclusion criteria included prior injuries to the operative knee, the presence of concomitant articular cartilage or ligamentous (collateral or posterior cruciate ligament) injury requiring concomitant treatment during ACLR, meniscal tears undergoing repair requiring restricted weightbearing after surgery, contralateral knee pathology affecting postoperative rehabilitation, and any other general conditions affecting proprioception or postural stability. Moreover, patients sustaining recurrent ACL tears or any other subsequent knee injuries to the operative or contralateral knee, as well as any patients lost to follow-up or missing 2 consecutive tests, were excluded. Concomitant debridement of meniscal tears at the time of ACLR was not a contraindication. Immediately after surgery, all patients were allowed to bear weight as tolerated.

Within two days of surgery, all eligible patients underwent dynamic postural stability testing on a motorized multidirectional platform (PROPRIO 5000 Reactive Balance System; Perry Dynamics) (Figure 1). By producing simultaneous motion in the anterior/posterior and medial/lateral directions, designed to challenge user balance and reaction ability, the PROPRIO device allows for accurate measurements of a user's center of mass when reacting to a dynamic stimuli intended to disrupt balance.[9,10,21,25] The maximum tilt of the platform in any direction is 18° and begins with slow movements (12.6 deg/s), increasing the rate of movement 12.6 deg/s every 10 seconds to a maximum speed of 126 deg/s. An integrated, ultrasonic position sensor is secured to an elastic hook-and-loop belt over the lumbosacral junction (L5-S1) of all patients to measure center of mass movements in 6 degrees of freedom every quarter second of testing. The sensor has a range of 1.52 m and measurement accuracy of ±0.10 mm.[24] Patients hold a 6-inch (15.2-cm) piece of rope with both hands to minimize the stabilizing effect of the upper extremities.

Dynamic motion analysis (DMA) testing began with the patient in an athletic stance with knees slightly flexed, feet placed a shoulder-width apart, and weight evenly distributed on each leg. Testing consisted of three 2-minute sessions, which concluded when one of the following criteria were met: 2 minutes elapsed, the patient exceeded 3 inches (7.6 cm) of movement in 0.25 seconds, the patient's center of mass moved >5 inches (12.7 cm) from the starting point, the patient let go of the rope, the patient moved his or her feet, or the patient asked to stop the test. All testing was performed by a single author (J.M.).

After the test, an overall mean DMA score was calculated based on the 3 trials, ranging from 0 to 1440 points, using integrated software to determine the sum of the sensor's vector moments, representing the total 3-dimensional displacement of the patient's center of mass throughout testing.[10] Lower scores reflect less displacement, indicative of better dynamic postural stability. The mean total time in which the patient was able to maintain both feet on the platform among the 3 trials at each time point was also recorded.

DMA scoring is dependent on total displacement of the patient's center of mass, with the calculated value being independent of time spent on the platform. DMA scores

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Ethical approval for this study was obtained from Washington University in St. Louis (reference No. 201102280).

**Figure 1.** User undergoing dynamic postural stability testing. The multidirectional platform moves in random directions. The patient's response to these stimuli is tracked using a wearable sensor, measuring the user's center of motion in 6 planes.

were then calculated in the 6 independent planes of motion, representing alterations in the patient's movement of the center of mass away from the starting position. These included 3 translational plane assessments (medial/lateral, anterior/posterior, up/down) and 3 rotational plane assessments of the pelvis (left/right, flexion/extension, and internal/external rotation). Medial/lateral referred to movement measured at the position sensor when weight shifted from one lower extremity to the other. Anterior/posterior referred to motion as a result of shifting weight to the toes or heels. Up/down referred to movement in compression or distraction from the starting position, with patients typically squatting lower to control for larger perturbations and standing up or extending when fatigued. Left/right referred to measures of pelvic tilt to the left or right. Flexion/extension was measured based on movement of the pelvis in the sagittal plane, and internal/external rotation referred to overall pelvic displacement in the transverse plane.

TABLE 1
Overview of Patient Participation, Mean Stability Score, and Time Based on Trial[a]

| Testing Trial | Patients Completing Trial, n | DMA Score | Time, s |
|---|---|---|---|
| Preoperative | 44 | 601.1 ± 143.9 | 89.6 ± 28.0 |
| Postoperative | | | |
| 3 mo | 41 | 500.6 ± 152.4 | 95.6 ± 16.5 |
| 6 mo | 43 | 433.4 ± 152.9 | 102.2 ± 15.5 |
| 9 mo | 41 | 407.8 ± 151.9 | 104.2 ± 15.3 |
| 12 mo | 40 | 371.3 ± 155.2 | 107.5 ± 15.4 |
| 15 mo | 40 | 372.4 ± 141.4 | 107.3 ± 14.4 |
| 18 mo | 39 | 354.2 ± 152.5 | 108.1 ± 14.3 |
| 24 mo | 35 | 304.4 ± 134.7 | 111.9 ± 12.4 |

[a]Data are presented as mean ± SD. DMA, dynamic motion analysis.

Three trials of DMA testing were subsequently performed at every 3-month interval from 3 months postoperatively to 18 months and at the 24-month follow-up. Patients without baseline testing before surgery were excluded, along with any patients missing 2 consecutive testing trials.

The mean overall DMA and DMA scores in each plane of motion, along with the total mean time on the platform, were calculated for each trial of testing. Repeated-measures analysis of variance was utilized to compare differences in mean and individual DMA scores, along with the total mean time on the platform, at each time point with the prior trial of testing (ie, 3-month trial compared with immediately preoperative trial, 12-month trial compared with 9-month trial, etc). Statistical significance was set at a $P$ value $<.05$. All statistical analyses were performed utilizing SPSS (Version 23; IBM Corp) statistical software.

## RESULTS

Of a total of 71 patients, 44 patients (28 women, 16 men) with a mean age of 19.7 ± 6.2 years completed the study protocol. Of the 27 patients excluded, 17 patients were lost to follow-up or missed 2 consecutive tests, 7 patients sustained ACL retears, 2 had meniscal tears in the operative knee, and 1 patient experienced a contralateral ACL tear. A total of 86% (n = 38) of the patients underwent ACLR using a bone–patellar tendon–bone autograft, 11% (n = 5) were treated using a hamstring autograft, and 2% (n = 1) were treated using hamstring allograft.

Overall, the mean DMA score significantly improved (decreased) with each successive testing trial out to 12 months after surgery (Table 1 and Figure 2). Continued improvement in the overall mean DMA score was appreciated from the 12- to 24-month time points. The length of time that patients remained on the platform increased significantly when compared with the previous trial at the 3-, 6-, and 24-month time points.

Analysis of the mean DMA scores based on individual translational plane of motion (Figure 3) demonstrated that

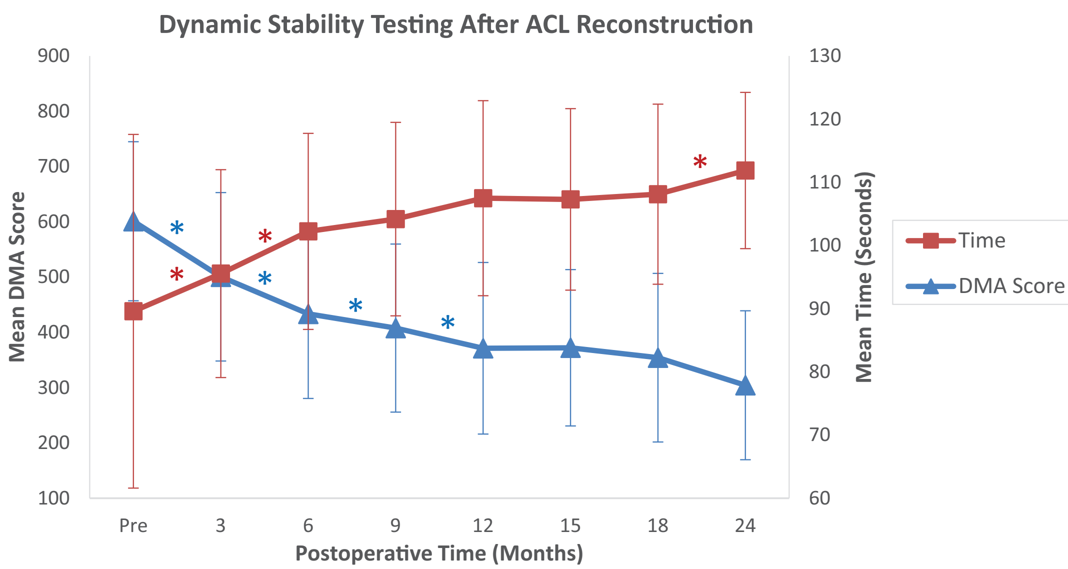


**Figure 2.** Overall dynamic postural stability based on dynamic motion analysis score over 24 months. Error bars represent SD. *Statistically significant improvement compared with prior dynamic motion analysis (DMA) score/time trial. ACL, anterior cruciate ligament.

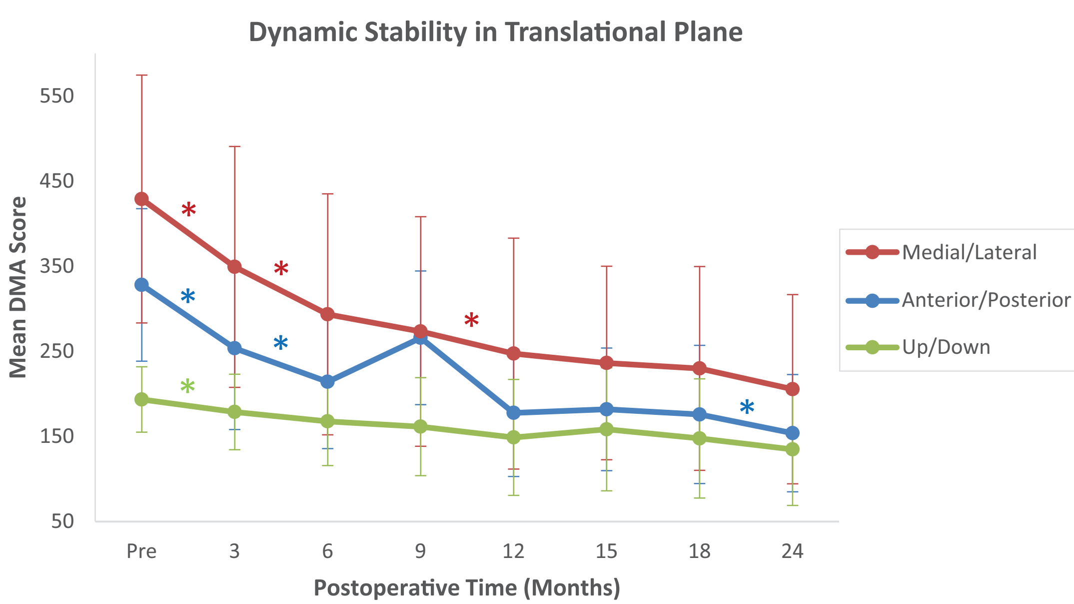


**Figure 3.** Plane-specific dynamic stability up to 24 months postoperatively in the translational planes. Error bars represent SD. *Statistically significant improvement compared with prior dynamic motion analysis (DMA) score/time trial.

stability in all translational planes improved at 3 months after surgery, with significant improvement in the medial/lateral and anterior/posterior planes out to 6 months. Incremental improvement was noted overall in all 3 translation planes out to 24 months, with significant improvement from 18 to 24 months in anterior/posterior stability.

The mean DMA scores in rotational planes of motion (Figure 4) showed that stability in the flexion/extension and internal/external rotational planes declined slightly at 3 months after surgery compared with baseline and then stabilized. Left/right measurements remained stable during the study period.

## DISCUSSION

The main findings from this investigation were that after ACLR, patients demonstrated significant improvements

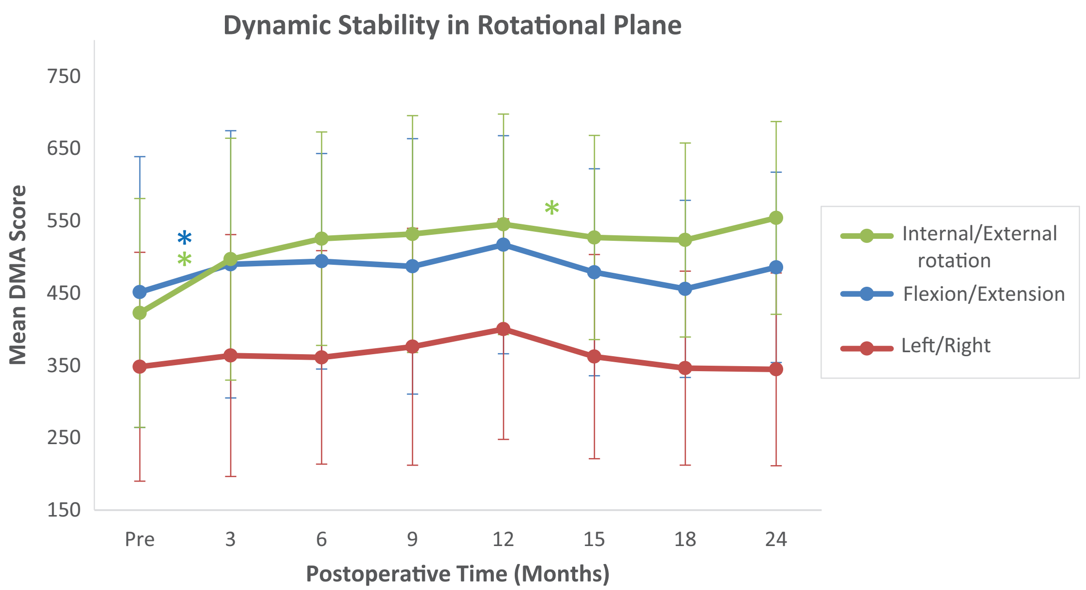


**Figure 4.** Plane-specific dynamic stability up to 24 months postoperatively in the rotational planes. Error bars represent SD. *Statistically significant improvement compared with prior dynamic motion analysis (DMA) score/time trial.

with each consecutive trial measuring dynamic postural stability based on DMA score to 12 months, with improved stability observed out to 24 months after surgery. When analyzing dynamic stability based on planes of motion, we appreciated the most notable improvements in the medial/lateral and anterior/posterior planes, with regression in internal/external rotation and flexion/extension stability when compared with values obtained immediately before surgery.

Prior investigations quantifying the timing of regaining postural stability in patients after ACLR have reported variable outcomes. Angoules et al[3] examined knee proprioception utilizing joint position sense and time threshold to detection of passive motion at 3, 6, and 12 months in 40 patients undergoing ACLR using either hamstring autograft or bone–patellar tendon–bone autograft. While no statistical difference was found in these measures between grafts, the authors reported that knee proprioception reached a maximum by 6 months, with no further improvement out to 12 months. Meanwhile, Bartels et al[6] evaluated postural regulation and stability before and after ACLR at 6 weeks, 12 weeks, 6 months, 1 year, and 2 years after ACLR in 30 patients (mean age, 32.0 ± 12.2 years) using the Interactive Balance System. The authors reported significant longitudinal improvement in postural stability at 2 years postoperatively when compared with preoperative values, with continued improvements in postural stability appreciated up to 1 year postoperatively. Furthermore, prior investigations have reported the time to achieve baseline joint health and function after ACLR to occur approximately 2 years after surgery, with patients remaining at high risk for repeat ACL rupture during the first year after surgery, leading to controversy regarding optimal return-to-sports timing.[31,34,44] As such, further investigations evaluating changes in postural stability after ACLR on return-to-sports timing utilizing comparable methodology are warranted to better understand the clinical implications of dynamic postural stability testing.

We found that dynamic postural stability demonstrated the greatest improvement in the medial/lateral and anterior/posterior planes. The lack of comparable improvement in rotational planes of motion may be secondary to the damage and loss of native ACL mechanoreceptors, contributing to the delayed recovery of afferent feedback and the stabilizing reflexes necessary to restore the more complex movements inherent to rotational motion compared with translational planes.[19,20,22] Moreover, compensatory neuromuscular patterns, which may develop during rehabilitation, could result in improved postural stability in the less complex, translational planes of motion.[1]

While the exact time frame required to regain preoperative neuromuscular control in the operative knee is difficult to determine largely because of the inability to assess postural stability at baseline before injury, the return of postural stability may be related to graft healing. Namely, during the healing process, changes in vascularity, cellularity, and extracellular matrix transform graft characteristics into properties similar to those of an intact ACL,[13,39,43] with full restoration of biologic properties reported to be an ongoing process beyond 12 months after ACLR.[42] While the concentration of mechanoreceptors lost within the ACL after rupture remains unknown, Sonnery-Cottet et al[41] reported that in 26 ACL remnants harvested from patients with partial tears, histologic analysis detected the presence of free nerve endings, along with Golgi or Ruffini corpuscles, in 41% of the specimens. Sha et al[40] evaluated the concentration of mechanoreceptors in ACL tibial remnants based on time from injury to surgery in 60 patients, reporting no significant difference in the number of mechanoreceptors based on injury duration, with Ruffini-like corpuscles being the primary mechanoreceptor. During ACLR, the benefit of retaining native mechanoreceptor via maintenance of remnant ACL tissue as a source of potential improvement in graft reinnervation or preservation of proprioceptive function remains unclear.[31,40] As such, future studies evaluating the cellular and biologic mechanisms responsible for reestablishing the proprioceptive control within the knee based on ACL healing are warranted to determine the timing of restoration of dynamic postural stability.

Prior investigations examining dynamic postural stability and proprioception after ACLR have primarily quantified displacement based on changes in foot position using a force plate.[3,28,35,46] However, assessment of the center of mass has been proposed to yield improved assessment of postural stability when compared with lower leg movements.[4] Namely, Zazulak et al[45] prospectively evaluated 277 collegiate athletes for predictors of knee injury based on trunk displacement after a sudden force release. The authors reported that in 25 athletes sustaining a knee injury over a 36-month period, lateral displacement of the trunk was found to be the best predictor of knee ligament injury.

Brophy et al[10] assessed differences in dynamic postural stability between 79 male and 72 female healthy adolescent controls by calculating a DMA score utilizing the PROPRIO 5000. Boys were found to remain on the platform significantly longer than girls (98 ± 14 vs 94 ± 13 seconds, respectively; $P = .04$), with girls possessing less dynamic postural stability in coronal plane translation (323 ± 126 vs 365 ± 128, respectively; $P = .04$) and rotational stability (318 ± 82 vs 403 ± 153, respectively; $P = .0002$). As women have been shown to possess weaker hip abductors compared with men,[9] landing with greater hip abduction and external rotation abduction moments,[14] evaluation of the center of mass and trunk movement appears to offer a better overall evaluation of dynamic postural stability after ACLR, especially in women. However, further studies are required to validate use of the PROPRIO 5000 in quantifying postural stability during rehabilitation, along with the ability of testing to assess appropriate return to sports and potential future injury risk.

## Limitations

This study is not without limitations. In evaluating dynamic postural stability, this investigation focused on movements of the center of mass; however, postural stability has been shown to require a complex integration of multiple sensorimotor parameters, including the peripheral-vestibular system, somatosensory system, cerebellar system, and visual and nigrostriatal system.[6,7] Moreover, because of the strong interactions between these subsystems, differentiating the relative contribution of each system to dynamic postural stability is beyond the scope of the current investigation.[7] No intrarater reliability testing during measurements was performed. Reasons for the absence of test data at certain time points during patient follow-up were not explicitly recorded.

In addition, owing to inconsistent methodologies in testing postural stability after ACLR, with multiple studies evaluating displacement of the platform in patients standing on a single limb,[11,26,30,32] as opposed to the center of mass, the ability to compare outcomes with other investigations is limited. Furthermore, measuring dynamic postural stability based on the center of mass does not allow for measurement of limb asymmetry. While single-limb testing for dynamic postural stability would be worth considering in a prospective assessment of injury risk in a population with intact ACLs, there are several reasons why a 2-leg stance is appropriate and perhaps optimal to single-leg testing in an already injured population. First, the majority of activities, sports and otherwise, are performed on 2 legs. Therefore, understanding the 2-leg stance is a clinically relevant and important parameter to measure. Second, none of the included patients had any limitations of the contralateral lower extremity, which could confound the findings. Third, we do not have equipoise assessing single-leg stability of a lower extremity after ACL injury or in the early phase of recovery given the risk for (re)injury. While that risk is present in the 2-leg stance, it is lower when compared with single-leg stance testing.

Recovery of knee stability after ACLR depends on both appropriate surgical reconstruction and the performance of a rehabilitation program focused on regaining proprioceptive control of the knee.[30] While all patients were provided with a standardized rehabilitation protocol, therapy was not performed at a single location under our care, creating the potential that protocols may not have been followed as precisely as prescribed. As patients were not identified and enrolled in the study until after injury, we are unable to determine if dynamic postural stability returned to preinjury levels by 24 months after ACLR.

Moreover, no control group of patients without ACL injury was enrolled to allow for comparative analysis. Because of the novelty of the study methodology utilizing the PROPRIO 5000, no comparable investigation was available to allow for performance of a reliable power analysis to determine a necessary sample size. No assessment of PROPRIO data with other commonly utilized tests during ACLR rehabilitation was performed. Because of the small sample size, no evaluation of difference in DMA score was performed based on graft type. The large standard deviations are likely a result of differences in patient health and strength after ACLR, as well as the high sensitivity and accuracy of the movement sensor. Patients with chondral lesions were excluded from this study because of the potential to confound the analysis, representing an area of interest for future investigation. Before and after testing, measures of patient strength, range of motion, and current functional level were not recorded. Patients who sustained repeat ACL tears or any other subsequent injury during the study period were not included in this cohort. Last, return-to-sports timing, as well as the incidence of repeat ACL injury or any other injuries in patients included within the study, was not examined. Future investigations are warranted to better understand the correlation between dynamic postural stability, as measured using the

PROPRIO 5000, to identify readiness to return to sports and the risk of new or repeat injury.

## CONCLUSION

Overall dynamic postural stability significantly improved up to 12 months after ACLR. Improvement in postural stability occurred primarily in the medial/lateral and anterior/posterior planes of motion, with initial decreases in the flexion/extension and internal/external rotational planes of motion.

## REFERENCES


1. Akbari A, Ghiasi F, Mir M, Hosseinifar M. The effects of balance training on static and dynamic postural stability indices after acute ACL reconstruction. *Glob J Health Sci*. 2015;8(4):68-81.
2. Anders JO, Venbrocks RA, Weinberg M. Proprioceptive skills and functional outcome after anterior cruciate ligament reconstruction with a bone-tendon-bone graft. *Int Orthop*. 2008;32(5):627-633.
3. Angoules AG, Mavrogenis AF, Dimitriou R, et al. Knee proprioception following ACL reconstruction: a prospective trial comparing hamstrings with bone–patellar tendon–bone autograft. *Knee*. 2011;18(2):76-82.
4. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med*. 1995;23(6):694-701.
5. Barrack RL, Skinner HB, Buckley SL. Proprioception in the anterior cruciate deficient knee. *Am J Sports Med*. 1989;17(1):1-6.
6. Bartels T, Brehme K, Pyschik M, et al. Postural stability and regulation before and after anterior cruciate ligament reconstruction—a two years longitudinal study. *Phys Ther Sport*. 2019;38:49-58.
7. Bartels T, Brehme K, Pyschik M, et al. Pre- and postoperative postural regulation following anterior cruciate ligament reconstruction. *J Exerc Rehabil*. 2018;14(1):143-151.
8. Bonfim TR, Jansen Paccola CA, Barela JA. Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. *Arch Phys Med Rehabil*. 2003;84(8):1217-1223.
9. Broglio SP, Sosnoff JJ, Rosengren KS, McShane K. A comparison of balance performance: computerized dynamic posturography and a random motion platform. *Arch Phys Med Rehabil*. 2009;90(1):145-150.
10. Brophy RH, Staples JR, Motley J, et al. Young females exhibit decreased coronal plane postural stability compared to young males. *HSS J*. 2016;12(1):26-31.
11. Davids K, Kingsbury D, George K, O'Connell M, Stock D. Interacting constraints and the emergence of postural behavior in ACL-deficient subjects. *J Mot Behav*. 1999;31(4):358-366.
12. Diermann N, Schumacher T, Schanz S, et al. Rotational instability of the knee: internal tibial rotation under a simulated pivot shift test. *Arch Orthop Trauma Surg*. 2009;129(3):353-358.
13. Falconiero RP, DiStefano VJ, Cook TM. Revascularization and ligamentization of autogenous anterior cruciate ligament grafts in humans. *Arthroscopy*. 1998;14(2):197-205.
14. Ford KR, Shapiro R, Myer GD, Van Den Bogert AJ, Hewett TE. Longitudinal sex differences during landing in knee abduction in young athletes. *Med Sci Sports Exerc*. 2010;42(10):1923-1931.
15. Frank CB, Jackson DW. The science of reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am*. 1997;79(10):1556-1576.
16. Fremerey RW, Lobenhoffer P, Zeichen J, et al. Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. *J Bone Joint Surg Br*. 2000;82(6):801-806.
17. Friemert B, Franke S, Gollhofer A, Claes L, Faist M. Group I afferent pathway contributes to functional knee stability. *J Neurophysiol*. 2010;103(2):616-622.
18. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes, part 2: a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med*. 2006;34(3):490-498.
19. Kapreli E, Athanasopoulos S. The anterior cruciate ligament deficiency as a model of brain plasticity. *Med Hypotheses*. 2006;67(3):645-650.
20. Konishi YU. ACL repair might induce further abnormality of gamma loop in the intact side of the quadriceps femoris. *Int J Sports Med*. 2011;32(4):292-296.
21. Larkin B, Nyazee H, Motley J, et al. Hip resurfacing does not improve proprioception compared with THA. *Clin Orthop Relat Res*. 2014;472(2):555-561.
22. Lehmann T, Paschen L, Baumeister J. Single-leg assessment of postural stability after anterior cruciate ligament injury: a systematic review and meta-analysis. *Sports Med Open*. 2017;3(1):32.
23. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med*. 1997;25(1):130-137.
24. Logitech Inc. *3D Mouse & Head Tracker: Technical Reference Manual*. Fakespace Inc; 1992.
25. Louer CR, Boone SL, Guthrie AK, et al. Postural stability in older adults with a distal radial fracture. *J Bone Joint Surg Am*. 2016;98(14):1176-1182.
26. Lysholm M, Ledin T, Odkvist LM, Good L. Postural control—a comparison between patients with chronic anterior cruciate ligament insufficiency and healthy individuals. *Scand J Med Sci Sports*. 1998;8(6):432-438.
27. MacDonald PB, Hedden D, Pacin O, Sutherland K. Proprioception in anterior cruciate ligament-deficient and reconstructed knees. *Am J Sports Med*. 1996;24(6):774-778.
28. Mattacola CG, Perrin DH, Gansneder BM, et al. Strength, functional outcome, and postural stability after anterior cruciate ligament reconstruction. *J Athl Train*. 2002;37(3):262-268.
29. Moezy A, Olyaei G, Hadian M, Razi M, Faghihzadeh S. A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after anterior cruciate ligament reconstruction. *Br J Sports Med*. 2008;42(5):373-378.
30. Mohammadi F, Salavati M, Akhbari B, et al. Static and dynamic postural control in competitive athletes after anterior cruciate ligament reconstruction and controls. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(8):1603-1610.
31. Nagelli CV, Hewett TE. Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological and functional considerations. *Sports Med*. 2017;47(2):221-232.
32. Okuda K, Abe N, Katayama Y, et al. Effect of vision on postural sway in anterior cruciate ligament injured knees. *J Orthop Sci*. 2005;10(3):277-283.
33. Papalia R, Franceschi F, Tecame A, et al. Anterior cruciate ligament reconstruction and return to sport activity: postural control as the key to success. *Int Orthop*. 2015;39(3):527-534.
34. Paterno MV, Rauh MJ, Schmitt LC, et al. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med*. 2014;42(7):1567-1573.
35. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Hewett TE. Altered postural sway persists after anterior cruciate ligament reconstruction and return to sport. *Gait Posture*. 2013;38(1):136-140.
36. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968-1978.
37. Relph N, Herrington L, Tyson S. The effects of ACL injury on knee proprioception: a meta-analysis. *Physiotherapy*. 2014;100(3):187-195.
38. Risberg MA, Holm I, Myklebust G, Engebretsen L. Neuromuscular training versus strength training during first 6 months after anterior cruciate ligament reconstruction: a randomized clinical trial. *Phys Ther*. 2007;87(6):737-750.

39. Rougraff B, Shelbourne KD, Gerth PK, Warner J. Arthroscopic and histologic analysis of human patellar tendon autografts used for anterior cruciate ligament reconstruction. *Am J Sports Med*. 1993;21(2): 277-284.
40. Sha L, Xie G, Zhao S, Zhao J. A morphologic and quantitative comparison of mechanoreceptors in the tibial remnants of the ruptured human anterior cruciate ligament. *Medicine*. 2017;96(5):e6081.
41. Sonnery-Cottet B, Bazille C, Hulet C, et al. Histological features of the ACL remnant in partial tears. *Knee*. 2014;21(6):1009-1013.
42. Staples JR, Schafer KA, Smith MV, et al. Decreased postural control in patients undergoing anterior cruciate ligament reconstruction compared to healthy controls. *J Sport Rehabil*. 2020;29(7):920-925.
43. van Groningen B, van der Steen MC, Janssen DM, et al. Assessment of graft maturity after anterior cruciate ligament reconstruction using autografts: a systematic review of biopsy and magnetic resonance imaging studies. *Arthrosc Sports Med Rehabil*. 2020;2(4):e377-e388.
44. Webster KE, Feller JA, Leigh WB, et al. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2014;42(3): 641-647.
45. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123-1130.
46. Zouita Ben Moussa A, Zouita S, Dziri C, Ben Salah FZ. Single-leg assessment of postural stability and knee functional outcome two years after anterior cruciate ligament reconstruction. *Ann Phys Rehabil Med*. 2009;52(6):475-484.