Optimal Tibial Tunnel Placement for Medial and Lateral Meniscus Root Repair on the Anteromedial Tibia in the Setting of Anterior and Posterior Cruciate Ligament Reconstruction of the Knee

Safa Gursoy,* MD, PhD, Allison K. Perry,* BS, Alex Brady,† PhD, Navya Dandu,* BS, Harsh Singh,* BA, Amar S. Vadhera,* BS, Adam B. Yanke,* MD, PhD, Robert F. LaPrade,‡ MD, PhD, and Jorge Chahla,*§ MD, PhD
Investigation performed at Midwest Orthopaedics at Rush, Chicago, Illinois, USA

Background: Although the risk of tibial tunnel convergence in the setting of multiligamentous reconstruction has been reported in the literature, the risk of tunnel convergence in the setting of posterior cruciate ligament (PCL), anterior cruciate ligament (ACL) reconstruction and medial and lateral meniscus root repair has not been defined.

Purpose: To examine the risk of tunnel convergence and to determine optimal tunnel placement for ACL and PCL reconstruction performed in conjunction with posterior medial and lateral meniscus root repairs on the anteromedial proximal tibia.

Study Design: Descriptive laboratory study.

Methods: Three-dimensional (3D) tibial models were created using computed tomography scans of 20 cadaveric specimens. After determining optimal tunnel entry and exit points for ACL and PCL reconstructions, and medial and lateral meniscus root reattachment to the anatomic footprints, we used image processing software to create root tunnels over the anteromedial tibia on the tibial models. ACL and PCL tunnels were kept constant. The meniscus root repair tunnels were then reoriented to match the angle of the ACL tunnel, making both tunnels parallel in the sagittal plane. Tunnel convergence risk was analyzed by identifying the shortest 3D distance between tunnel axes and subtracting the radius of each tunnel from this distance for single- and double-tunnel repair techniques in both case scenarios.

Results: All specimens demonstrated convergence between the ACL and lateral meniscus root tunnels when the root tunnel's entry was created proximal to the ACL tunnel's entry for single- and double-tunnel techniques, but no convergence was seen between these tunnels using the parallel orientation in the sagittal plane. There were no cases of convergence between the ACL and medial meniscus root tunnels in any of the configurations. The greatest distance between the ACL and medial meniscus root tunnels was achieved using the single-tunnel technique in parallel orientation (12.1 ± 2.8 mm). There were no cases of convergence between the PCL and medial meniscus root tunnels in the original orientation; however, 2 of 20 specimens demonstrated convergence using the parallel orientation with the double-tunnel technique, and there were no cases of convergence using the single-tunnel technique. The PCL and lateral meniscus root tunnels did not demonstrate convergence in any configuration.

Conclusion: There was a high risk of convergence between ACL and posterior meniscus root tunnels when all the tunnels were created on the anteromedial tibia. Reorienting meniscus root tunnels parallel to ACL tunnels may help reduce this risk. There is increased risk of tunnel convergence with root repairs in cases of bicruciate reconstructions, and therefore a double-tunnel root repair technique should be used with caution.

Clinical Relevance: To avoid tibial tunnel convergence when performing ACL and PCL reconstruction with medial and lateral meniscus root repair, surgeons should reorient the meniscus root repair tunnels to be parallel on the sagittal plane to the ACL tunnel to decrease the risk of convergence. In cases of bicruciate ligament reconstruction, use of the double-tunnel technique requires caution to avoid convergence risk with the PCL tunnel.

Keywords: root repair; cruciate reconstruction; knee; tibia; meniscus root; tunnel convergence

The American Journal of Sports Medicine
1–8
DOI: 10.1177/03635465221074312

Tears of the meniscus root have been estimated to account for 10% to 21% of all meniscal tears, affecting 100,000 patients annually.[6] Posterior lateral meniscus root tears

(PLMRTs) are particularly common in association with anterior cruciate ligament (ACL) injuries.[9,19] Posterior medial meniscus root tears are more commonly degenerative in nature but may be seen in the setting of multiligament knee injuries and revision ACL reconstruction.[8,10,20] Kim et al[13] reported posterior cruciate ligament (PCL) injury in 6 of 10 cases in which ligament injury was accompanied by a medial meniscus root tear. Meniscus root repair is often recommended in patients without severe osteoarthritis to prevent joint overloading and restore biomechanics.[3,20] Repair is often performed using a transtibial pull-out method involving reaming of single[23] or double[5,17] tunnels in the tibia, as it allows for anatomic root reduction.

Because of the limited bone mass in the proximal tibia, there is risk for root tunnel tibial convergence, which can compromise graft integrity and cause damage to fixation devices with concurrent cruciate ligament reconstructions. Although previous studies have described different surgical techniques for posterior meniscus root repairs,[5,17,23] there are limited data regarding the risk of tunnel convergence in the setting of concomitant ACL and PCL injuries in those studies. Moatshe et al[21] described intertunnel relationships in the setting of multiligament knee injuries. The authors reported that the tunnel orientation of the posterior oblique ligament (POL) and the superficial medial collateral ligament (sMCL) should be adjusted to avoid convergence with the PCL tunnel. However, the evidence on risk of tunnel convergence and ideal angles to prevent tunnel convergence in the setting of ACL and PCL reconstruction with concomitant posterior meniscus root repairs is limited. As such, an evidence-based method to investigate the risk of tunnel convergence and optimal root repair tunnel placement for ACL and PCL reconstruction performed in conjunction with posterior meniscus root tears is warranted.

The purpose of this study was to examine the risk of tunnel convergence and to determine optimal tunnel placement for posterior medial and lateral meniscus root repairs performed in conjunction with ACL and PCL reconstruction on the anteromedial proximal tibia. The authors hypothesized that possible tunnel convergence between the ACL and meniscus root tunnels could be avoided by reaming the root repair tunnels parallel to the ACL tunnel and that this configuration would not lead to a risk of convergence with the PCL tunnel.

METHOD

Imaging Protocol

Twenty nonpaired fresh-frozen cadaveric knees, without a history of knee surgery or trauma, were obtained (MedCure). Because of the use of deidentified specimens, this study was exempt from institutional review board approval. The cadaveric specimens used in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. Computed tomography (CT) of each knee was performed using a 16-row CT scanner (Brilliance 16-slice scanner; Philips) at Rush University Medical Center. The knee was positioned in full extension with the patella facing anteriorly. The image sequence, obtained using standard 120-kVp and 250-m collection techniques, provided 0.75-mm axial slices of the knees. The CT images were exported and handled via an imaging processing program (Mimics; Materialise Inc). The CT scans were segmented above a minimum grayscale threshold to remove any soft tissue and produce a 3-dimensional (3D) geometric representation of the tibia from each knee as consistent with similar studies previously performed.[21] The locations of the ligamentous attachment sites on the tibial plateau, with the tunnel diameters of an anatomic reconstruction of the ACL, PCL, and meniscus roots defined in previous studies,[1,11,12,24] were used to re-create the tunnels as seen in a true surgical case with respect to the repair and reconstructions of the aforementioned structures (Figure 1).

Reconstruction Tunnel Creation

In accordance with previous studies, the exit points of 4 tunnels (representing ACL and PCL reconstructions, medial and lateral meniscus root repairs) on the tibial plateau were identified on the 3D renderings.[1,11,12,24] In the initial configuration, the meniscus root tunnels' entry points on the anteromedial aspect of the tibia were first identified proximal to the ACL tunnel entry point, and the root repair tunnels' exit points were defined on the tibial plateau surface at the anatomic footprints of the meniscus roots. This configuration was determined by the senior author's (J.C.) clinical experience with tunnel convergence.

§Address correspondence to Jorge Chahla, MD, PhD, Department of Orthopaedic Surgery, Rush University Medical Center, 1611 W Harrison Street, Suite 300, Chicago, IL 60612, USA (email: jorge.chahla@rushortho.com).
*Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, Illinois, USA.
†Steadman Philippon Research Institute and The Steadman Clinic, Vail, Colorado, USA.
‡Twin Cities Orthopedics, Edina, Minnesota, USA.
Submitted May 17, 2021; accepted December 6, 2021.
Presented at the interim meeting of the AOSSM, Chicago, Illinois, USA, March 2022.
One or more of the authors has declared the following potential conflict of interest or source of funding: A.B.Y. has received support for education from Arthrex/Medwest, consulting fees from JRF Ortho and Olympus American, and honoraria from JRF Ortho. R.F.L. has received consulting fees from Arthrex and Smith & Nephew, speaking fees from Smith & Nephew, support for education from Arthrex, and royalties from Arthrex and Smith & Nephew. J.C. has received support for education from Arthrex and Smith & Nephew; consulting fees from DePuy Synthes Product, Linvatec, Smith & Nephew, and Arthrex; speaking fees from Linvatec; and hospitality payments from Medical Device Business Services, Medwest Associates, and Stryker. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

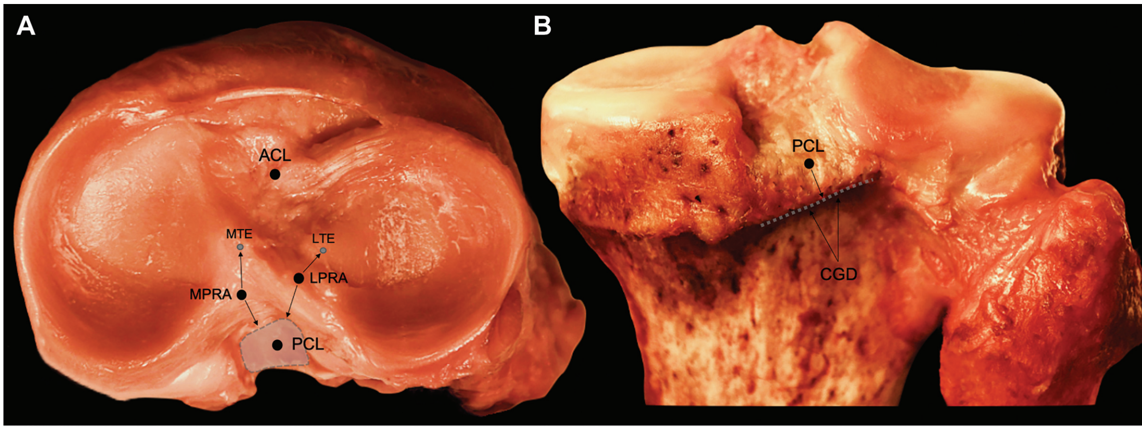

Figure 1. Photographs of the medial and lateral meniscal posterior root, anterior and posterior cruciate ligament attachments, and relevant anatomy. (A) Superior view and (B) posterior view. ACL, anterior cruciate ligament bundle attachment; CGD, champagne glass dropoff; LPRA, lateral meniscus posterior root attachment; LTE, lateral tibial eminence apex; MPRA, medial meniscus posterior root attachment; MTE, medial tibial eminence apex; PCL, posterior cruciate ligament bundle attachment.

The angle of the tunnel formed between the randomly marked entry point of the ACL tunnel in the anteromedial tibia and the anatomic exit point on the tibial plateau was measured in the sagittal plane. The ACL tunnel was created to not exceed an angle of >65° with respect to the tibial plateau in the sagittal plane. The meniscus root tunnels' entry points were created at the same distance to the joint line, with the lateral root tunnel entry point being placed closer to the tibial tubercle. Each tunnel was re-created using the image processing software by measuring the angle of each tunnel relative to the defined global anatomic coordinate frame in the sagittal, coronal, and transverse planes. The ACL tunnel, 10 mm in diameter and of variable length, was created on the anatomic ACL tibial footprint,[24] while the PCL tunnel, 12 mm in diameter and of variable length, was placed 60 mm distal to the joint line while exiting at the bundle ridge of the tibial footprint.[1,11] Spiridonov et al[22] previously described creating the entry point of the PCL tunnel 6 cm distal to the joint line and at the midline of the anteromedial tibia. It has been shown in further studies that the PCL tunnel created according to the entry point at this distance can reach the PCL attachment center 5.5 mm superior to the champagne glass dropoff in the proximal tibia without penetrating the posterior tibial cortex.[1,11]

In the second configuration, commercial software MATLAB (The MathWorks) was used to set the meniscus root tunnels parallel to the ACL tunnel by calculating the orientation of the ACL tunnel axis according to the previously identified ACL entry and exit points on the 3D model and setting the orientation of the root tunnels to match this orientation while conserving the exit point at the anatomic location of the root. In the reoriented tunnel configuration, posterior meniscus root tunnels were expected to appear distal to the entrance of the ACL tunnel and proximal to the PCL entrance, as Campbell et al[4] observed in their anteromedial-based orientation. The initial and reoriented configurations are illustrated in Figure 2.

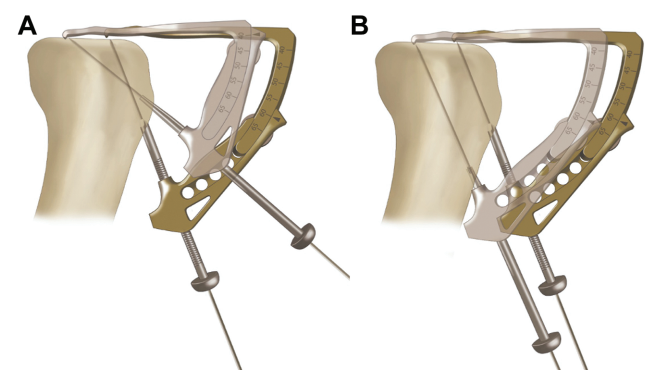

Figure 2. Illustration of the reconstruction of the lateral meniscus root repair and ACL tunnels. (A) Initial orientation where the meniscus root tunnels' entry points on the anteromedial aspect of the tibia were created proximal to the ACL tunnel. (B) The meniscus root tunnels were reoriented and placed parallel to the ACL tunnel and aimed to exit at the anatomic attachment of the posterior roots of the meniscus. The dark guide is for the creation of the ACL tunnel, and the light guide is for the creation of the meniscus root tunnel.

Root repair tunnels were created separately in accordance with single- and double-tunnel techniques. In the single-tunnel technique, the tunnel diameter was determined as 3.5 mm.[23] For the double-tunnel technique, each tunnel diameter was determined as 2.8 mm, with a gap of 5 mm between the 2 tunnels.[5] Since the 2 tunnels can be vertical, horizontal, or oblique in the axial plane, the overall tunnel diameter was determined to be 10.6 mm in total in the 2 tunnel techniques and simulated as a single tunnel (2.8 + 2.8 + 5 mm). Tunnel clearance was measured by identifying the shortest 3D distance between tunnel axes and subtracting the radius of each tunnel from this distance. Tibial tunnel convergence was defined as a <2-mm distance between tunnels, as previously described.[21]

TABLE 1
Mean Distance of Tibial Tunnels[a]

	Tibial Tunnel[b]	Distance, mm, Mean ± SD (Range)	No. of Cases With Distance <2 mm Between Tunnels
	ACL and PCL	15.3 ± 3.2	0
Single-tunnel technique	ACL and medial root		
	Initial anatomic RRTs	9.3 ± 2.1 (5.8 to 14.8)	0
	Reoriented anatomic RRTs parallel to ACL	12.1 ± 2.8 (8.2 to 18.4)	0
	ACL and lateral root		
	Initial anatomic RRTs	−4.2 ± 2.1 (−6.7 to −0.2)	**20**
	Reoriented anatomic RRTs parallel to ACL	9.0 ± 2.6 (6.5 to 13.7)	0
	PCL and medial root		
	Initial anatomic RRTs	11.6 ± 2.0 (7.3 to 14.5)	0
	Reoriented anatomic RRTs parallel to ACL	8.8 ± 2.3 (4.4 to 12.6)	0
	PCL and lateral root		
	Initial anatomic RRTs	11.6 ± 2.4 (6.3 to 15.1)	0
	Reoriented anatomic RRTs parallel to ACL	10.9 ± 2.2 (5.9 to 14.6)	0
Double-tunnel technique	ACL and medial root		
	Initial anatomic RRTs	5.8 ± 2.1 (2.3 to 11.3)	0
	Reoriented anatomic RRTs parallel to ACL	8.5 ± 2.8 (4.7 to 14.9)	0
	ACL and lateral root		
	Initial anatomic RRTs	−8.03 ± 1.8 (−10.2 to −3.7)	**20**
	Reoriented anatomic RRTs parallel to ACL	5.8 ± 2.2 (2.9 to 10.1)	0
	PCL and medial root		
	Initial anatomic RRTs	8.0 ± 2.0 (3.7 to 11.0)	0
	Reoriented anatomic RRTs parallel to ACL	5.3 ± 2.3 (0.9 to 9.1)	**2**
	PCL and lateral root		
	Initial anatomic RRTs	8.1 ± 2.4 (2.8 to 11.5)	0
	Reoriented anatomic RRTs parallel to ACL	7.4 ± 2.2 (2.3 to 11.0)	0

[a]Negative values indicate the maximum overlap distance between tunnels at convergence, while positive values indicate the minimum distance between tunnels. Bold denotes at least 1 case of convergence. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; RRT, root repair tunnel.

[b]The initial configuration defines the meniscus root tunnels' entry points proximal to the ACL tunnel entry point and was created at the same distance to the joint line, with the lateral root tunnel entry point being placed closer to the tibial tubercle and aimed to exit at the anatomic attachment of the posterior medial and lateral roots. The reoriented configuration defines the meniscus root tunnels' entry points as reoriented to be parallel to the ACL tunnel and aimed to exit at the anatomic attachment of the posterior medial and lateral roots.

Statistical Analysis

All statistical analysis was performed using Stata Version 16.1 (Stata Corp). Data were determined to be normally distributed using the Shapiro-Wilk test, and therefore parametric tests were utilized. All results are presented as mean ± SD. Tunnel distances were compared between the drilling technique groups using 1-way repeated-measures analysis of variance (ANOVA) models. Pairwise Bonferroni multiple-comparison tests were utilized post hoc for significant ANOVA models. The overall alpha level was set to .05. Power analysis conducted using G*Power 3.1 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) with an alpha of .05 for repeated-measures ANOVA demonstrated adequate power to detect an effect size (f) of 0.61.

RESULTS

Twenty specimens (13 male, 7 female) with a mean age of 49.7 ± 5.0 years were utilized for this study. No specimens were excluded by evidence of previous trauma or history of surgery to the tibia as demonstrated on CT scan. Table 1 demonstrates the mean, minimum, and maximum distances of each tunnel configuration, as well as the number of cases where the distance between tunnels was <2 mm.

The ACL and PCL had a fixed distance of 15.3 ± 3.2 mm in all specimens.

ACL and Medial Meniscus Root Tunnels

No cases of convergence between the ACL and medial meniscus root tunnels were observed using the 4 configurations. The greatest distance between tunnels was achieved via the single-tunnel reoriented technique (12.1 ± 2.8 mm), which was significantly greater than the distances of the single-tunnel original (9.3 ± 2.1 mm; P = .004), double-tunnel reoriented as the anatomic root repair tunnel parallel to the ACL tunnel (8.5 ± 2.8 mm; P < .001), and double-tunnel original (5.8 ± 2.1 mm; P < .001) techniques.

ACL and Lateral Meniscus Root Tunnels

There were 20 of 20 cases of convergence between the ACL and lateral root tunnels using both single- and double-tunnel

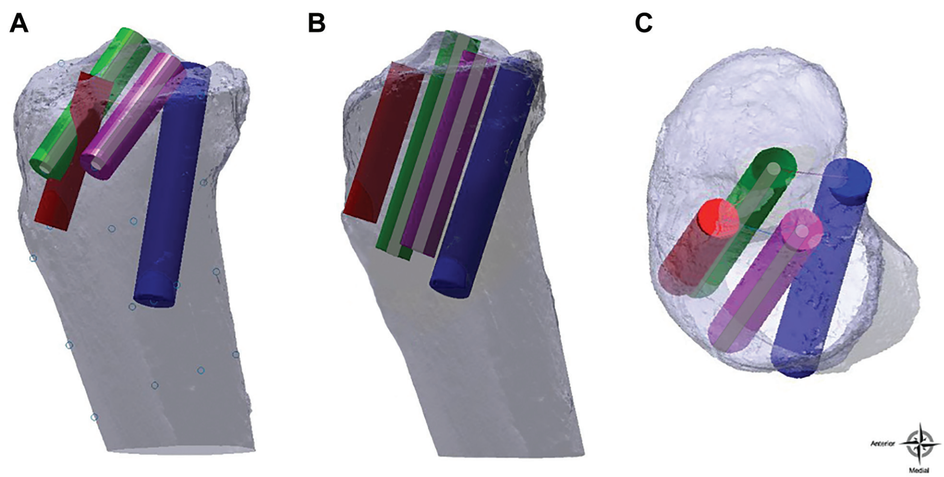

Figure 3. Reconstruction of the tunnels on the 3-dimensional renderings. Sagittal views of the (A) initial tunnel configuration and (B) reoriented tunnel configuration, and (C) axial view of the reoriented tunnel configuration for single- and double-tunnel root repair techniques. The convergence risk between anterior cruciate ligament (ACL) (red) and lateral root (green) tunnels decreased with the reoriented lateral (green) and medial (purple) root tunnels parallel to the ACL tunnel. Note the close intertunnel relationship between medial root and posterior cruciate ligament (blue) tunnels in the reoriented configuration. The gray tunnels inside the medial (purple) and lateral (green) root tunnels demonstrate the single-tunnel technique of a 3.5-mm diameter each.

original techniques. With reorientation, the cases of convergence decreased to 0 of 20 for both tunnel techniques. The distance between tunnels was optimized via the single-tunnel reoriented technique (9.0 ± 2.6 mm), which had significantly greater clearance than the double-tunnel reoriented technique (5.8 ± 2.2 mm) ($P < .001$). Figures 3 and 4 illustrate the reduction in the convergence risk when the meniscus root tunnels are reoriented as parallel to the ACL tunnel.

PCL and Medial Meniscus Root Tunnels

There were no cases of convergence between the PCL and the medial meniscus root tunnels using either original tunnel technique. When reoriented, there were 2 of 20 cases of convergence using the double-tunnel technique, and no cases of convergence using the single-tunnel technique. The greatest tunnel distance was observed using the single-tunnel original configuration (11.6 ± 2.0 mm), which was significantly greater than the greatest distance between tunnels using the single-tunnel reoriented (8.8 ± 2.3 mm; $P = .001$), double-tunnel original (8.0 ± 2.0 mm; $P = .001$), and double-tunnel reoriented (5.3 ± 2.3 mm; $P < .001$) techniques.

PCL and Lateral Meniscus Root Tunnels

There were no cases of convergence between the PCL and lateral meniscus root tunnels using any configuration. The single-tunnel original and reoriented techniques conferred equivalent tunnel distances of 11.6 ± 2.4 mm and 10.9 ± 2.2 mm, respectively ($P = .327$). Both techniques had significantly greater tunnel distance than the double-tunnel original (8.1 ± 2.4 mm; $P < .001$ and $P = .001$, respectively) and double-tunnel reoriented (7.4 ± 2.2 mm; $P < .001$ for both) techniques. The double-tunnel original and reoriented techniques provided equivalent tunnel clearance ($P = .327$).

A summary of the preferred tunnel configurations for each setting, ranked by greatest tunnel distance conferred and cases of convergence, is reported in Table 2.

DISCUSSION

The most important finding of this study was that there was a high risk of tibial tunnel convergence between lateral meniscus root and ACL tunnels (100% cases) in the setting of combined ACL and PCL reconstructions and both lateral and medial meniscus root repair while creating all tunnels on the anteromedial tibia. This risk can be reduced by reorienting the root tunnels to be at the same angle and parallel to the ACL tunnel in the sagittal plane while preserving the reattachment sites on the tibial plateau surface. Because the defined reorientation of the meniscus root tunnels brings the meniscus root repair tunnels' entry points closer to the PCL tunnel, use of the double-tunnel technique requires caution to avoid convergence risk.

There are a few studies demonstrating the intertunnel relationship between the created tunnels in the proximal tibia. Moatshe et al[21] investigated the intertunnel relationships during reconstruction of multiple ligaments in the proximal tibia and reported that, of the tunnels created for ACL, PCL, POL, sMCL, and posterolateral corner reconstructions, there was a high risk of tunnel convergence between PCL and sMCL tunnels and between PCL and POL tunnels. They also demonstrated that the said risk could be reduced via reorientation of the sMCL and POL tunnels by aiming the POL tunnel 15 mm medial to Gerdy tubercle and the sMCL tunnel transversely across the tibia and 30° distal to the horizontal plane. However,

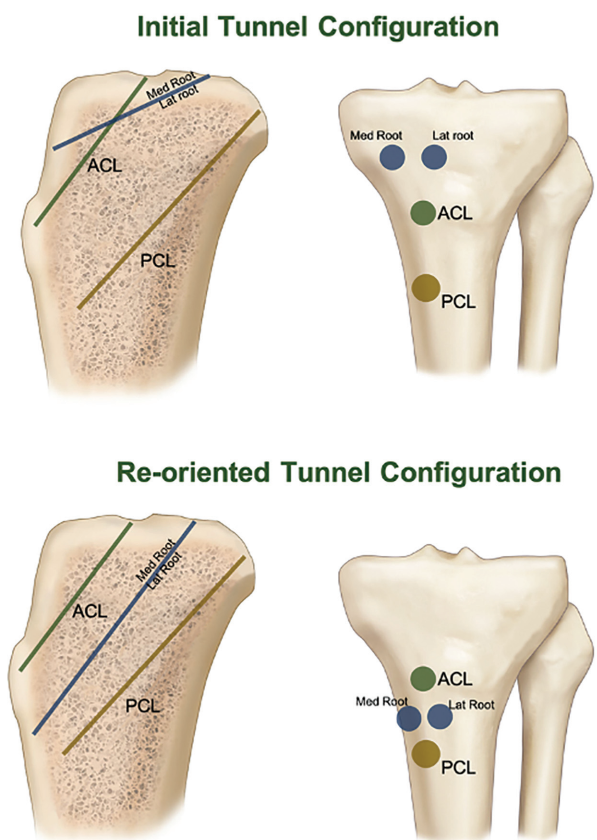

Figure 4. Illustration of the initial and reoriented tunnel configurations in the sagittal and coronal planes. In the initial orientation, medial (Med) and lateral (Lat) meniscus root tunnels were created proximal to the anterior cruciate ligament (ACL) tunnel. The ACL tunnel was created to not exceed an angle of 65° with respect to the tibial plateau in the sagittal plane. While ACL and posterior cruciate ligament (PCL) tunnels were kept constant in reoriented configuration, the medial and lateral meniscus root tunnels were reoriented parallel to the ACL tunnel in the sagittal plane. In the reoriented tunnel configuration, the entry points of the root tunnels were created parallel to the ACL tunnel in the sagittal plane, corresponding to points between the ACL and PCL tunnels in the coronal plane.

the authors did not provide any information about the tunnels created for tears of the meniscus root that are frequently observed along with ACL injuries. Campbell et al[4] reported the intertunnel relation between the ACL and PCL tunnels and the posterior meniscus root tunnels. Their study was designed such that the meniscus root tunnels were created based on the single-tunnel technique, and the entry points were randomly determined according to the remaining bone stock in the proximal tibia after the ACL and PCL tunnels were created. Similar to our results, the authors reported the posterior meniscus root repair tunnels to be in close proximity to the tunnels used for cruciate ligament reconstruction in the proximal tibia. However, a quantitative orientation has not been defined to avoid the risk of tunnel convergence between root tunnels and bicruciate reconstruction tunnels. In the current study, a clinically easy-to-apply angle-based orientation has been defined to maintain the optimal placement of both the medial and the lateral single- and double-root tunnels accompanied by ACL and PCL reconstructions. Unlike the study by Campbell et al, in which cadaveric and synthetic tibias were used, 3D tibial models obtained via segmentation of CT scans were used in the current study. The 3D model allows reliable measurement of the exact amount of clearance between tunnels on each configuration. In addition, numerous configurations, which may not be physically re-created on a cadaver, can be created on a 3D model.

In this study, convergence was observed between the ACL and lateral root tunnels in all 20 cases when the lateral meniscus root tunnel was placed proximal to the ACL tunnel in the anteromedial aspect of the tibia, but this convergence did not occur when the lateral meniscus root tunnels were reoriented to be parallel to the ACL tunnel, with the same tunnel angle corresponding to the tibial plateau in the sagittal plane. The importance of conducting reconstruction of ACL and PCL tears and tears of the meniscus root in accordance with the anatomic landmarks on the tibial plateau surface to achieve the desired clinical and biomechanical outcomes has been clearly underlined in the literature.[14-18] The landmarks of these ligaments on the tibial plateau surface have been precisely demonstrated in anatomic studies.[1,11,12,24] However, there is limited information about the entry points of these tunnels on the anteromedial aspect of the tibia in reconstruction or repair procedures. The scarcity of literature on proper tunnel entry position on the anteromedial aspect of the tibia during multiligamentous reconstruction leads to variation in entry position for each surgeon and the risk of tunnel convergence. In this study, the initial configuration involved a high risk of convergence between the ACL and lateral root tunnels, which was reported based on the configuration experienced by the senior author in a clinical setting. This high risk was eliminated by reorienting and placing the root tunnels parallel to ACL tunnels, using the same tunnel angle in the sagittal plane.

There were 2 of 20 cases of convergence between the PCL and medial root tunnels using the double-tunnel technique when meniscus root tunnels were reoriented and placed parallel to the ACL tunnel. Although PCL injuries do not often coexist with tears of the meniscus root, the relationship between PCL and root tunnels has also been investigated, with the hypothesis that reorientation of root tunnels parallel to the ACL tunnel will bring the root tunnels closer to the PCL tunnel entry point. With reorientation of the tunnels, our study showed evidence of convergence in 2 of 20 knees using the double-tunnel technique, with no evidence of convergence using the single-tunnel technique. Thus, in the setting of concomitant ACL, PCL, and medial and lateral meniscus root injuries, our results lead to a recommendation that use of the double-tunnel technique requires caution, as there may be an increased risk of convergence between meniscus root repair and PCL tunnels compared with the single-tunnel technique.

PLMRTs are among the meniscal injuries that frequently coexist with ACL injury.[2] Forkel et al[9] reported

TABLE 2
Descriptive Summary of Preferred Tunnel Configurations for Each Setting[a]

	ACL and Medial Root	ACL and Lateral Root	PCL and Medial Root	PCL and Lateral Root	
Preferred tunnel configuration ↑	Single-root tunnel reoriented	Single-root tunnel reoriented	Single-root tunnel initial	Single-root tunnel initial = single-root tunnel reoriented	↑ Greater distance between tunnels
	Single-root tunnel initial	Double-root tunnel reoriented	Single-root tunnel reoriented	Double-root tunnel initial = double-root tunnel reoriented	
	Double-root tunnel reoriented	Single-root tunnel initial = double-root tunnel original	Double-root tunnel initial		
	Double-root tunnel initial		Double-root tunnel reoriented		

[a]The initial configuration defines the meniscus root tunnels' entry points proximal to the ACL tunnel entry point and was created at the same distance to the joint line, with the lateral root tunnel entry point being placed closer to the tibial tubercle and aimed to exit at the anatomic attachment of the posterior medial and lateral roots. The reoriented configuration defines the meniscus root tunnels' entry points as reoriented to be parallel to the ACL tunnel and aimed to exit at the anatomic attachment of the posterior medial and lateral roots. Highlighted boxes denote at least 1 case of convergence and "=" denotes equivalent tunnel distance between configurations. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

that PLMRTs were observed in 14% of ACL injuries, and Matheny et al[19] stated that lateral root tears were 10.3-fold more prevalent than medial root tears in cases of ACL injury. Because of the lack of data on optimal tunnel angles and tunnel entry points on the anteromedial tibia, numerous configurations can be created between the tunnels reamed for the structures included in the study while preserving the anatomic tunnel exit points on the tibial plateau surface. In this study, which considered and prioritized the incidence of coexisting ACL injuries and root tears, we aimed to describe a method that is easy to use in a clinical setting to prevent the risk of tunnel convergence between ACL and root tunnels. To place ACL and root tunnels parallel to each other during surgery, it is important to place the guides parallel to the sagittal plane of the tibial plateau, as shown in Figure 2. Distance between the guide pins placed for the ACL and root tunnels that are planned to be created at the same level in the axial plane on the anteromedial tibia should respectively be 12.3 mm and 8.75 mm for the double- and single-tunnel techniques, considering tunnel diameters and a minimum safe distance of 2 mm to prevent tunnels from overlapping.

It was confirmed that the angle of the tunnel created between the randomly marked entry point of the ACL tunnel in the anteromedial tibia and the anatomic exit point on the tibial plateau was not $>65°$ in the sagittal plane. As the literature regarding the tibial tunnel angle of the ACL is limited, 65° was determined as the cutoff value based on the clinical preference of the senior author. Regardless of this angle, the entrance of the PCL tunnel was determined to be 6 cm distal to the joint line and in the middle of the anteromedial tibia, as previously defined in the literature.[1,11] The angle of the PCL tunnel formed between the entry point and the anatomic exit point was not taken into consideration. Increasing the ACL tunnel angle leads to the meniscus root tunnel entry points being closer to the PCL tunnel entry. No overlap was observed between the entry points of the root tunnels, reoriented to be parallel to the $\leq 65°$ ACL tunnel angle, and the PCL tunnel entry points. It is also possible to make predictions about more isolated injuries based on the relationship between the PCL and root tunnels from images obtained in the study, such as Figure 3. In this study, there was no difference between the initial orientation and reorientation of the lateral root tunnel placed closer to the tibial crest compared with the medial root tunnel in terms of distance to the PCL tunnel ($P = .327$). Therefore, it can be assumed that the placement of a medial meniscus root tunnel close to the tibial crest in the anterior aspect increases the distance to the PCL tunnel while preserving its parallel orientation to the ACL tunnel, thereby not posing an additional risk of convergence in a clinical presentation that does not involve a lateral root tear.

In this study, all tunnels were created according to the scenario to be performed from a single longitudinal incision on the anteromedial tibia, where there is less tibial space and where the senior author observed the tunnel convergence. During ACL reconstruction to be performed using bone-tendon-bone autograft, it is possible to reach the anterolateral tibia from the anterior midline longitudinal incision for graft harvesting. Creating the entry point of the lateral meniscus root repair tunnel that could accompany the ACL tunnel close to Gerdy tubercle in the anterolateral tibia will eliminate the potential risk of convergence with the ACL tunnel.

Ethnicity, sex, and tibial dimensions, which may be thought to affect proximal tibia morphometry, were not accounted for in this study. However, the high risk of tunnel convergence (100% cases) between lateral meniscus root and ACL tunnels in the initial tunnel orientation was resolved in all specimens via reoriented tunnel configuration, where the root tunnels were created parallel to the ACL tunnel in the sagittal plane, without any exception (0% cases). In fact, Dai and Bischoff[7] have also reported that medial and lateral anteroposterior dimensions were strongly correlated with plateau mediolateral width, with minimal differences in correlation because of sex or ethnicity.

This study was not without limitations. First, a single location was used for the entry points of the tunnels created for repair and reconstruction of the structures included in the study on the anteromedial tibia, despite the fact that these entry points can vary by surgeon and patient. Numerous configurations and different intertunnel measurements could have been obtained based on the mediolateral or proximodistal orientation of the tunnel entry points on the anteromedial tibia. In this study, all tunnels were created in the anteromedial tibia, and any tunnel orientation lateral to the tibial tubercle was not included in the study. Another limitation was that the ACL and PCL tunnels were created 10 mm and 12 mm in diameter, respectively, although tunnel diameter may vary depending on the type of graft used in reconstruction. In addition, relatively older adult specimens were used in the study. Considering that cruciate ligament surgeries are performed more frequently in the younger population, age-related changes in the proximal tibia may have affected intertunnel measurements. Another important limitation was that the study only included 3D model data. Although this methodology was chosen to facilitate accurate calculations of intertunnel relationships, the results presented here will ultimately need to be validated in a true anatomic model. Future studies should be directed toward describing this intertunnel relationship using a cadaveric model, utilizing the safe configurations derived in the 3D models from the current study.

CONCLUSION

There was a high risk of convergence between ACL and posterior meniscus root tunnels when all the tunnels were created on the anteromedial tibia. Reorienting meniscus root tunnels parallel to ACL tunnels may help reduce this risk. There is an increased risk of tunnel convergence with root repairs in cases of bicruciate reconstructions, and therefore a double-tunnel root repair technique should be used with caution.

ORCID iD

Amar S. Vadhera https://orcid.org/0000-0001-5225-4641

REFERENCES

1. Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am*. 2012;94(21):1936-1945.
2. Bernholt DL, DePhillipo NN, Grantham WJ, et al. Morphologic variants of posterolateral tibial plateau impaction fractures in the setting of primary anterior cruciate ligament tear. *Am J Sports Med*. 2020;48(2):318-325.
3. Bhatia S, LaPrade CM, Ellman MB, LaPrade RF. Meniscal root tears: significance, diagnosis, and treatment. *Am J Sports Med*. 2014;42(12):3016-3030.
4. Campbell A, Narvaez M, Caldwell JM, Banffy M. Stay ipsilateral: an analysis of tibial tunnel distance between cruciate ligament reconstruction and posterior meniscal root repair. *Arthrosc Sports Med Rehabil*. 2021;3(4):e1031-e1035.
5. Chahla J, Moulton SG, LaPrade CM, Dean CS, LaPrade RF. Posterior meniscal root repair: the transtibial double tunnel pullout technique. *Arthrosc Tech*. 2016;5(2):e291-296.
6. Cinque ME, Chahla J, Moatshe G, et al. Meniscal root tears: a silent epidemic. *Br J Sports Med*. 2018;52(13):872-876.
7. Dai Y, Bischoff JE. Comprehensive assessment of tibial plateau morphology in total knee arthroplasty: influence of shape and size on anthropometric variability. *J Orthop Res*. 2013;31(10):1643-1652.
8. DePhillipo NN, Dekker TJ, Aman ZS, et al. Incidence and healing rates of meniscal tears in patients undergoing repair during the first stage of 2-stage revision anterior cruciate ligament reconstruction. *Am J Sports Med*. 2019;47(14):3389-3395.
9. Forkel P, Reuter S, Sprenker F, et al. Different patterns of lateral meniscus root tears in ACL injuries: application of a differentiated classification system. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(1):112-118.
10. Hwang BY, Kim SJ, Lee SW, et al. Risk factors for medial meniscus posterior root tear. *Am J Sports Med*. 2012;40(7):1606-1610.
11. Johannsen AM, Anderson CJ, Wijdicks CA, Engebretsen L, LaPrade RF. Radiographic landmarks for tunnel positioning in posterior cruciate ligament reconstructions. *Am J Sports Med*. 2013;41(1):35-42.
12. Johannsen AM, Civitarese DM, Padalecki JR, et al. Qualitative and quantitative anatomic analysis of the posterior root attachments of the medial and lateral menisci. *Am J Sports Med*. 2012;40(10):2342-2347.
13. Kim YJ, Kim JG, Chang SH, et al. Posterior root tear of the medial meniscus in multiple knee ligament injuries. *Knee*. 2010;17(5):324-328.
14. LaPrade CM, Foad A, Smith SD, et al. Biomechanical consequences of a nonanatomic posterior medial meniscal root repair. *Am J Sports Med*. 2015;43(4):912-920.
15. LaPrade CM, Jisa KA, Cram TR, LaPrade RF. Posterior lateral meniscal root tear due to a malpositioned double-bundle anterior cruciate ligament reconstruction tibial tunnel. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(12):3670-3673.
16. LaPrade RF, Cinque ME, Dornan GJ, et al. Double-bundle posterior cruciate ligament reconstruction in 100 patients at a mean 3 years' follow-up: outcomes were comparable to anterior cruciate ligament reconstructions. *Am J Sports Med*. 2018;46(8):1809-1818.
17. LaPrade RF, Matheny LM, Moulton SG, James EW, Dean CS. Posterior meniscal root repairs: outcomes of an anatomic transtibial pull-out technique. *Am J Sports Med*. 2017;45(4):884-891.
18. Lim HC, Yoon YC, Wang JH, Bae JH. Anatomical versus non-anatomical single bundle anterior cruciate ligament reconstruction: a cadaveric study of comparison of knee stability. *Clin Orthop Surg*. 2012;4(4):249-255.
19. Matheny LM, Ockuly AC, Steadman JR, LaPrade RF. Posterior meniscus root tears: associated pathologies to assist as diagnostic tools. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(10):3127-3131.
20. Moatshe G, Chahla J, Slette E, Engebretsen L, LaPrade RF. Posterior meniscal root injuries. *Acta Orthop*. 2016;87(5):452-458.
21. Moatshe G, Slette EL, Engebretsen L, LaPrade RF. Intertunnel relationships in the tibia during reconstruction of multiple knee ligaments: how to avoid tunnel convergence. *Am J Sports Med*. 2016;44(11):2864-2869.
22. Spiridonov SI, Slinkard NJ, LaPrade RF. Isolated and combined grade-III posterior cruciate ligament tears treated with double-bundle reconstruction with use of endoscopically placed femoral tunnels and grafts: operative technique and clinical outcomes. *J Bone Joint Surg Am*. 2011;93(19):1773-1780.
23. Woodmass JM, Mohan R, Stuart MJ, Krych AJ. Medial meniscus posterior root repair using a transtibial technique. *Arthrosc Tech*. 2017;6(3):e511-e516.
24. Ziegler CG, Pietrini SD, Westerhaus BD, et al. Arthroscopically pertinent landmarks for tunnel positioning in single-bundle and double-bundle anterior cruciate ligament reconstructions. *Am J Sports Med*. 2011;39(4):743-752.