Anterior Cruciate Ligament Augmentation for Rotational Instability Following Primary Reconstruction With an Accelerated Physical Therapy Protocol

Timothy Carey, DO[1]; David Oliver, MD[2]; Josh Pniewski, DPT[3]; Terry Mueller, DO[2]; and John Bojescul, MD[2]

The purpose of the present study is to present the results of anterior cruciate ligament (ACL) augmentation for patients having rotational instability despite an intact vertical graft in lieu of conventional revision ACL reconstruction. ACL augmentation surgery with a horizontal graft was performed to augment a healed vertical graft on five patients and an accelerated rehabilitation protocol was instituted. Functional outcomes were assessed by the Lower Extremity Functional Scale (LEFS) and the Modified Cincinnati Rating System (MCRS). All patients completed physical therapy within 5 months and were able to return to full military duty without limitation. LEFS and MCRS were significantly improved. ACL augmentation with a horizontal graft provides an excellent alternative to ACL revision reconstruction for patients with an intact vertical graft, allowing an earlier return to duty for military service members. (Journal of Surgical Orthopaedic Advances 22(1):59–65, 2013)

Key words: ACL, anterior cruciate ligament reconstruction, augmentation, double bundle, revision reconstruction, rotational instability

One of the most common procedures in orthopaedic surgery is anterior cruciate ligament reconstruction, with an estimated 60,000 to 75,000 procedures performed annually in the United States alone (1). A cornerstone of orthopaedic surgery is to restore native anatomy. Previous techniques for anterior cruciate ligament reconstruction were less focused on this concept, leading to potential rotational instability (2). One of the most common causes of anterior cruciate ligament reconstruction failure is technical error, accounting for 22% to 79% of failures (3–6). Although technical error also encompasses errors in graft tensioning, graft selection, and failure to recognize other sources of instability, inappropriate tunnel placement is thought to be the most significant technical error (4). During a transtibial technique, the femoral tunnel is dependent on the placement and angle of the tibial tunnel, making anatomic graft placement challenging. The most common result is a tibial tunnel that is too posterior and lateral in the anatomic tibial footprint and a femoral tunnel that is anterior and superior in the anatomic femoral footprint (4, 7, 8). The net effect of these tunnel positions is a vertically oriented graft in the coronal and sagittal planes. These grafts often run from the posterolateral position on the tibia to the anteromedial position on the femur. As noted in previous studies, this creates vertical mismatch (7). Patients regain sagittal stability but continue to complain of rotational instability secondary to the verticality of the graft. On physical examination, these patients will present with a grade I anterior drawer and 1A Lachman test with a positive pivot shift test (9).

Recently described medial portal techniques enable surgeons to better recreate the anterior cruciate ligament anatomy by placing the tibial and femoral tunnels independently (2, 8). The result is a more anatomic graft with improved functional results (2, 8). Surgeons are increasingly utilizing these medial portal techniques over

From [1]Department of Orthopaedic Surgery, Irwin Army Community Hospital, Fort Riley, Kansas; [2]Department of Orthopaedic Surgery, Dwight David Eisenhower Army Medical Center, Fort Gordon, Georgia; [3]Department of Physical Therapy, Dwight David Eisenhower Army Medical Center, Fort Gordon, Georgia. Address correspondence to: David Oliver, MD, Orthopaedic Clinic, Building 300, Dwight David Eisenhower Army Medical Center, Fort Gordon, GA 30905; e-mail: david.oliver9@us.army.mil.

All work was completed at Dwight David Eisenhower Army Medical Center. Clinical encounters were performed in the orthopaedic clinic as well as the outpatient physical therapy clinic.

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nonanatomic transtibial techniques, enabling independent anatomic placement of the femoral and tibial tunnels in the central portion of each footprint.

The clinically failed anterior cruciate ligament reconstruction patient with an intact graft, but with rotational instability, has limited options (10). Revision anterior cruciate ligament reconstructions can be a daunting process for active patients. Revision procedures can involve a preliminary procedure to remove previous hardware and may require bone grafting of the previous tunnels before proceeding with revision anterior cruciate ligament reconstruction (2, 4, 7). Additionally, revision surgery requires patients to undergo a standard physical therapy treatment plan, further delaying the patients' return to their previous level of function (11).

We present a case series of six anterior cruciate ligament augmentation procedures in lieu of primary revision anterior cruciate ligament reconstructions in five active duty United States Army soldiers with clinically failed anterior cruciate ligament reconstructions. We describe a technique for anterior cruciate ligament reconstruction augmentation of the existing anterior cruciate ligament reconstruction coupled with an accelerated physical therapy protocol that is intended to return the soldiers back to duty faster than standard protocols.

Methods

Anterior cruciate ligament augmentations were performed on five active duty service members from April 2011 to January 2012. Institutional review board approval was obtained before data collection. All prior surgeries were done at another institution using the transtibial tunnel technique. Patients who had undergone prior anterior cruciate ligament reconstructions resulting in translational stability but continued rotational instability were selected if they had an intact vertically oriented graft on plain-film radiographs. Rotational instability was assessed clinically using history and a physical examination with a positive pivot shift test (9). Five active duty U.S. Army soldiers (one of them bilateral) were identified as meeting inclusion criteria. Additionally, all patients demonstrated full, active, pain-free, range of motion with no instability to varus or valgus stress at 0° and 30° and negative dial tests at 30° and 90°. Alignment films demonstrated either normal alignment or mild symmetric varus. Radiographs demonstrated anterior cruciate ligament grafts in a nonanatomic, vertical position in the 11 to 1 o'clock position (Fig. 1). One patient in this series demonstrated bilateral rotational instability after undergoing separate primary autograft patellar bone–tendon–bone ligament reconstructions. His surgical augmentation procedures were staged 6 months apart and both augmentation procedures were performed using the same technique.

FIGURE 1 Anteroposterior radiograph of the left knee following anterior cruciate ligament augmentation. Note the more horizontally placed femoral button relative to the prior fixation from the index procedure. The previous button is superior to the augmentation button on this radiograph.

Before surgery the patients completed the Lower Extremity Functional Scale (LEFS) (12) and Modified Cincinnati Rating System (MCRS) (13) to assess functional ability (Tables 1 and 2). The LEFS and MCRS were re-administered 6 months following augmentation. Diagnostic arthroscopy and examination under anesthesia were performed at the initiation of the procedure to verify an intact vertical graft (Figs. 2–4). Using the medial portal technique previously described by Harner et al., a posterior tibialis or semitendinosis tendon allograft was used for augmentation (8). The previous tibial tunnel was avoided by placing the graft more anterior in the tibial footprint as described by Kamath et al. (4) (Figs. 2 and 5). The femoral tunnel was created through an accessory medial portal, placing it centered in the anatomic footprint to slightly posterior (Figs. 3 and 6). The ACL Tightrope (Arthrex, Naples, FL) was used for femoral fixation and the BioComposite Interference Screw (Arthrex, Naples, FL) for tibial fixation. Intraoperatively, all patients were assessed for translational and rotational ligamentous stability and range of motion. Postoperative films were obtained that verified the placement of the augmentation graft. Following surgery all patients began an accelerated anterior cruciate ligament augmentation protocol (Table 3). Data analysis was performed using the paired *t* test for the MCRS and LEFS data points.

On completion of the accelerated physical therapy protocol, all service members were returned to full duty to include availability for deployment on combat tours and full participation in unit level physical training. No profiles were provided to any of the soldiers who

TABLE 1 **Preoperative and postoperative Lower Extremity Functional Scale**

Patient Number	Side	Age	Gender	Preoperative LEFS Score	Postoperative LEFS Score	Change in LEFS Score
1	R	30	M	24	79	55
2	L	22	M	67	80	13
3	L	39	M	27	55	28
4	R	35	M	18	78	60
4	L	35	M	20	73	53
5	L	43	F	28	78	50
				Mean: 30.7, SD: 18.2	Mean: 73.8, SD: 9.5	Mean:43.2, SD 18.5

Note: The table shows the preoperative and postoperative Lower Extremity Functional Scale (LEFS) scores. The mean and standard deviation (SD) are provided for each column. Analysis by paired t test with $t = 5.72$, 5 degrees of freedom. p Value $< .002$; 99% confidence interval 12.75–73.57.

TABLE 2 **Preoperative and postoperative Modified Cincinnati Rating System**

Patient Number	Side	Age	Gender	Preoperative MCRS Score	Postoperative MCRS Score	Change in MCRS Score
1	R	30	M	27	97	70
2	L	22	M	58	100	42
3	L	39	M	38	84	46
4	R	35	M	38	100	62
4	L	35	M	26	100	74
5	L	43	F	43	100	57
				Mean: 38.3, SD: 11.7	Mean: 96.8, SD: 6.4	Mean: 58.5, SD: 12.8

Note: The table shows the preoperative and postoperative Modified Cincinnati Rating System (MCRS) scores. The mean and standard deviation (SD) are provided for each column. Analysis performed by paired t test with $t = 11.220$, 5 degrees of freedom. p Value $< .0005$; 99% confidence interval of 37.48–79.52.

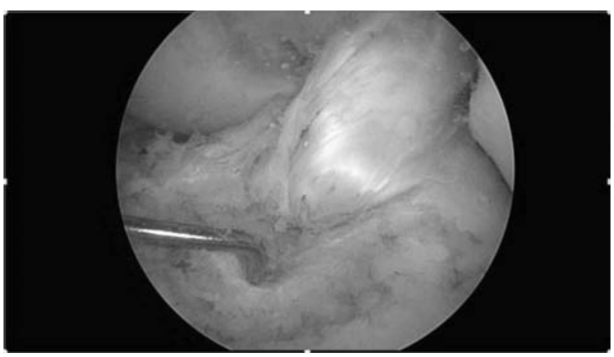

FIGURE 2 Left knee arthroscopy with prior anterior cruciate ligament graft that is intact but vertical and posterior lateral in the anatomic footprint on the tibia. The probe tip in the image illustrates a more anterior medial tunnel placement.

FIGURE 3 Left knee arthroscopy demonstrating a prior anterior cruciate ligament reconstruction with a vertical graft. Here the probe is pointing to the proposed augmentation femoral tunnel placement with the knee in hyperflexion.

underwent anterior cruciate ligament augmentation after completion of the accelerated physical therapy protocol, which was completed within 6 months in all cases.

Physical Therapy

The anterior cruciate ligament rehabilitation protocol at our institution consists of specific exercises that keep in mind the healing process involved with anterior cruciate ligament reconstruction (Table 3) (14, 15). The early progressive introduction of plyometric and propioceptive weight bearing has been demonstrated to expedite the recovery of knee mechanoreceptors and return to preinjury activity (11, 16). Based on these concepts, and on the established protocol parameters, a revised protocol was designed and implemented for anterior cruciate ligament augmentation (Table 3). Postoperative therapy for anterior cruciate ligament reconstruction considers graft

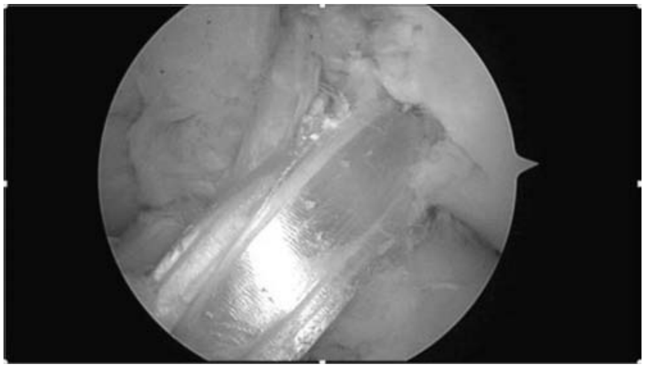

FIGURE 4 Left knee arthroscopy demonstrating an augmentation graft in the foreground with prior vertical graft in the background.

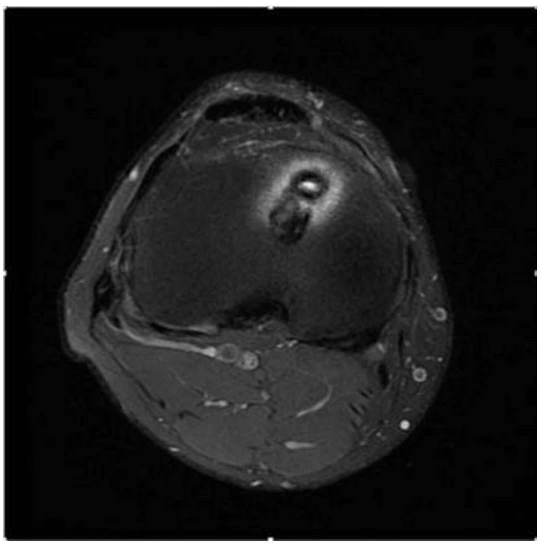

FIGURE 5 Axial MRI of the knee demonstrating the initial posterior lateral placement of the tibial tunnel and the more anteromedially placed augmentation graft.

healing before advancement of activity to decrease the risk for reinjury or graft failure. Following augmentation procedures, the concerns of reinjury are tempered by the fact that anterior translation is stabilized by the previously placed vertical graft and only rotational instability requires initial avoidance (17, 18). Discharge criterion was successful performance of equal single-leg broad jump test, equal single-leg triple hop test, and equal single-leg hop test. On achieving the discharge criterion, service members were released to full duty without limitation. Service members were allowed full participation in unit-level physical training and were cleared for deployment.

Results

Following anterior cruciate ligament augmentation, all patients demonstrated translational and rotational stability.

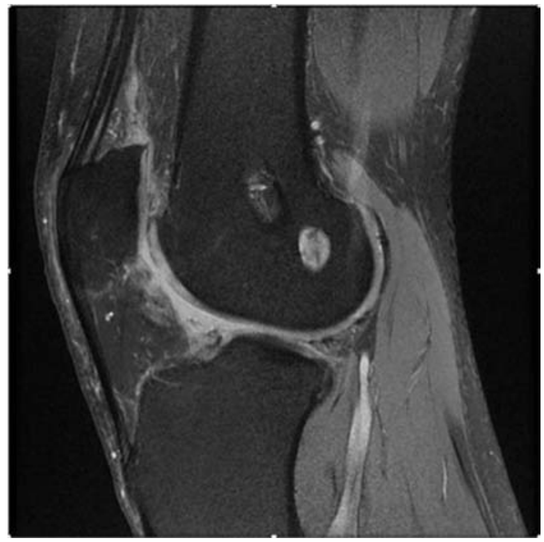

FIGURE 6 Sagittal MRI of the knee demonstrating anterior placement of the original graft and the posterior placement of the augmentation graft.

Figures 5 and 6 demonstrate the horizontal position of the anterior cruciate ligament augmentation relative to the initial graft on 1-year follow-up magnetic resonance images (MRIs) and plain-film radiographs (Figs. 5 and 6). At the initial postoperative visit, patients had near full passive range of motion and the ability to perform a straight-leg raise (SLR) for 10 repetitions with no extension lag. At 5 months, patients were able to complete the accelerated physical therapy protocol (Table 3). At 6 months, the LEFS and MCRS were repeated demonstrating return to full knee function (Tables 1 and 2). Lower Extremity Functional Scale scores improved from a mean of 30.7 (SD, 18.2) to a mean of 73.8 (SD, 9.5), p value $< .002$ with a 99% confidence interval from 12.75 to 73.57. Modified Cincinnati Rating System scores of a mean 38.3 (SD, 11.7) preoperatively, improved to 96.8 (SD, 6.4), p value $< .0005$ with 99% confidence interval from 37.48 to 79.52. All patients had a Modified Cincinnati Rating System score greater than 90, except one patient who improved from a preoperative score of 38 to a postoperative score of 84. The mean improvement in Lower Extremity Functional Scale score was 43.2 (SD, 18.5). Mean improvement in Modified Cincinnati Rating System score was 58.5 (SD, 12.8). No service members required a work-limiting profile on completion of the physical therapy protocol. Physical examination at follow-up revealed a negative pivot shift test, negative anterior drawer, and stable Lachman test in all patients. All service members were able to pass the standard Army Physical Fitness Test to include the 2-mile run and were able to participate fully with their unit's physical fitness training program. Review of electronic medical records and the Army computerized profile system just before manuscript

TABLE 3 Protocol progression for accelerated anterior cruciate ligament augmentation versus Dwight David Eisenhower Army Medical Center anterior cruciate ligament reconstruction

Phase	Accelerated Anterior Cruciate Ligament Augmentation	Standard Anterior Cruciate Ligament Reconstruction
1 (0–2 weeks)	-Hinged postop knee brace open to 90° - Crutches and weight bear as tolerated (crutches discontinued at 1 week postop)	-Hinged postop knee brace locked in extension with weight bear as tolerated using crutches as needed -Initiate 4-way SLR in brace/isometrics/active range of motion
2 (2–6 weeks)	-Brace discharged and crutches -Opened chain quadriceps strengthening → closed chain -Phase 1 proprioception/lunge phase 1 plyometric phase 1	-Open brace to available range of motion once SLR performed without extensor lag and discharge crutch use -Progress to resisted 4-way hip/close chain activity -Phase 1 proprioceptive activity →SLS -Treadmill walking with brace
3 (6–8 weeks)	-Progressive walk to jog program initiated -Phase 2 transition to phase 3 Proprioception/plyometrics	-Discontinue brace 6 weeks postop -Progress treadmill walking to include retro walking -Progress proprioception phase 1 to include dynamic training on stable surface/lunge
4 (2–3 months)	-Squat jump, pattern jumping -Phase 1 direction change ladder drills	-Elliptical/bike/Stairmaster -SL close chain weight machine progression/lunge progression -Progress proprioception phase to include dynamic training on unstable surfaces
5 (4–5 months)	Single-leg advanced plyometric and shuttle high-speed direction change drills	-Initiate walk to jog program -Introduce plyometric training
6 (6–8 months)	Patient discharged at 5 months	Level 2–3 plyometrics (box jumps/pattern jumping SL) Directional running
Discharge criteria	Equal single-leg broad jump test, equal single-leg triple hop test, and equal single-leg hop test	Equal single-leg broad jump test, equal single-leg triple hop test, and equal single-leg hop test.

submission (August 2012) provided an average follow-up of 13 (range, 9–17) months from the date of surgery. Follow-up at that time revealed that all service members were still on active duty and maintained a deployable status. At the time of submission for publication, only one service member has not reached at least 1 year from the date of surgery. That patient is currently 9 months from the date of surgery and does not have a profile or any physical limitations.

Discussion

Restoring the native anatomy is a cornerstone of orthopaedic surgery. The anterior cruciate ligament is a double-bundle structure consisting of an anterior medial and a posterior lateral bundle. The predominant blood supply to both bundles is from the middle geniculate artery with minor contributions from the medial and lateral geniculate arteries via the anterior fat pad (19). The two bundles of the anterior cruciate ligament are named according to their origin and insertions on the tibia and femur (20). The anterior medial bundle is tight in flexion and the posterior lateral bundle is tight in extension. Additionally, the posterior lateral bundle contributes to rotational stability (7, 21). Transtibial tunnel anterior cruciate ligament surgeries tend to be located mostly in the posterior lateral part of the tibial footprint and the anterior medial portion of the femoral footprint. The result of these tunnels is a vertical mismatched graft in both the coronal and sagittal planes (7). If the graft heals, the result is a good to excellent outcome in most patients (7). However, in the subset that is unable to return to sport or reach previous activity level, a more advantageous or anatomic graft placement may improve their result (1).

With the advent of the medial portal techniques and resurgence of outside-in techniques, double-bundle and single anatomic anterior cruciate ligament reconstructions have become possible. These tunnels can be placed independently and the tunnels drilled in the appropriate position in the anatomic footprint of the anterior cruciate ligament. Gadikota et al. (22) has shown that larger posterolateral bundle coverage is achieved by the anterior medial portal and outside-in techniques than by the transtibial tunnel technique. “Furthermore, the centers of the tunnels created by the accessory medial portal and outside-in techniques were closer to the native anterior cruciate ligament footprint center than the center of the transtibial technique tunnel” (22).

Revision anterior cruciate ligament reconstruction is the accepted treatment to prevent instability when a primary graft has ruptured and failed. However, many surgeons will be presented with the dilemma of what to do for patients with instability if the graft is intact on magnetic resonance imaging. This is especially true if the patient is translationally stable in the sagittal plane and tunnels are in the traditionally accepted position. A potential treatment in this scenario is removal of the graft and associated implants, with possible bone grafting of the tunnels and future procedure for revision anterior cruciate ligament reconstruction. However, a graft placed in the same position will be subject to failure as well. Anatomic double-bundle reconstructions have proven superior in terms of laxity measurements (7, 23). However, we do not know the best course of action in those anterior cruciate ligament patients with an intact vertically mismatched graft with rotational instability and the inability to achieve their preinjury activity level.

A treatment for this scenario was first proposed by Brophy et al. in 2006 (1). They were the first to augment the prior intact anterior cruciate ligament reconstruction with a new graft placed in the anterior portion of the tibia footprint and slightly more laterally in the femoral footprint than the traditional placement in a transtibial technique. They reported on three patients, but did not utilize outcome measures. Additionally, the technique used in their series did not allow for independent tunnel placement, and therefore the posterior lateral portion of the femoral footprint was left unfilled. Our technique relies on a horizontal mismatched graft (i.e., a graft placed in the anterior medial part of the tibial footprint with femoral placement of the graft in the central to posterior lateral portion of the femoral footprint). Brophy and Pearle have shown in recent cadaveric studies with computer navigation that the horizontal position of the graft (anterior medial tibia footprint to posterior lateral femoral footprint) is superior to all other single-bundle placements of the graft (7). They further state that this graft position has excellent obliquity and acceptable isometry. It also appears to be the best location to resist internal rotation and translational forces (1).

Revision anterior cruciate ligament reconstruction patient outcomes are inferior to primary anterior cruciate ligament reconstruction (3). There is currently a paucity of large high-quality studies comparing primary and revision anterior cruciate ligament reconstruction outcomes. Much of the difficulty is the small number of patients who undergo revision anterior cruciate ligament reconstruction. Because of this, many of the studies are single-institution studies with small sample sizes and various outcome criteria. Despite this limitation, a review article noted an inferior return to normal clinical parameters (sagittal translation, range of motion, pivot shift), decreased patient satisfaction, and increased failure rate when comparing primary anterior cruciate ligament reconstruction and revision anterior cruciate ligament reconstruction (24). The MARS Group is attempting to overcome these limitations by compiling data on more than 400 patients by involving 87 enrolled surgeons at 54 sites (6). However, data compilation and analysis are not yet complete. Additionally, the problem of various outcome measures continues.

Another consideration is the time lost while undergoing revision, particularly a staged revision with bone graft. The time lost is a detriment to a service member's unit as well as potential detriment to the service member's career progression. In contrast, the patients in the present study undergoing anterior cruciate ligament augmentation completed therapy and returned to full activities in 6 months. One patient with bilateral knee anterior cruciate ligament augmentations completed the accelerated rehabilitation protocol for both knees and returned to full active military duty without restriction within 1 year. He was able to engage in combat exercises with a scheduled future deployment. Based on subjective and objective outcomes in this case series, an accelerated rehabilitation protocol was successfully implemented following anterior cruciate ligament augmentation. Like most rehabilitation protocols, individual variance requires consideration during the rehabilitative process, and this protocol may not be appropriate in all cases. However, the potential for reduced rehabilitation time is clear. Successfully implementing a shortened rehabilitation protocol is not only beneficial to the patient but also could have a significantly favorable impact on return to duty for service members. Further study is needed to assess whether the results presented in this case report would be typical for augmentation surgery, and it should be stressed that the accelerated rehabilitation protocol is only advisable in patients who have an intact graft that provides appropriate anterior-posterior translational stability.

Long-term data are needed to determine whether or not this technique has an impact on future development of arthritic change or if there may be any long-term complications of the procedure. It would seem unlikely in comparison to a revision anterior cruciate ligament reconstruction that this procedure would have significant deleterious effects, but this possibility warrants further investigation with a larger sample size. To date there are very few data on anterior cruciate ligament augmentation in the revision setting. No long-term studies were found in the literature.

In summary, the placement of a horizontal graft to augment a prior healed vertical graft produced a stable knee in rotation and translation with return to full activity. Additionally, our case series demonstrates a successfully implemented accelerated rehabilitation protocol. Statistical analysis shows a statistically significant improvement in both functional outcome measures utilized. Our study is limited by a relatively small sample size. Additionally, our study does have limited follow-up. Given the potential benefit to service members and the military as a whole, we felt that it was important to publish our promising results as quickly as possible. Further long-term outcome studies with a larger group of patients will need to be investigated in order to assume that our present results will accurately reflect long-term results in all patients. However, our results are encouraging in this active duty military population.

References

1. Brophy, R. H., Selby, R. M., Altchek, D. W. Anterior cruciate ligament revision: double-bundle augmentation of primary vertical graft. Arthroscopy 22:e681–685, 2006.
2. van Eck, C. F., Schreiber, V. M., Liu, T. T., et al. The anatomic approach to primary, revision and augmentation anterior cruciate ligament reconstruction. Knee Surg. Sports Traumatol. Arthrosc. 18:1154–1163, 2010.
3. Getelman, M. H., Friedman, M. J. Revision anterior cruciate ligament reconstruction surgery. J. Am. Acad. Orthop. Surg. 7:189–198, 1999.
4. Kamath, G. V., Redfern, J. C., Greis, P. E., et al. Revision anterior cruciate ligament reconstruction. Am. J. Sports Med. 39:199–217, 2011.
5. van Eck, C. F., Schkrohowsky, J. G., Working, Z. M., et al. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. Am. J. Sports Med. 40:800–807, 2012.
6. Wright, R. W., Huston, L. J., Spindler, K. P., et al. Descriptive epidemiology of the Multicenter ACL Revision Study (MARS) cohort. Am. J. Sports Med. 38:1979–1986, 2010.
7. Brophy, R. H., Pearle, A. D. Single-bundle anterior cruciate ligament reconstruction: a comparison of conventional, central, and horizontal single-bundle virtual graft positions. Am. J. Sports Med. 37:1317–1323, 2009.
8. Harner, C. D., Honkamp, N. J., Ranawat, A. S. Anteromedial portal technique for creating the anterior cruciate ligament femoral tunnel. Arthroscopy 24:113–115, 2008.
9. Lane, C. G., Warren, R., Pearle, A. D. The pivot shift. J. Am. Acad. Orthop. Surg. 16:679–688, 2008.
10. Beynnon, B. D., Johnson, R. J., Abate, J. A., et al. Treatment of anterior cruciate ligament injuries, part 2. Am. J. Sports Med. 33:1751–1767, 2005.
11. Shelbourne, K. D., Nitz, P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. Am. J. Sports Med. 18:292–299, 1990.
12. Binkley, J. M., Stratford, P. W., Lott, S. A., et al. The Lower Extremity Functional Scale (LEFS): scale development, measurement properties, and clinical application. Phys. Ther. 79:371–383, 1999.
13. Noyes, F. R., Barber, S. D., Mooar, L. A. A rationale for assessing sports activity levels and limitations in knee disorders. Clin. Orthop. Relat. Res. 246:238–249, 1989.
14. Claes, L. E., Cunningham, J. L. Monitoring the mechanical properties of healing bone. Clin. Orthop. Relat. Res. 467:1964–1971, 2009.
15. Kalfas, I. H. Principles of bone healing. Neurosurg. Focus 10:E1, 2001.
16. De Carlo, M. S., McDivitt, R. Rehabilitation of patients following autogenic bone-patellar tendon-bone ACL reconstruction: a 20-year perspective. North Am. J. Sports Phys. Ther. 1:108–123, 2006.
17. Brady, M. F., Bradley, M. P., Fleming, B. C., et al. Effects of initial graft tension on the tibiofemoral compressive forces and joint position after anterior cruciate ligament reconstruction. Am. J. Sports Med. 35:395–403, 2007.
18. Gabriel, M. T., Wong, E. K., Woo, S. L., et al. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. J. Orthop. Res. 22:85–89, 2004.
19. Arnoczky, S. P. Blood supply to the anterior cruciate ligament and supporting structures. Orthop. Clin. North Am. 16:15–28, 1985.
20. Hussein, M., van Eck, C. F., Cretnik, A., et al. Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. Am. J. Sports Med. 40:512–520, 2012.
21. Beynnon, B. D., Johnson, R. J., Abate, J. A., et al. Treatment of anterior cruciate ligament injuries, part I. Am. J. Sports Med. 33:1579–1602, 2005.
22. Gadikota, H. R., Sim, J. A., Hosseini, A., et al. The relationship between femoral tunnels created by the transtibial, anteromedial portal, and outside-in techniques and the anterior cruciate ligament footprint. Am. J. Sports Med. 40:882–888, 2012.
23. Zelle, B. A., Vidal, A. F., Brucker, P. U., et al. Double-bundle reconstruction of the anterior cruciate ligament: anatomic and biomechanical rationale. J. Am. Acad. Orthop. Surg. 15:87–96, 2007.
24. George, M. S., Dunn, W. R., Spindler, K. P. Current concepts review: revision anterior cruciate ligament reconstruction. Am. J. Sports Med. 34:2026–2037, 2006.