Interbundle Impingement Pressure in Individualized and Nonindividualized Double-Bundle Anterior Cruciate Ligament Reconstruction

A Cadaveric Study

Bing Wu,* MD, Daqiang Liang,[†] MD, Lei Yang,[†] MD, Sheng Li,[†] MD, Zhihe Qiu,[†] MD, Qihuang Qin,[†] MD, Xinzhi Liang,[†] MD, Haifeng Liu,[†‡] MD, Kan Ouyang,[†] MD, Jianyi Xiong,[†] MD, PhD, Daping Wang,[†] MD, PhD, and Wei Lu,[†‡] MD, PhD
Investigation performed at the Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China

Background: Graft impingement is one of the main concerns in double-bundle anterior cruciate ligament reconstruction (DB-ACLR). Impingement between the anteromedial (AM) and posterolateral (PL) bundles has been postulated to cause graft deterioration or rerupture, but this has not been thoroughly investigated, and the interbundle impingement pressure (IIP) has not been well researched.

Purpose: To determine the IIP between the AM and PL bundles in the native anterior cruciate ligament (ACL) and in DB-ACLR with individualized and nonindividualized double-tunnel placement.

Study Design: Controlled laboratory study.

Methods: A total of 30 fresh-frozen, nonpaired, human cadaveric knees were randomly divided into 3 groups of 10 knees: native intact ACL (NI group), DB-ACLR tunnel placement using the preserved remnant procedure (individualized reconstruction) (PR group), and DB-ACLR tunnel placement using the bony landmark procedure (nonindividualized reconstruction) (BL group). Pressure sensors were inserted between the AM and PL bundles. The knee was moved passively from full extension to full flexion, and the IIP between the 2 ACL bundles was measured every 15°. Similarly, the impingement pressure was measured between the ACL and intercondylar roof and between the ACL and posterior cruciate ligament (PCL).

Results: No significant differences were found in the maximum, mean, or minimum ACL-roof and ACL-PCL impingement pressures among the 3 groups. The IIP significantly increased when the knee joint was flexed >120° in all 3 groups (*P* < .001). Compared with the other 2 groups, the BL group had significantly higher maximum and mean IIP throughout the range of knee movement (*P* < .001) and from maximum extension to 120° of flexion (*P* < .001). The BL group also had significantly higher minimum IIP than the other 2 groups when knee flexion was >120° (*P* < .001). No significant differences were seen in maximum, minimum, or mean IIP between the NI and PR groups.

Conclusion: The PR procedure (individualized DB-ACLR) was more consistent with the interbundle biomechanical conditions of the native ACL, whereas the BL procedure (nonindividualized DB-ACLR) had higher maximum and mean IIP. The IIP was higher than the ACL–intercondylar roof or ACL-PCL pressures, and it increased significantly when knee flexion was >120°.

Clinical Relevance: These data suggest that surgeons can perform individualized DB-ACLR using preserved remnants for tunnel placement as impingement-free DB-ACLR.

Keywords: anterior cruciate ligament; reconstruction; individualized; double bundle; impingement; pressure

In past decades, the basic concept of anterior cruciate ligament (ACL) reconstruction (ACLR) changed from isometric to anatomic[17,18]; thus, double-bundle ACLR (DB-ACLR) is performed because the ACL structures as

reported in most cadaveric and clinical studies consist of 2 major functional bundles, the anteromedial (AM) and the posterolateral (PL) bundles.[4,5,8,9,11] However, an increasing number of studies have questioned the outcomes of DB-ACLR, as it has shown no significant difference in functional outcomes,[2,6,20,25,37] incidence of postoperative knee osteoarthritis,[2] or risk of revision[1] compared with single-bundle (SB) ACLR. Some studies [3,36] have even found more cases of graft abrasion or rerupture in DB-ACLR during second-look procedures or on postoperative magnetic resonance imaging. These findings suggest that identifying the reasons for graft failure and the corresponding unsatisfactory clinical outcomes in DB-ACLR is important to understand the present controversy regarding this technique.

Generally, the DB-ACLR technique is considered a bony landmark (BL)–dependent technique, because osseous ridges are usually used as bony landmarks for tunnel placement. The fact that ACL remnants deteriorate after ACL rupture and cannot be defined clearly to distinguish the AM and PL insertions or bundle orientations in an old ACL injury could contribute to the popularity of the BL procedure. Given that there are numerous variations in ACL footprints, bundle arrangements, and fiber directions[21,29] and that the relationship between the bony landmarks and the footprints is controversial,[27,28,33] DB-reconstructed grafts that do not match the individual native anatomic features may cause more impingement than SB-reconstructed grafts. Although the lack of impingement between the ACL and intercondylar roof and between the ACL and posterior cruciate ligament (PCL) is regularly confirmed by surgeons intraoperatively, there is another possibility that abnormal contact pressure exists between the AM and PL grafts (ie, interbundle impingement). Interbundle impingement might be overlooked and could possibly result in graft abrasion and rerupture, especially for the relatively frail PL bundle. To the best of our knowledge, no published reports have addressed ACL graft interbundle impingement pressure (IIP) in DB-ACLR.

In contrast to the BL technique, preserved remnant (PR)–dependent DB-ACLR is an individualized technique that is customized to the patient based on an objective evaluation of the individual ACL footprint, bundle arrangements, and fiber directions. A randomized controlled clinical trial[23] demonstrated that an individualized DB-ACLR procedure based on the PR technique yielded better arthroscopic second-look assessment results than the BL technique for ACL grafts, with no revision cases. However,

the mechanism by which the PR technique protects grafts from damage is unclear.

The purpose of this study was to accurately measure the impingement pressure between the AM and PL bundles in DB-ACLR with individualized (PR technique) and nonindividualized (BL technique) tunnel placement. The impingement pressure was compared with that of the native intact (NI) ACL to determine whether the contact between the 2 bundles was physiological. We hypothesized that the IIP in individualized DB-ACLR is more similar to that in NI ACL.

METHODS

Specimen Preparation

This study used 30 fresh-frozen, nonpaired human knee specimens that satisfied the following conditions: no previous surgery; no bone fractures, congenital abnormalities, or arthritis (on radiograph); intact ACL; and no injury to other ligaments or the meniscus (according to physical examination and anatomy). The knees were obtained from cadavers with a mean age of 57.2 ± 11.3 years at the time of death; there were 18 male specimens, 12 female specimens, 15 left knees, and 15 right knees. All specimens were obtained through the cadaver program at Shenzhen University.

Each specimen included sections approximately 20 cm above and below the knee joint line. The knees were stored at $-20°C$ and thawed overnight at room temperature before testing. The mean flexion-extension range of motion of the intact knees was $0° \pm 1°$ to $143.8° \pm 7°$, as assessed using a digital goniometer (Exploit Inc). During the tests, the specimen was kept moist with saline solution.

Surgical Techniques

The knee specimens were randomly divided into 3 groups of 10 knees in each group. There were no differences in age, sex, or tunnel size between the 3 groups. All procedures were performed by a single senior surgeon (W.L.). The knee joints were opened via both medial and lateral parapatellar approaches. Adequate exposure of the anterior articular cavity was obtained by tibial tubercle osteotomy and upturning of the patella. Infrapatellar fat pads and synovium were dissected carefully to sufficiently expose the ACL, and the integrity of all the tendons, meniscus, cartilage, and muscles was verified and preserved. The AM and PL bundles were

Figure 1. Interbundle impingement pressure measurement. (A) A 1.0-mm K-wire was inserted between the 2 bundles to help visually define the 2 bundles and their insertions. The green and blue lines show posterolateral (PL) and anteromedial (AM) bundles, respectively. (B) Ultra-thin, flexible printed circuit pressure sensors were used for the pressure measurements. (C) The sensors were trimmed and inserted into the interbundle contact area. (D) Tibial tubercle reduction and suturing of the capsule and patellar retinaculum were performed to reset the knee to a physiological state.

identified by the difference in the tension pattern across the entire knee range of motion. With the knee at 90° of flexion, the relaxed ACL fibers were regarded as the PL bundle, whereas the taut fibers were regarded as the AM bundle.[12,15] Next, the surface synovial tissue of the ACL was dissected carefully, and a 1.0-mm K-wire was then inserted between the 2 bundles to further visually define and mark the boundary of the 2 bundles and their center points on both the femoral and the tibial sides (Figure 1). Measurement of the interbundle contact area was performed with a Vernier caliper (Deli) to determine the shape of the pressure sensors.

Technique for the PR Group. Both the AM and the PL bundles were transected from the midpoint of the ligament, and the ACL fibers and attachment were preserved to mimic the remnant fibers and footprints. First, the femoral insertion and center point of the AM and PL bundles were visually defined and marked with a 1.0-mm K-wire along the bundle direction. Next, femoral tunnels were drilled along the native bundle orientations in the femoral footprints of anatomic AM and PL bundles (Figure 2). The femoral tunnels were drilled from the anterior region of the knee without using an offset guide system, as in the transportal technique. A 2.4 mm–diameter guide K-wire was drilled first, and then the cannulated drill and dilator were used to establish the tunnel. The knee was positioned at 120° of flexion for the AM

bundle and 135° for the PL bundle when the femoral tunnels were drilled; this technique guarantees the 2 tunnels to be positioned divergent to each other to prevent tunnel or rear bone fracture.[23] Finally, the tibial insertion and center point of the AM and PL bundles were defined and marked using the methods mentioned above. Tibial tunnels were drilled in the anatomic AM and PL bundle footprints and along the native fiber directions with an Acufex ACL tip guide (Smith & Nephew). The PL and AM tibial tunnels were placed at 45° and 55° of flexion, respectively. The tunnel diameters were selected according to the graft diameter and ranged from 5 to 7 mm. No tunnel connections were observed in this group.

The semitendinosus and gracilis tendons were harvested for ACLR in fresh knee specimens used in other studies. The diameters of the AM and PL bundle grafts (usually 5-8 mm and 5-7 mm, respectively) were selected according to the native AM and PL bundle diameters to ensure that the sizes of the native ACL and the grafts were matched. Both grafts were inserted via the tibial tunnels into the femoral tunnels. Femoral fixation of the graft was achieved using a double titanium button (Endobutton CL, 1.5-2.5 cm; Smith & Nephew), and a preconditioning procedure of 20 cycles of knee joint passive flexion and extension was performed. Tibial fixation of the graft was accomplished by applying hydroxyapatite interference screws (BioRCI-
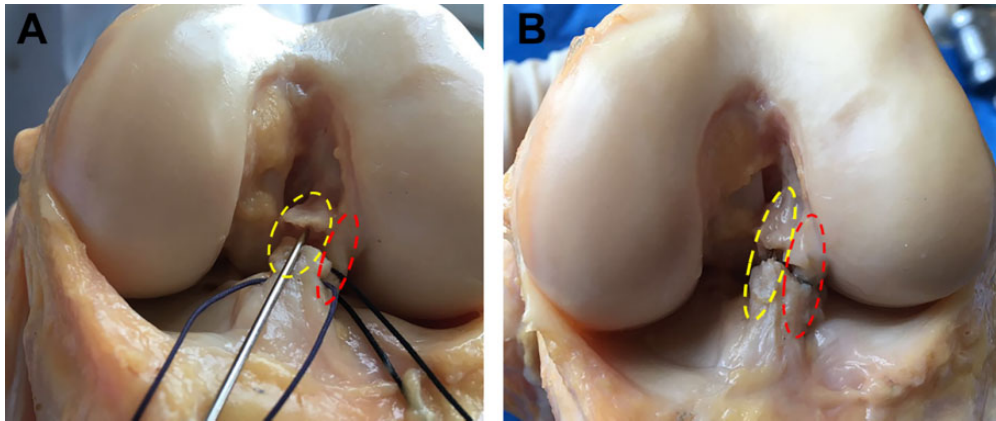
Figure 2. Tunnel placement in double-bundle anterior cruciate ligament reconstruction using the preserved remnant procedure. Femoral and tibial tunnels were drilled at the center of the footprint following the orientation of the anteromedial (AM) and posterolateral (PL) bundles. Proximal and distal segments of the AM bundle (yellow circles) and PL bundle (red circles).
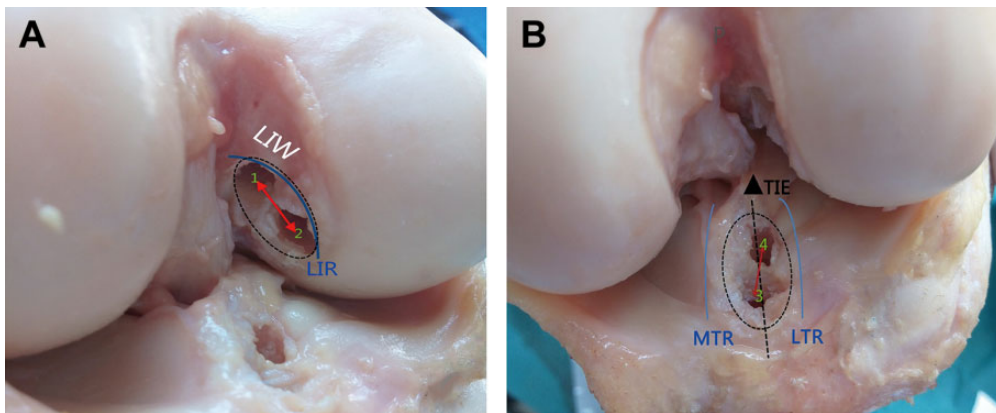
Figure 3. (A) Femoral tunnels were placed directly under the lateral intercondylar ridge (LIR), with the posterolateral (PL) tunnel anterior and inferior to the anteromedial (AM) tunnel (black dotted circle show femoral tunnel area, 1 and 2 show AM and PL tunnel respectively). (B) Tibial tunnels were placed in front of the tibial intercondylar eminence (TIE, the black arrowhead) and between the medial tibial ridge and lateral tibial ridge (blue tangents), with the AM tunnel anteromedial and the PL tunnel posterolateral (black dotted circle shows tibial tunnel area; 3 and 4 show AM and PL tunnel, respectively; straight dotted black line shows central axis of tibial plateau). LIW, lateral intercondylar wall; LTR, lateral tibial ridge; MTR, medial tibial ridge.

HA screws, 6-8 × 25 mm; Smith & Nephew). The PL bundle was fixed first with the knee at full extension and the AM bundle fixed next with the knee at 45° of flexion[23]; both bundles were fixed under maximal manual tension.[15]

Technique for the BL Group. The native ACL and its insertions were completely removed to ensure that there were no indicators from the ACL. When the knee was flexed at 90°, the lateral intercondylar ridge (LIR), the lateral bifurcate ridge (LBR), and the entire medial wall of the intercondylar notch were denoted, and the tunnels were placed below the LIR separately. The LBR was used as a landmark to separate the 2 femoral tunnels, with the PL tunnel anterior and inferior to the AM tunnel, 2 to 3 mm apart on the bone bridge. The tibial tunnels were placed in front of the tibial intercondylar eminence and between the tibial ridges, with the AM tunnel anteromedial and the PL tunnel posterolateral[23] (Figure 3).

Graft passage, tensioning, and fixation were exactly the same as those in the PR group.

Impingement Pressure Measurement

Typical double-bundle reconstructed ACL using PR and BL procedure are shown in Figure 4. A FlexiForce standard force and load sensor (A201; Tekscan) was used to measure pressure (Figure 1). The sensor is an ultrathin, flexible printed circuit with an active sensing size (diameter/width) of 9.53 mm and a force range of 0 to 100 lb (440 N). Before pressure testing, the sensors were trimmed in accordance with the shape and size of the AM and PL contact areas. A piece of tape was applied to both sides of the sensor to create a seal around the sensor to help keep out water and stains. Load was converted to pressure according to sensing size.
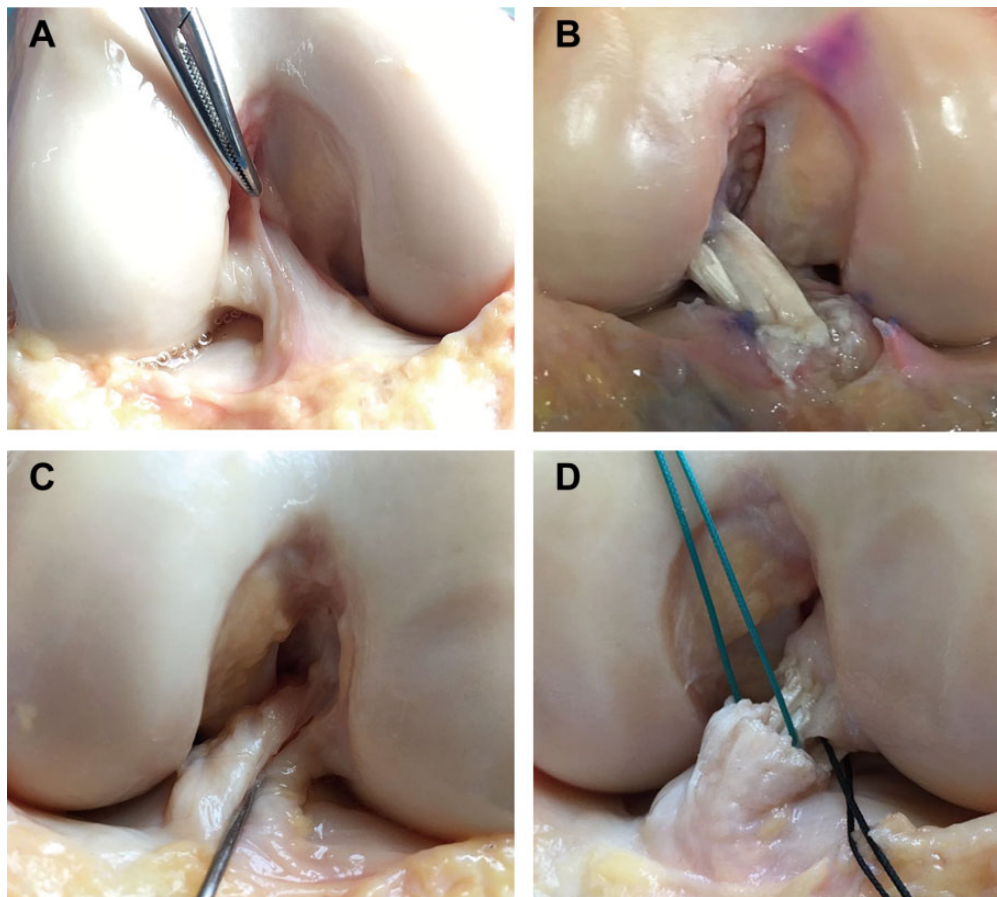
Figure 4. Double-bundle reconstructed anterior cruciate ligament (ACL) with different tunnel placement methods. (A, C) Native intact ACL. (B) Double-bundle reconstructed ACL using bony landmark procedure. (D) Double-bundle reconstructed ACL using the preserved remnant procedure.

The same method was used to measure the impingement pressure between the ACL and intercondylar roof and the PCL (ie, the sensor was inserted between the ACL and inter-condylar roof and between the ACL and PCL). A pressure acquisition system (FlexiForce OEM Development Kit; Teks-can) was used to acquire the impingement pressure data. The sensor was set to zero before implantation and was cali-brated before and after the pressure test. Sensor measure-ments have been proven to be accurate and sensitive (repeatability, ±3.6% of full scale; linearity, ±1.2% of full scale; hysteresis, 3.4% of full scale; drift, 3.4% per log time).

The pressure sensor fit within the contact area over the entire range of flexion motion was carefully confirmed after the sensor was implanted. Tibial tubercle reduction and fixation were performed with a 4-mm lag screw of cancel-lous bone (Weigao Co Ltd). The knee was reset to physical conditions by suturing the capsule, patellar retinaculum, and other soft tissues. Approximately 3 cm of soft tissue on both the tibial and femoral sides was dissected to expose the proximal femur and distal tibiofibula, and both ends were embedded in denture acrylic. The fixture device allowed natural tibial rotation during the entire range of knee flexion motion and helped to keep the knee joint in a

specific position. Subsequently, the knee joint was moved from maximum extension to maximum flexion with 40 N of force applied to the quadriceps and 10 N to the biceps femoris (Figure 5), and the impingement pressure was mea-sured every 15° of flexion. The full range of motion in each specimen was tested 3 times, and mean values were avail-able for analysis.

Statistical Analysis

Data are presented as the mean ± SD. The obtained pressure values were compared for different degrees of knee flexion within the same group and for the same degrees of knee flexion between different groups. A 2-way analysis of variance (ANOVA) was used to examine the effects of group and flexion angle. The initial step was to determine whether the interaction of independent variables had statistical significance on the dependent variables. Next, a 1-way ANOVA was performed. Tukey post hoc testing was used for multiple comparisons when the main effect of the 2-way ANOVA was statistically significant. A P value of $<.05$ was accepted as statistically significant. All statistical data were analyzed with SPSS Version 24.0.
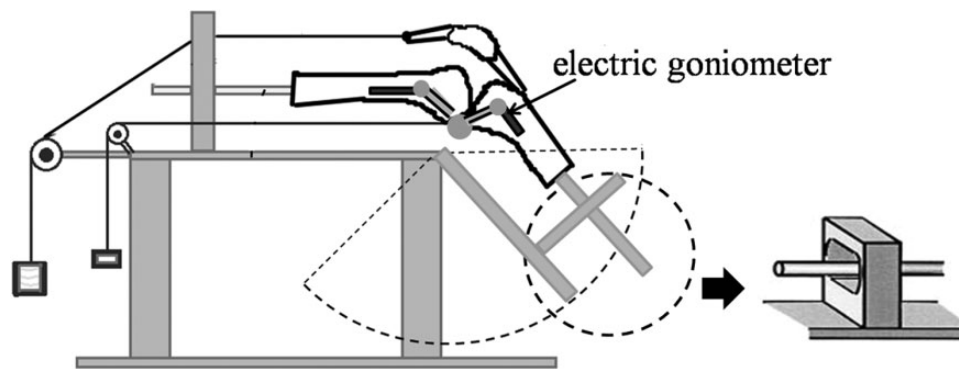
Figure 5. A schematic diagram of the custom-made loading device. The tibial side of the specimen was placed in a frame stand that could prevent extraneous movements and allow natural tibial rotation during the range of knee motion and could be fixed at specific positions. The femoral side was fixed at the base of this device. A 6 degrees of freedom electric goniometer was affixed to the lateral side of the knee joint.
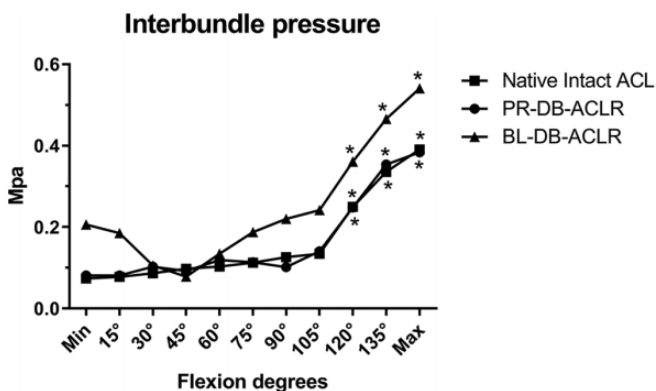
Figure 6. All 3 groups showed a rapid increase in the interbundle impingement pressure when the knee joint passed 120° of flexion ($P < .001$). ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; BL, bony landmark procedure; DB, double-bundle; PR, preserved remnant procedure. *$P < .001$.

RESULTS

ACL Interbundle Impingement Pressure

A significant increase in the IIP occurred when the knee was flexed to >120° in all 3 groups ($P < .001$) (Figure 6). Compared with the other 2 groups, the BL group had significantly higher maximum and mean IIP throughout the entire range of knee movement ($P < .001$) (Figure 7). Next, comparisons were performed among the 3 groups in terms of the maximum, mean, and minimum IIP at different flexion intervals. Significantly higher maximum and mean impingement pressures were seen in the BL group from maximum extension to 120° of knee flexion ($P < .001$) (Figure 7); the most significant increases in pressure occurred between 0° and 30° and between 75° and 105°. In addition to the higher maximum and mean impingement pressures, a significantly higher minimum impingement pressure was observed in the BL group when the knee was

flexed to >120° ($P < .001$) (Figure 7). No significant differences were seen in the maximum, minimum, or mean IIP between the NI and PR groups in any testing position ($P < .001$) (Figure 7).

ACL–Intercondylar Roof and ACL-PCL Impingement

No significant differences were found in the maximum, mean, or minimum impingement pressures between the ACL and intercondylar roof or between the ACL and PCL among the NI, PR, and BL groups (Figure 8).

Measurement of Tunnel Position

The computed tomography measurements of the different AM and PL tunnel placements are shown in Figure 9. We found different AM and PL tunnel placements for the PR and BL groups. There was a greater distance between both tibial and femoral tunnels in the BL group. More posterior tibial placement and more inferior and anterior femoral placement were found in the BL group.

DISCUSSION

The main finding of the present study was that DB-ACLR with nonindividualized double-tunnel placement (BL technique) resulted in a significantly higher IIP versus DB-ACLR with individualized double-tunnel placement (PR technique).

Graft impingement is a potentially troubling complication of ACLR.[13,32,35] When the graft is misplaced, ACL fibers will impinge against surrounding structures during the range of knee motion. Impingements of the ACL graft with the femoral intercondylar roof and with the PCL have been most widely studied in this field.[14-16,26,31,34] Continuous graft impingement can cause graft deterioration or rerupture and result in persistent knee instability.[10] Although the underlying mechanism has not been identified, it might be explained by the damage of ACL graft
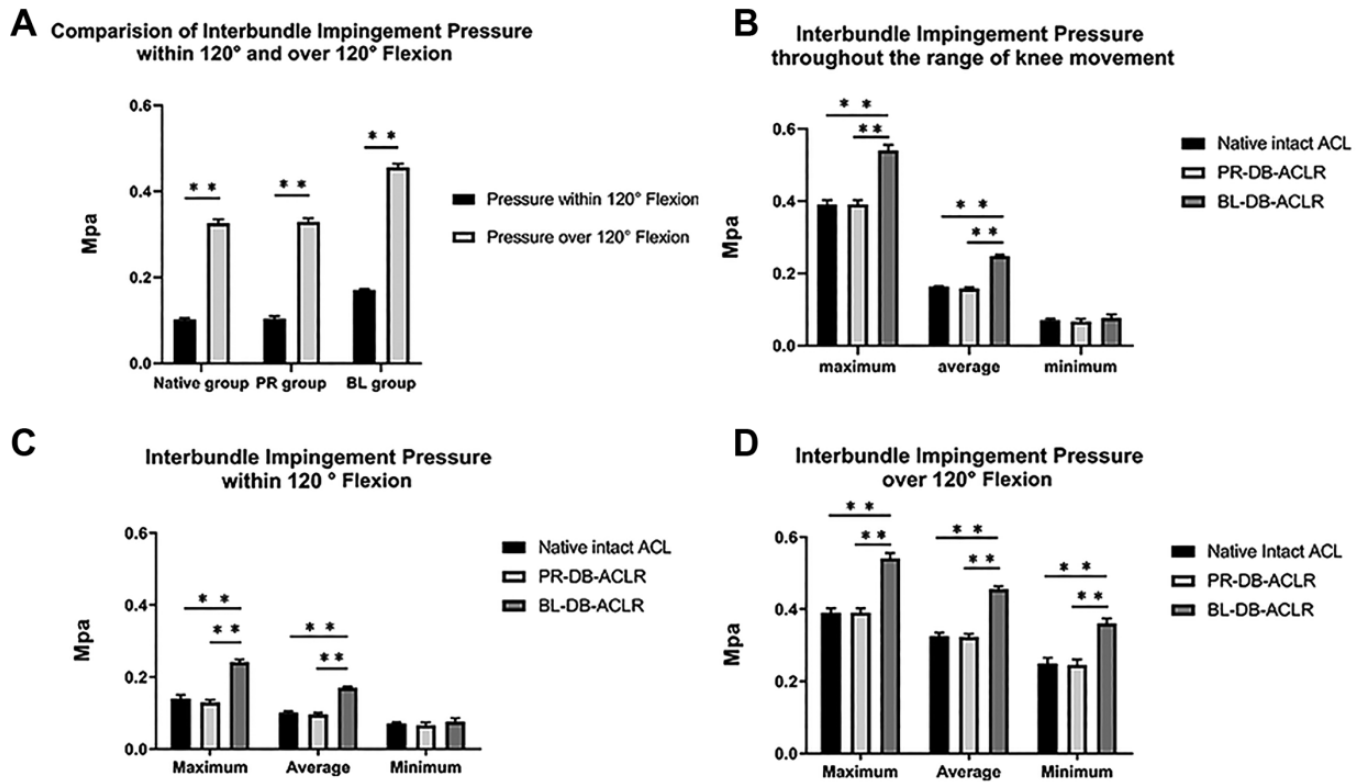
Figure 7. (A) All 3 groups had a significant increase in the IIP as the knee joint moved beyond 120°. (B and C) Compared with the other 2 groups, the BL group had significantly higher maximum and mean IIP throughout the range of knee movement and from the minimum to 120° of knee flexion. (D) The BL group also had a significantly higher minimum IIP than the other 2 groups beyond 120° of knee flexion. (B, C, and D) There were no significant differences in the maximum, minimum, or mean IIP among the NI and PR groups in any testing position. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; BL, bony landmark procedure; DB, double-bundle; IIP, interbundle impingement pressure; PR, preserved remnant procedure. **$P < .001$.

caused by a significant increase in maximum and/or mean impingement pressure, which affects the integrity of the grafts. Thus, avoiding graft impingement is essential to achieve optimal graft remodeling and good clinical results after ACLR.

Despite the goal of restoring the ACL to its original shape and original position as much as possible, the DB procedure places the graft at a greater risk of impingement with more crowding in high-traffic space compared with the SB procedure, unless the DB grafts are placed exactly in positions mimicking the native ACL. If the 2 tunnels are drilled relying solely on bony landmarks regardless of the numerous variations in the ACL footprints and bundle orientations,[21,24,29] the native ACL anatomic features might not be duplicated in all cases (particularly for the PL bundle).[23] Thus, there are reasonable grounds to believe that the BL procedure could lead to a condition in which DB-reconstructed grafts do not match the individual native anatomic features of the ACL. Therefore, DB-ACLR using the BL technique might cause more impingement than SB-ACLR, thus resulting in unsatisfactory clinical outcomes.

In a previous clinical study, Lu et al[23] demonstrated that the individualized DB-ACLR procedure based on the PR

technique yielded better arthroscopic second-look assessment results for ACL grafts, with no revision cases, than the nonindividualized DB-ACLR procedure based on the BL technique. However, the mechanism by which the PR technique protects grafts from damage is still unclear. Because the lack of impingement between the ACL and intercondylar roof and between the ACL and PCL is regularly confirmed by surgeons during DB-ACLR, it is possible that abnormal contact pressure between the AM and PL grafts (ie, interbundle impingement) may be an underlying cause of graft failure, especially for the relatively frail PL bundle. However, no published reports are available comparing graft impingement pressures between the PR and BL procedures. Although a few studies measuring ACL impingement have been conducted, no studies on the dynamic status of impingement pressure in ACLR have been reported. To the best of our knowledge, the present study is the first report comparing the dynamic status of impingement pressure between the native ACL and the DB-reconstructed ACL with different tunnel placement methods.

There are reasons to believe that the superiority of the PR technique lies in the fact that it is a complete anatomic
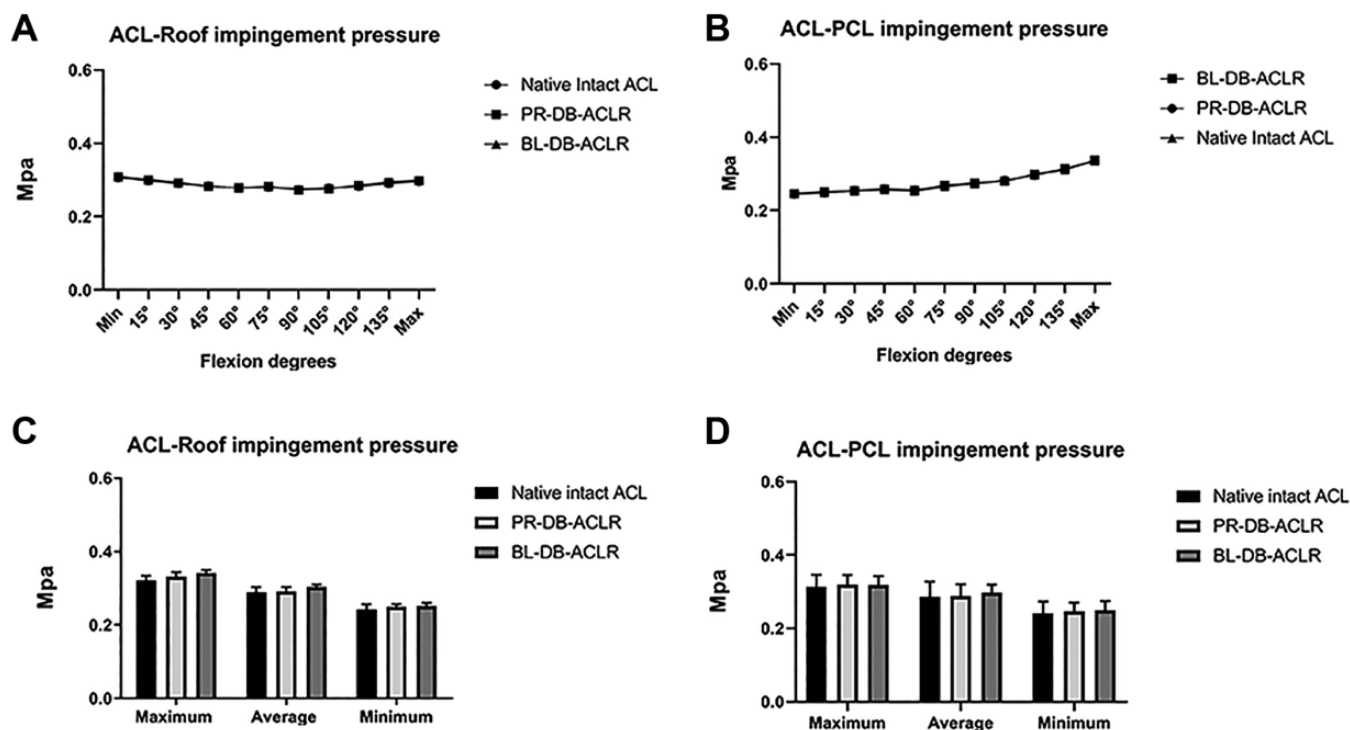
Figure 8. . The PR and BL groups did not have significant differences in the roof or PCL impingement pressure compared with the native intact group. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; BL, bony landmark procedure; DB, double-bundle; PCL, posterior cruciate ligament; PR, preserved remnant procedure.

reconstruction method that reproduces native ACL insertions and bundle orientations, thus leading to a more normal contact pressure between the 2 bundles. In contrast, the BL technique is an approximate simulative tunnel placement method that is always "off track" relative to the native bundle positions to some extent. The present study showed that there was a greater distance between both tibial and femoral tunnels in the BL group, which means closer contact of DB grafts in the BL group than the PR group. Under these circumstances, the 2 bundles will generate pathological impingement, which includes abnormally increased or prematurely occurring IIP during the range of knee motion. In our study, the BL group showed a significantly higher IIP within 120° of flexion than the PR or NI groups, which can be explained by the premature occurrence of tense interbundle contact with improper graft positioning.

Iriuchishima et al[15] performed anatomic DB-ACLR using double-bundle footprints for tunnel placement and found no significant difference in the ACL-roof, ACL-PCL, or IIP between the native ACL and DB-reconstructed ACL. Those investigators therefore concluded that anatomic DB-ACLR is an impingement-free reconstruction method. Our results were similar to those of Iriuchishima et al[15] regarding individualized DB-ACLR, and moreover we did not find significant differences in ACL-roof or ACL-PCL impingement pressures among any of the 3 groups studied. Theoretically, spatial displacement from the native ligament sites could result in abnormal contact between ACL grafts and surrounding structures, thus producing pathological ACL-roof and ACL-PCL impingement. The lack of significant impingement changes may be explained by the relative spatial distance of the different structures. The 2 bundles of the ACL tightly impinge against each other throughout the range of knee motion, so a slight deviation in the 2 bundles could bring about a significant change in the interbundle pressure, whereas the intercondylar roof and PCL are located relatively farther away from the ACL than the 2 bundles themselves. Consequently, a significant increase in the ACL-roof and ACL-PCL impingement pressure is relatively rare compared with an increase in the IIP. This discovery indicates that surgeons should pay careful attention to interbundle impingement in DB-ACLR, as it is more likely to be affected by graft displacement.

Another important finding of the present study is that the interbundle pressure of the ACL increased significantly at knee flexion angles of >120°. The ACL is not always isometric during knee motion. In the cadaveric study reported by Smith et al,[30] anatomic ACL positioning resulted in anisometry comparable with that of the native ACL. Lee et al[22] also found that the anatomic femoral tunnel was nonisometric. Kim et al[19] evaluated intraoperative graft isometry in anatomic SB-ACLR in vivo and found that the reconstructed ACL graft was isometric when the flexion angle of the knee was <90° and nonisometric when the flexion angle was ≥90°. Ebersole et al[7] compared the ACL graft length and tension throughout the knee range of motion among transtibial, AM portal, and all-epiphyseal >120° drilling techniques and found that all
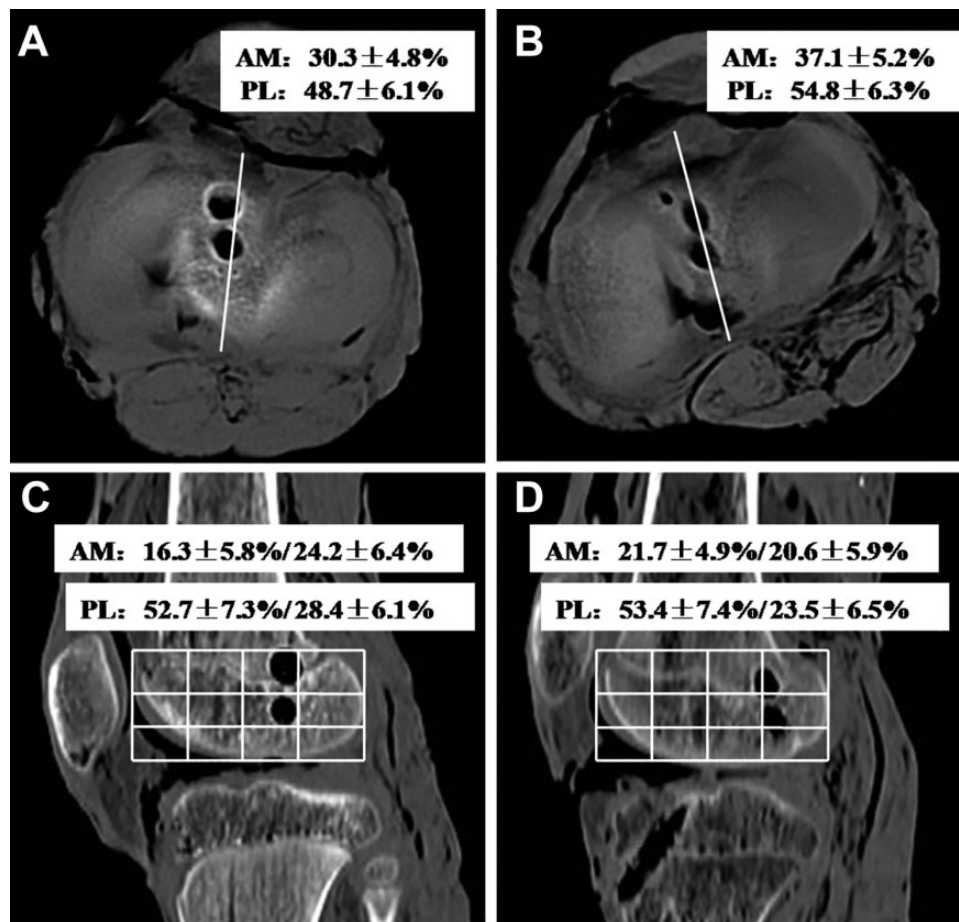
Figure 9. Postoperative computed tomography scans showing different anteromedial (AM) and posterolateral (PL) tunnel placements in the cadaveric knee. (A, C) Tunnel placements for preserved remnant group. (B, D) Tunnel placements for the bony landmark group.

techniques demonstrated decreased graft length and tension with knee flexion up to 60°, after which the graft length and tension increased with further knee flexion. Our results are in line with the results of these studies. The interbundle pressure remained basically unchanged under knee flexion up to 90° and increased past 90° of flexion, and the most significant increase in the impingement pressure occurred at knee flexion angles of >120°.

This phenomenon could be explained by the isometry of the ACL. Previous studies[12,15] have indicated that the PL bundle is taut at 0° of knee flexion, when the AM bundle is relaxed, whereas the AM bundle is taut at 90° of knee flexion, when the PL relaxed. From 0° to 90° of knee flexion, 1 bundle remains tense while another bundle remains relaxed, which leads to a relatively low interbundle pressure and basically no variation in the native ACL or PR-reconstructed grafts. With increasing degrees of flexion, more ACL fibers tend to be nonisometric, and there are reasons to conclude that both the AM and PL bundles become nonisometric under extreme flexion (>120°). However, BL-reconstructed grafts may break the rule of ACL isometry with

prematurely occurring anisometry of the 2 bundles, which results in a significantly higher interbundle pressure than that of the native ACL within 120° of flexion. Our practice is to avoid flexion >120° for 6 weeks after ACLR with the BL technique.

DB-ACLR has not shown definite clinical superiority over SB-ACLR. There may be a theoretical advantage of PR DB-ACLR over SB-ACLR, but that has not been proven. Regarding clinical relevance, surgeons can perform SB-ACLR or individualized DB-ACLR using preserved remnants for tunnel placement as an interbundle impingement-free reconstruction method when the remnant ACL footprint and bundle orientation can be clearly defined during the operation. Otherwise, to reduce the risk of graft failure caused by interbundle impingement, SB-ACLR is more advisable than nonindividualized DB-ACLR based on uniform landmark tunnel placement.

This study has some limitations. First, although the knees were reset to a physiological biomechanical status before the pressure test as much as possible, the knees were not loaded with a force comparable with that of a normal knee joint. However, Iriuchishima et al[15] verified

that a small load on the quadriceps and flexion muscle was sufficient to study impingement pressure with natural tibial rotation during the range of passive knee motion. Second, all tunnel placement procedures were performed only by macroscopic evaluation and careful dissection. Although an experienced surgeon performed the procedures, human error and bias might still have existed. Third, the average age of the cadaveric specimens was significantly higher than the average age of patients who undergo ACLR, and an effect of age on the impingement pressure cannot be eliminated. Fourth, the sensitivity of the pressure measurements may be another limitation of the study. Fifth, this was a time-zero study. Sixth, both bundles were fixed under maximal manual tension in the present study, and fixation tension might affect the IIP. Further investigation is needed to determine the IIP under different fixation tensions. Seventh, although the physiological IIP has been measured in the native ACL, we did not explore how much pressure increase would cause a pathological impingement.

CONCLUSION

This study evaluated the effect of 2 different double-tunnel placement methods on the IIP after DB-ACLR. The PR procedure (individualized DB-ACLR) was more consistent with the interbundle biomechanical conditions of the native ACL, whereas the BL procedure (nonindividualized DB-ACLR) had higher maximum and mean IIP. Interbundle pressure was higher than that of ACL-roof or ACL-PCL impingement pressures, and it increased significantly when knee flexion was >120°. Findings are valid only at the time of surgery, given that the effects of graft healing were not considered.

AUTHORS

Mingjin Zhong, MD, PhD (Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China); Ying Li, MD (Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China); Hao Li, MD (Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China); Wenzhe Feng, MD (Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China); Kang Chen, MD (Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China); Liangquan Peng, MD (Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China); Weiming Zhu, MD, PhD (Department of Sports Medicine, 1st Affiliated Hospital, Shenzhen University, Shenzhen, China).

REFERENCES

1. Aga C, Kartus JT, Lind M, Lygre SHL, Granan LP, Engebretsen L. Risk of revision was not reduced by a double-bundle ACL reconstruction technique: results from the Scandinavian registers. *Clin Orthop Relat Res*. 2017;475(10):2503-2512.

2. Aga C, Risberg MA, Fagerland MW, et al. No difference in the KOOS quality of life subscore between anatomic double-bundle and anatomic single-bundle anterior cruciate ligament reconstruction of the knee: a prospective randomized controlled trial with 2 years' follow-up. *Am J Sports Med*. 2018;46(10):2341-2354.

3. Ahldén M, Sernert N, Karlsson J, Kartus J. A prospective randomized study comparing double- and single-bundle techniques for anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41(11):2484-2491.

4. Buoncristiani AM, Tjoumakaris FP, Starman JS, Ferretti M, Fu FH. Anatomic double-bundle anterior cruciate ligament reconstruction. *Arthroscopy*. 2006;22(9):1000-1006.

5. Dienst M, Burks RT, Greis PE. Anatomy and biomechanics of the anterior cruciate ligament. *Orthop Clin North Am*. 2002;33(4):605-620.

6. Dong Z, Niu Y, Qi J, Song Y, Wang F. Long term results after double and single bundle ACL reconstruction: is there any difference? A meta-analysis of randomized controlled trials. *Acta Orthop Traumatol Turc*. 2019;53(2):92-99.

7. Ebersole GM, Eckerle P, Farrow LD, Cutuk A, Bledsoe G, Kaar S. Anterior cruciate ligament graft isometry is affected by the orientation of the femoral tunnel. *J Knee Surg*. 2016;29(3):260-266.

8. Forsythe B, Kopf S, Wong AK, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am*. 2010;92(6):1418-1426.

9. Girgis FG, Marshall JL, Monajem A. The cruciate ligaments of the knee joint: anatomical, functional and experimental analysis. *Clin Orthop Relat Res*. 1975;106:216-231.

10. Goss BC, Howell SM, Hull ML. Quadriceps load aggravates and roofplasty mitigates active impingement of anterior cruciate ligament grafts against the intercondylar roof. *J Orthop Res*. 1998;16(5):611-617.

11. Irarrazaval S, Albers M, Chao T, Fu FH. Gross, arthroscopic, and radiographic anatomies of the anterior cruciate ligament: foundations for anterior cruciate ligament surgery. *Clin Sports Med*. 2017;36(1):9-23.

12. Iriuchishima T, Ingham SJ, Tajima G, et al. Evaluation of the tunnel placement in the anatomical double-bundle ACL reconstruction: a cadaver study. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(9):1226-1231.

13. Iriuchishima T, Shirakura K, Fu FH. Graft impingement in anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(3):664-670.

14. Iriuchishima T, Tajima G, Ingham SJ, et al. Intercondylar roof impingement pressure after anterior cruciate ligament reconstruction in a porcine model. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(6):590-594.

15. Iriuchishima T, Tajima G, Ingham SJ, Shen W, Smolinski P, Fu FH. Impingement pressure in the anatomical and nonanatomical anterior cruciate ligament reconstruction: a cadaver study. *Am J Sports Med*. 2010;38(8):1611-1617.

16. Iriuchishima T, Tajima G, Ingham SJ, Shirakura K, Fu FH. PCL to graft impingement pressure after anatomical or non-anatomical single-bundle ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(5):964-969.

17. Järvelä S, Kiekara T, Suomalainen P, Järvelä T. Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective randomized study with 10-year results. *Am J Sports Med*. 2017;45(11):2578-2585.

18. Kim HS, Seon JK, Jo AR. Current trends in anterior cruciate ligament reconstruction. *Knee Surg Relat Res*. 2013;25(4):165-173.

19. Kim YK, Yoo JD, Kim SW, Park SH, Cho JH, Lim HM. Intraoperative graft isometry in anatomic single-bundle anterior cruciate ligament reconstruction. *Knee Surg Relat Res*. 2018;30(2):115-120.

20. Kongtharvonskul J, Attia J, Thamakaison S, Kijkunasathian C, Woratanarat P, Thakkinstian A. Clinical outcomes of double- vs single-bundle anterior cruciate ligament reconstruction: a systematic review of randomized control trials. *Scand J Med Sci Sports*. 2013;23(1):1-14.

21. Kopf S, Musahl V, Tashman S, Szczodry M, Shen W, Fu FH. A systematic review of the femoral origin and tibial insertion morphology of the ACL. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(3):213-219.

22. Lee JS, Kim TH, Kang SY, et al. How isometric are the anatomic femoral tunnel and the anterior tibial tunnel for anterior cruciate ligament reconstruction? *Arthroscopy*. 2012;28(10):1504-1512, e1501-e1502.

23. Lu W, Wang D, Zhu W, et al. Placement of double tunnels in ACL reconstruction using bony landmarks versus existing footprint remnant: a prospective clinical study with 2-year follow-up. *Am J Sports Med*. 2015;43(5):1206-1214.

24. Lu W, Zhu W, Peng L, et al. Femoral footprint variation of the posterolateral bundle of the anterior cruciate ligament and double-bundle reconstruction. *Knee*. 2015;22(3):169-173.

25. Mayr HO, Bruder S, Hube R, Bernstein A, Suedkamp NP, Stoehr A. Single-bundle versus double-bundle anterior cruciate ligament reconstruction-5-year results. *Arthroscopy*. 2018;34(9):2647-2653.

26. Orsi AD, Canavan PK, Vaziri A, Goebel R, Kapasi OA, Nayeb-Hashemi H. The effects of graft size and insertion site location during anterior cruciate ligament reconstruction on intercondylar notch impingement. *Knee*. 2017;24(3):525-535.

27. Shafizadeh S, Balke M, Hagn U, Grote S, Bouillon B, Banerjee M. Variability of landmark acquisition affects tunnel calculation in image-free ACL navigation. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(7):1917-1924.

28. Siebold R, Ellert T, Metz S, Metz J. Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. *Arthroscopy*. 2008;24(2):154-161.

29. Siebold R, Schuhmacher P, Fernandez F, et al. Flat midsubstance of the anterior cruciate ligament with tibial "C"-shaped insertion site. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(11):3136-3142.

30. Smith JO, Yasen S, Risebury MJ, Wilson AJ. Femoral and tibial tunnel positioning on graft isometry in anterior cruciate ligament reconstruction: a cadaveric study. *J Orthop Surg (Hong Kong)*. 2014;22(3):318-324.

31. Tanksley JA, Werner BC, Conte EJ, et al. ACL roof impingement revisited: does the independent femoral drilling technique avoid roof impingement with anteriorly placed tibial tunnels? *Orthop J Sports Med*. 2017;5(5):2325967117704152.

32. Thein R, Spitzer E, Doyle J, et al. The ACL graft has different cross-sectional dimensions compared with the native ACL: implications for graft impingement. *Am J Sports Med*. 2016;44(8):2097-2105.

33. Tsukada S, Fujishiro H, Watanabe K, et al. Anatomic variations of the lateral intercondylar ridge: relationship to the anterior margin of the anterior cruciate ligament. *Am J Sports Med*. 2014;42(5):1110-1117.

34. Udagawa K, Niki Y, Enomoto H, Toyama Y, Suda Y. Factors influencing graft impingement on the wall of the intercondylar notch after anatomic double-bundle anterior cruciate ligament reconstruction. *Am J Sports Med*. 2014;42(9):2219-2225.

35. Wilson R, Barhorst AA. Intercondylar notch impingement of the anterior cruciate ligament: a cadaveric in vitro study using robots. *J Healthc Eng*. 2018;2018:8698167.

36. Xu Y, Ao YF, Wang JQ, Cui GQ. Prospective randomized comparison of anatomic single- and double-bundle anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(2):308-316.

37. Yoon KH, Kim JS, Kim SJ, Park M, Park SY, Park SE. Eight-year results of transtibial nonanatomic single-bundle versus double-bundle anterior cruciate ligament reconstruction: clinical, radiologic outcomes and survivorship. *J Orthop Surg (Hong Kong)*. 2019;27(2):2309499019840827.