Creating a Femoral Tunnel Aperture at the Anteromedial Footprint Versus the Central Footprint in ACL Reconstruction

Comparison of Contact Stress Patterns

Sung-Jae Kim,* MD, Si Young Song,* MD, Tae Soung Kim,* MD, Yoon Sang Kim,[†]
Seong-Wook Jang,[†] and Young-Jin Seo,*[‡] MD, PhD

Investigation performed at Department of Orthopaedic Surgery, Hallym University, Dongtan Sacred Heart Hospital, Gyeonggi-do, Republic of Korea

Background: It remains unclear whether an anteromedial (AM) footprint or a central footprint anterior cruciate ligament (ACL) graft exhibits less contact stress with the femoral tunnel aperture. This contact stress can generate graft attrition forces, which can lead to potential graft failure.

Purpose/Hypothesis: The purpose of this study was to compare the difference in contact stress patterns of the graft around a femoral tunnel that is created at the anatomic AM footprint versus the central footprint. It was hypothesized that the difference in femoral tunnel positions would influence the contact stress at the interface between the reconstructed graft and the femoral tunnel orifice.

Study Design: Controlled laboratory study.

Methods: A total of 24 patients who underwent anatomic single-bundle ACL reconstruction were included in this study. In 12 patients, the femoral tunnels were created at the center of the native AM footprint (AM group), and in the remaining 12 patients the center of the femoral tunnel was placed in the anatomic central footprint (central group). Three-dimensional knee models were created and manipulated using several modeling programs, and the graft-tunnel angle (GTA) was determined using a special software program. The peak contact stresses generated on the virtual ACL graft around the femoral tunnel orifice were calculated using a finite element method.

Results: The mean GTA was significantly more obtuse in the AM group than in the central group (124.2° ± 5.9° vs 112.6° ± 7.9°; $P = .001$). In general, both groups showed high stress distribution on the anterior surface of the graft, which came in contact with the anterior aspect of the femoral tunnel aperture. The degree of stress in the central group (5.3 ± 2.6 MPa) was significantly higher than that in the AM group (1.2 ± 1.1 MPa) ($P < .001$).

Conclusion: Compared with the AM footprint ACL graft, the central footprint ACL graft developed significantly higher contact stress in the extended position, especially around the anterior aspect of the femoral tunnel orifice.

Clinical Relevance: The contact stress of the ACL graft at the extended position of the knee may be minimized by creating the femoral tunnel at the AM-oriented footprint.

Keywords: anterior cruciate ligament; reconstruction; graft-tunnel angle; contact stress

Although anatomic femoral tunnel placement is widely accepted in anterior cruciate ligament (ACL) reconstruction, the femoral tunnel in the anatomic single-bundle (SB) ACL reconstruction cannot capture the entire femoral footprint.[40] The center of the femoral tunnel is placed at the native anteromedial (AM) bundle or centrally between the AM and posterolateral (PL) bundles. Both femoral tunnel positions have been accepted as "anatomic." Each method is associated with its own advantages in terms of isometry and rotational stability. The enhanced isometry of anatomic AM footprint ACL reconstruction may have a protective effect against graft elongation during knee range of motion.[37,41]

Anatomic central footprint ACL reconstruction may overcome the potentially inferior rotational stability provided by the AM graft because a central graft position is

---

The Orthopaedic Journal of Sports Medicine, 9(4), 23259671211001802
DOI: 10.1177/23259671211001802

created between the AM and PL footprints in the hope of capturing the function of both the AM and the PL bundles.[8,12,18] Multiple cadaveric studies have shown that centrally placed anatomic SB reconstruction and anatomic double-bundle reconstruction have similar time-zero biomechanical outcomes, including both anterior and rotational stability.[14,15,23,24]

A recent biomechanical study using human cadavers demonstrated no biomechanical differences between the AM footprint and central footprint grafts at time zero.[7] That study compared the anterior and rotational stability of the AM and the central grafts. However, many surgeons are concerned about postoperative graft failure, which may be affected by other biomechanical factors associated with different tunnel positions. Stress load on the graft is regarded as one of these factors.[31] It is still unclear whether the AM or the central graft exhibits less contact stress–generating graft attritional force.

The purpose of this study was to compare the difference in graft contact stress patterns between a femoral tunnel created at the anatomic AM footprint and at the central footprint. We hypothesized that the femoral tunnel position would influence the contact stress at the interface between the reconstructed graft and the femoral tunnel orifice.

METHODS

Patient Characteristics and Surgical Procedures

This institutional review board–approved study included 24 patients (16 men and 8 women) who underwent anatomic SB ACL reconstruction. The mean ± SD age at the index operation was 35.4 ± 5.3 years (range, 18-49 years). Patients were excluded if they had multiple ligament injuries that required additional ligament surgery, had a partial ACL tear that required selective bundle reconstruction, or were undergoing revision ACL reconstruction or if their femoral tunnels were created in undesired positions, such as nonanatomic placement.

All operations were performed between December 2016 and November 2019 by a single surgeon (Y.J.S.) using a traditional transportal technique. In this study, the aiming point of the femoral tunnel center changed in 2018 from a central footprint to an AM footprint in response to several clinical and biomechanical studies demonstrating the higher failure rate in the central graft and major load-sharing behavior by the femoral AM region.[20,32,39]

Thus, in 12 patients, femoral tunnels measuring 8 to 10 mm in diameter were created at the center of the native AM footprint from the accessory AM (AAM) portal (AM group). A pilot hole of 5 mm in depth was made by the guide wire with the help of a 5- to 6-mm offset guide, which was introduced through the AAM portal. The use of an offset guide system enables reproducible femoral tunnel placement. The placement of the pilot hole was carefully inspected, and fine-tuning of the location was performed by piercing a microfracture awl through the AAM portal to establish a final marking.

In the remaining 12 patients, the center of the femoral tunnel was placed in the anatomic central footprint (located centrally between the AM and PL footprint) (central group). The AM portal was used to inspect the ACL femoral attachment. This portal enables visualization of the entire medial wall of the lateral femoral condyle. The center of the entire femoral footprint was identified by the tissue remnants and the intercondylar and bifurcate ridges. A single 8- to 10-mm tunnel was then drilled in the center of the ACL femoral insertion site.

The final reaming process for the femoral tunnel was conducted through the AAM portal at 120° of knee flexion in both groups, and the angle of knee flexion was verified using a sterilized goniometer during the surgery. The tibial tunnel was created within the native tibial footprint corresponding to each center of the femoral tunnel. Doubled semitendinosus and gracilis tendon autografts or doubled loops of tibialis anterior allograft over a suspensory fixation system (EndoButton CL; Smith & Nephew Endoscopy) were used as grafts for both groups. After the graft was passed, the knee was then cycled 20 times under constant manual tension to eliminate creep, and then tibial fixation was conducted with the knee in full extension using a bioabsorbable interference screw of the same diameter as the tunnel and reinforced with a 5.0-mm cancellous screw and spiked washer (Smith & Nephew). The tibial fixation methods were identical in both groups.

The operated knees were scanned via a high-resolution computed tomography (CT) (Siemens) scanner using 1-mm slices in neutral rotation and full extended position at a mean of 3.7 ± 2.4 days postoperatively. The postoperative CT and arthroscopic images were retrospectively evaluated to inspect precise locations of the femoral tunnel.

3-Dimensional Models of the Knee and Graft

The DICOM (Digital Imaging and Communications in Medicine) file of the CT images was imported using the Rapidform 2006 program (Rapidform INUS). Using a reverse-engineering process, 3-dimensional (3D) models of the knee were constructed by interpolating the slices made

---

[‡]Address correspondence to Young-Jin Seo, MD, PhD, Department of Orthopaedic Surgery, Hallym University, Dongtan Sacred Heart Hospital, 7, Keunjaebong-gil, Hwaseong, Gyeonggi-do, 18450, Republic of Korea (email: yjseo-os@hanmail.net).

[*]Department of Orthopaedic Surgery, Hallym University, Dongtan Sacred Heart Hospital, Hwaseong, Gyeonggi-do, Republic of Korea.

[†]BioComputing Lab, School of Computer Science and Engineering, Korea University of Technology and Education (KOREATECH), Cheonan, Republic of Korea.

Final revision submitted November 4, 2020; accepted December 15, 2020

The authors declared that there are no conflicts of interest in the authorship and publication of this contribution. 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.

Ethical approval for this study was obtained from Dongtan Sacred Heart Hospital, Hwaseong, Gyeonggi-do, Republic of Korea.

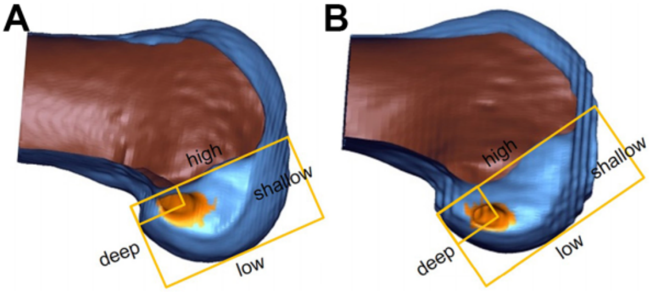

Figure 1. Lateral view of reconstructed 3-dimensional knee model. The medial and femoral condyles were superimposed, and the medial femoral condyle was deleted to provide a strict lateral position of the lateral femoral condyle. (A) An anteromedial (AM)–oriented graft tunnel and (B) a central graft tunnel. The AM-oriented graft tunnel was positioned higher and deeper than was the central graft tunnel.

by stacking separate regions based on image-processing methods. The reconstructed 3D models were identical to the morphology of the operated knees placed in neutral rotation and full extension. We have verified the anatomic interpretation and accuracy of the image processing algorithms in a separate study.[17]

The measurement of femoral tunnel locations was determined based on a true side view of the 3D model, according to the method of Forsythe et al[11] (Figure 1). The true side view of the 3D knee model was established after the medial and lateral femoral condyles were superimposed, followed by removal of the medial condyle image at the center of the intercondylar notch. The femoral tunnel positions were determined in the posterior-to-anterior (deep/shallow) and proximal-to-distal (high/low) directions and are presented as the percentage distance from the posterior border of the lateral femoral condyle and intercondylar notch roof, similar to the radiographic quadrant method of Bernard et al.[3] Measurements were performed by 2 orthopaedic surgeons (Y.J.S., T.S.K.) twice with a 1-week interval between measurements.

The femoral graft-tunnel angle (GTA), which affects the stress patterns on the graft, was determined using a special software program (Rapidform). The GTA was defined as the angle between a virtual ACL line connecting the centers of the femoral and tibial tunnel apertures and an axial line along the center of the femoral socket (Figure 2).

The virtual graft was modeled as a nonlinear hyperelastic material and inserted into the corresponding bone tunnel (Figure 3). The hyperelastic model is generally used in engineering applications to represent human knee ligament. The model is characterized by strain energy potential, represented by mathematical equations.[38,46] After the femoral end of the graft was fixed, the tibial side of the graft was fixed at the middle in the tibial tunnel under 40 N of tension at full extension to simulate the suspensory fixation. The grafts were bonded to the tunnel by use of mesh tie kinematic constraints. The degree of the tension applied to the graft was determined based on previous testing protocols demonstrating the graft tension required to match intact knee laxity.[7,30]

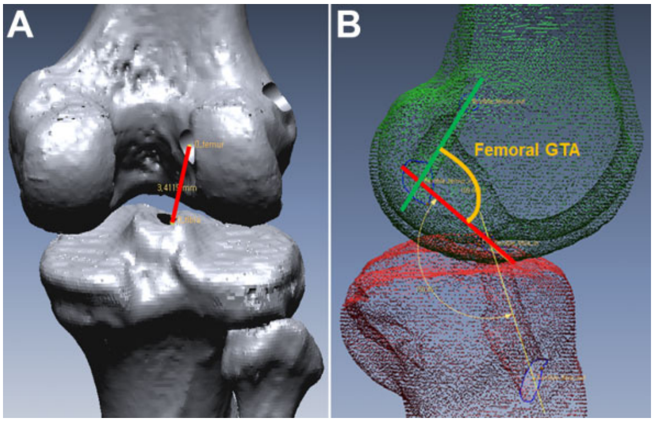

Figure 2. Measurement of femoral graft-tunnel angle (GTA). The GTA was defined as the angle between a virtual anterior cruciate ligament (ACL) line connecting the centers of the femoral and tibial tunnel apertures and an axial line along the center of the femoral socket. (A) Posterior view of the virtual ACL line (red line). (B) Lateral view of the femoral GTA with the virtual ACL line (red line) and the axial line of the femoral socket (green line).

Figure 3. The virtual graft was inserted into the corresponding bone tunnel.

The rigidity of the femur and tibia was attributed to their significantly higher stiffness compared with that of soft tissues. The potential frictional contact was induced by the graft wrapping around the bone tunnel edge. Several potential contact sites were triggered, and the value of the contact stress was determined using finite element analysis with ABAQUS/Explicit code.

Statistical Analysis

The femoral tunnel locations, the femoral GTA, and the contact stress in the 2 groups were compared using the Student t test. Statistical significance was set at $P < .05$.

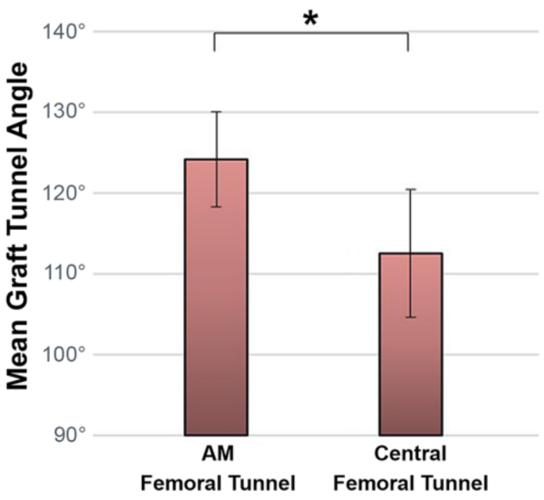

Figure 4. Comparison of the mean femoral graft-tunnel angle between groups. Error bars indicate SDs. *Statistically significant difference ($P < .05$). AM, anteromedial.

All statistical analyses were performed using SPSS for Windows (Version 12.0; SPSS Inc).

An a priori power analysis was conducted using G*Power (Version 3.1.2) to determine the sample size required to detect a between-group difference of 4.0 MPa in contact stress based on preliminary data.[10] Alpha was set at .05, and the power was set at 0.8. The calculations showed that a minimum of 10 patients per group was required to detect between-group differences in contact stress. Hence, 12 patients per group were identified as enough to detect significance between the groups.

The inter- and intraobserver reliability of the femoral tunnel location measurements were calculated using the intraclass correlation coefficient (ICC).

RESULTS

Femoral Tunnel Position

The femoral tunnel for the AM group was located at 29.3% ± 4.1% in the posterior-to-anterior direction and at 25.3% ± 4.5% in the proximal-to-distal direction. The femoral tunnel of the central femoral tunnel group was located at 36.3% ± 5.3% in the posterior-to-anterior direction and at 40.3% ± 5.8% in the proximal-to-distal direction. Significant differences were noted regarding the percentage difference in the mean femoral tunnel locations between the 2 groups in terms of the posterior-to-anterior and proximal-to-distal directions ($P = .001$ and $P < .001$, respectively). The ICC values for the inter- and intraobserver reliability were 0.92 and 0.95, respectively, which was considered to be excellent.

Graft-Tunnel Angle

The mean graft/femoral tunnel angle was 124.2° ± 5.9° in the AM group and 112.6° ± 7.9° in the central group. The mean GTA was significantly obtuse in the AM group compared with the central group ($P = .001$). The intergroup comparison of the femoral GTA is illustrated in Figure 4.

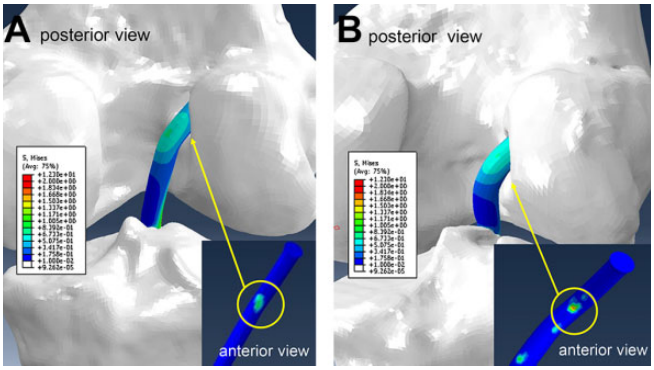

Figure 5. Stress patterns at the interaction between the graft and surrounding bone for the (A) anteromedial (AM) graft and (B) central graft. Circles detail the anterior view of the graft, where bony structure was removed. The contact stresses generated by the anterior tunnel edge on the graft were higher in the central graft than in the AM graft.

Contact Stress

Local contact stress was the highest when the grafts wrapped over the sharp edges of the tunnels and bent to create an acute angle (Figure 5). The highest localized stress occurred at the tunnel edge of the femur in a very small area, possibly resulting in graft damage.

In general, both groups showed high stress distribution on the anterior surface of the graft, which contacted the surrounding bony structure at the anterior aspect of the femoral tunnel aperture. The mean ± SD highest stress was 5.3 ± 2.6 MPa in the central group, which was significantly higher than in the AM group (1.2 ± 1.1 MPa; $P < .001$). The fringe pattern distribution of the contact stresses is presented in Figure 6.

DISCUSSION

The most important finding of this study was that the central footprint ACL graft generated significantly greater contact stress at the edge of the femoral tunnel than did the AM footprint ACL graft. The AM footprint ACL reconstruction group showed greater GTA than did the central footprint ACL reconstruction group. Sharper turning of the graft at the tunnel orifice may trigger higher contact stress at the interface between the graft and the bone tunnel edge.

Many surgeons have attempted to reproduce the anatomy as closely as possible by placing the femoral bundles in the center of the native insertion sites between the native AM and PL footprints. The central tunnel has been regarded as “anatomic” based on several anatomic and biomechanical studies arguing that the central femoral footprint tunnel position is intuitively the anatomic

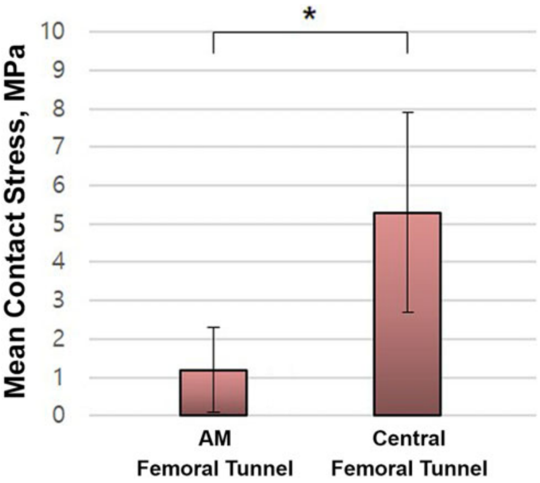

Figure 6. Comparison of the mean highest contact stresses between groups. Error bars indicate SD. *Statistically significant difference ($P < .05$). AM, anteromedial.

position, which provides superior rotational stability.[2,5,9,12,34]

The trend suggested a shift in femoral tunnel placement from the nonanatomic high-noon position to a lower position abutting the inferior cartilage margin, which covered the footprint maximally at the center of the femoral footprint.[11,19,33] However, this lower and centrally placed tunnel reveals indirect insertion, which plays a less significant role when compared with the direct insertion.[42,45]

Based on several histologic and biomechanical studies, an eccentric femoral socket within the native femoral footprint as well as the direct insertion and AM bundle orientation has been advocated.[32,36,39] The eccentric location of the femoral tunnel has been demonstrated to provide better isometry than the central femoral tunnel provides. A previous cadaveric study by Lubowitz[25] demonstrated that the centrally located ACL graft reached its maximum length at full knee extension, followed by a gradual decrease in length under increased knee flexion. The degree of the length change in the central graft was greater than that in the AM bundle–oriented graft.

Previous studies have reported that this nonisometric behavior of the central graft is a physiologic phenomenon.[4,26,27] However, the centrally located ACL graft, which was finally fixated at the extension position, slackened under knee flexion, resulting in undesirable knee laxity, especially in the flexed knee position. In addition, if this central graft was fixated in the flexed position, excessive tension was generated within the graft, resulting in potential graft failure.[4,26,27]

Thus, the term “revisitation” has been recently suggested based on isometry, which is also one of the important biomechanical factors preventing undesirable knee laxity or potential graft failure due to excessive tension according to the final fixation angle of the graft.[25,32,49]

According to the cadaveric study conducted by Kawaguchi et al,[20] the fibers attached to the AM direct fiber yielded a graft load ranging from 66% to 84% of the total resistance to the anterior drawer. The study also showed that the AM direct fiber was most important in resisting the rotational force.

Previously, central graft placement was performed based on the concept of maximal footprint coverage. Thus, an excessively inferior femoral tunnel was created, resulting in a graft location within the indirect insertion area where the contribution of the load was relatively low.[29,36,42]

Furthermore, several studies, such as the Danish Knee Ligament Reconstruction Register[39] and the prospective and comparative study of Clatworthy et al,[6] reported that the central graft yielded a higher revision rate than the AM graft. The Danish registry study proposed that the steep technical learning curve resulted in higher failure using the transportal technique targeting the femoral central footprint. However, Clatworthy et al suggested another cause for the high failure rate in the central femoral ACL graft, based on the high-volume ACL experience. They concluded that transportal central femoral tunnel ACL reconstruction resulted in a higher and earlier failure rate than did the transtibial AM femoral tunnel ACL reconstruction. Furthermore, they reported a lower failure rate in an ongoing study of the AM femoral tunnel drilled transportally. These findings have been corroborated by several biomechanical studies demonstrating that a low femoral tunnel position, which is regarded as the central graft, may experience excessive force due to greater length change during the knee range of motion.[25,26,32] These previous studies speculated that the trend toward lower tunnel placement in the femoral footprint was detrimental to the graft.

However, some surgeons still believe that increased risk for failure in lower ACL graft is due to increased graft force in the lower flexion angle, implying that the lower position of the ACL graft works well.[1,2,8,12,18] This concept conflicts with the foregoing studies demonstrating the eccentric location of the AM graft in the femoral footprint bears the major load distribution.[20,32] Furthermore, there is a paucity of solid evidence showing that the increased graft strain is related to the increased risk of ACL revision. In addition, no significant differences have been reported between the central and AM grafts in terms of anterior and rotational stability at time zero.[7]

Hence, we investigated factors other than the kinematic stability of the postoperative knee to determine the optimal femoral tunnel placement. The AM graft through a transportal technique lies in a different trajectory in the distal femur compared with that of the central graft because of the different center of the femoral tunnel. These different trajectories of the ACL graft could yield different biomechanical consequences, such as stress patterns around the femoral tunnel, which could be affected by different femoral GTAs. In particular, stresses arising on the graft that result from the interaction between the ACL graft and edge of the bone tunnels have not been well investigated. Increased contact pressure around the femoral tunnel may abrade the graft, subsequently resulting in graft failure.

We, therefore, focused on the contact stress arising at the interface between the graft and the surrounding bony structures. Several studies have demonstrated the effects of acute bending on the development of attritional force on the graft.[28,31] A recent cadaveric biomechanical study demonstrated that differences in graft bending angle at the tunnel entrance generated different peak contact pressures, suggesting that increased acute bending of the graft resulted in greater peak contact pressures.[28,31]

The finite element model of the ACL by Song et al[43] revealed an interaction between the grafts and the bony structures, suggesting that the development of contact stress on the graft was influenced by the intensity of the frictional force. The results of the finite element study of Kim et al[21] that analyzed the local contact stress of the double-bundle ACL graft were consistent with results of this study on the effect of GTA on the contact pressure on the graft. They have demonstrated that the contact stress was highest when the grafts wrapped over the sharp edges of the tunnels.[21] In this study, the contact stress was also induced and calculated using the finite element tools. The GTA had a possible effect on the contact stress on the grafts triggered by the interaction between the graft and the tunnel edge when the graft bent around the tunnel orifice.

The results of this study are clinically relevant because the graft's contact stress at the extended position was minimized by creating the femoral tunnel at the AM-oriented footprint. Given the previous reviews regarding the locations of the native AM and PL footprints, our results regarding the central and AM femoral tunnel locations are consistent with the locations of the native femoral footprint demonstrated by previous anatomic studies.[3,11,22,35]

As discussed earlier, it is well known that excessive tension due to graft elongation occurs in low-placed graft near 0°, which occasionally results in graft failure during simulated loading tests.[4,25-27,32] On the other hand, contact stress between the graft and the tunnel aperture could be another cause of graft failure because contact between grafts and surrounding bone may also induce graft stretching without an increment in distance between the insertion points.[21] In addition, stress generated by frictional contact between the graft and the tunnel aperture could be a possible cause of graft abrasion. Thus, the findings of recent clinical studies, suggesting a significantly higher rate of graft failure in the central footprint ACL reconstruction group than in the AM footprint reconstruction group, could be reinforced by our results.[6,39]

However, the results and clinical relevance of this study should be carefully interpreted in light of its several limitations. First, the effect on potential graft failure of an approximate 10° difference in GTA and 4-MPa difference in contact stress has yet to be clearly defined. Second, the realistic biomechanical representation of the graft was limited because the virtual graft used in this study was created on the basis of biomechanical properties such as hyperelasticity and incompressibility. Hyperelasticity and incompressibility have been widely used in finite element modeling of the ligament to describe large deformation with an assumption of negligible time- and rate-dependent effects in the preconditioned state.[13,47,48] Further studies are needed for the development of more realistic tissue properties under the finite element modeling process. Third, we did not plot the changes in graft contact stress according to the various knee flexions. Because we did not test different knee flexion angles, we did not represent the entire knee biomechanics, such as gliding or the screw home mechanism. Instead, we compared the highest contact stress between the AM and central grafts with the knee in full extension because the maximum stress is generated between bone and the ACL graft under full knee extension, based on the previous biomechanical studies.[16,21] In addition, the amounts of radiation administered to the patients could be minimized by positioning the operated knees at only 1 flexion angle (fully extended position) during scanning. Fourth, we did not compare the size of the femoral tunnels, and thus this variable may play a role. Fifth, with respect to intra-articular graft rupture patterns, the risk of potential proximal graft rupture could be extrapolated by our simulated model ACL graft, whereas a clinical study by van Eck et al[44] following SB ACL reconstruction reported that the most common rupture pattern was elongation of the graft (58.3%), followed by proximal rupture (21.7%). Although data regarding the tunnel location were not available in the study of van Eck et al,[44] the clinical effect of our results on gradual elongation of the graft could be elucidated by future investigations.

CONCLUSION

Compared with the AM footprint ACL graft, the central footprint ACL graft developed significantly higher contact stress in the extended position, especially around the anterior aspect of the femoral tunnel aperture.

REFERENCES

1. Araujo PH, Asai S, Pinto M, et al. ACL graft position affects in situ graft force following ACL reconstruction. *J Bone Joint Surg Am*. 2015;97(21):1767-1773.
2. Bedi A, Musahl V, Steuber V, et al. Transtibial versus anteromedial portal reaming in anterior cruciate ligament reconstruction: an anatomic and biomechanical evaluation of surgical technique. *Arthroscopy*. 2011;27(3):380-390.
3. Bernard M, Hertel P, Hornung H, Cierpinski T. Femoral insertion of the ACL: radiographic quadrant method. *Am J Knee Surg*. 1997;10(1):14-22.
4. Beynnon BD, Uh BS, Johnson RJ, et al. The elongation behavior of the anterior cruciate ligament graft in vivo: a long-term follow-up study. *Am J Sports Med*. 2001;29(2):161-166.
5. Chu CR, Williams AA, West RV, et al. Quantitative magnetic resonance imaging UTE-T2* mapping of cartilage and meniscus healing after anatomic anterior cruciate ligament reconstruction. *Am J Sports Med*. 2014;42(8):1847-1856.
6. Clatworthy M, Sauer S, Roberts T. Transportal central femoral tunnel placement has a significantly higher revision rate than transtibial AM femoral tunnel placement in hamstring ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(1):124-129.
7. Cross MB, Musahl V, Bedi A, et al. Anteromedial versus central single-bundle graft position: which anatomic graft position to choose? *Knee Surg Sports Traumatol Arthrosc*. 2012;20(7):1276-1281.

8. Driscoll MD, Isabell GP Jr, Conditt MA, et al. Comparison of 2 femoral tunnel locations in anatomic single-bundle anterior cruciate ligament reconstruction: a biomechanical study. *Arthroscopy*. 2012;28(10):1481-1489.
9. Duffee A, Magnussen RA, Pedroza AD, et al. Transtibial ACL femoral tunnel preparation increases odds of repeat ipsilateral knee surgery. *J Bone Joint Surg Am*. 2013;95(22):2035-2042.
10. Faul F, Erdfelder E, Lang A-G, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*. 2007;39:175-191.
11. 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.
12. Fu FH, van Eck CF, Tashman S, Irrgang JJ, Moreland MS. Anatomic anterior cruciate ligament reconstruction: a changing paradigm. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(3):640-648.
13. Fung YC. *Biomechanics: Mechanical Properties of Living Tissues*. Springer Science & Business Media; 2013.
14. Goldsmith MT, Jansson KS, Smith SD, et al. Biomechanical comparison of anatomic single- and double-bundle anterior cruciate ligament reconstructions: an in vitro study. *Am J Sports Med*. 2013;41(7):1595-1604.
15. Herbort M, Domnick C, Raschke MJ, et al. Comparison of knee kinematics after single-bundle anterior cruciate ligament reconstruction via the medial portal technique with a central femoral tunnel and an eccentric femoral tunnel and after anatomic double-bundle reconstruction: a human cadaveric study. *Am J Sports Med*. 2016;44(1):126-132.
16. Hoshino Y, Kuroda R, Nishizawa Y, et al. Stress distribution is deviated around the aperture of the femoral tunnel in the anatomic anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(4):1145-1151.
17. Jang SW, Seo YJ, Yoo YS, Kim YS. Computed tomographic image analysis based on FEM performance comparison of segmentation on knee joint reconstruction. *Sci World J*. 2014;2014:235858.
18. Kato Y, Ingham SJ, Kramer S, et al. Effect of tunnel position for anatomic single-bundle ACL reconstruction on knee biomechanics in a porcine model. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(1):2-10.
19. Kato Y, Maeyama A, Lertwanich P, et al. Biomechanical comparison of different graft positions for single-bundle anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(4):816-823.
20. Kawaguchi Y, Kondo E, Takeda R, et al. The role of fibers in the femoral attachment of the anterior cruciate ligament in resisting tibial displacement. *Arthroscopy*. 2015;31(3):435-444.
21. Kim HY, Seo YJ, Kim HJ, et al. Tension changes within the bundles of anatomic double-bundle anterior cruciate ligament reconstruction at different knee flexion angles: a study using a 3-dimensional finite element model. *Arthroscopy*. 2011;27(10):1400-1408.
22. Kim YM, Joo YB, Lee KY, Hwang SJ. Femoral footprint for anatomical single-bundle anterior cruciate ligament reconstruction: a cadaveric study. *Knee Surg Relat Res*. 2018;30(2):128-132.
23. Kondo E, Merican AM, Yasuda K, Amis AA. Biomechanical comparison of anatomic double-bundle, anatomic single-bundle, and nonanatomic single-bundle anterior cruciate ligament reconstructions. *Am J Sports Med*. 2011;39(2):279-288.
24. Lord BR, El-Daou H, Sabnis BM, et al. Biomechanical comparison of graft structures in anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(2):559-568.
25. Lubowitz JH. Anatomic ACL reconstruction produces greater graft length change during knee range-of-motion than transtibial technique. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(5):1190-1195.
26. Markolf KL, Park S, Jackson SR, McAllister DR. Anterior-posterior and rotatory stability of single and double-bundle anterior cruciate ligament reconstructions. *J Bone Joint Surg Am*. 2009;91(1):107-118.
27. Markolf KL, Park S, Jackson SR, McAllister DR. Contributions of the posterolateral bundle of the anterior cruciate ligament to anterior-posterior knee laxity and ligament forces. *Arthroscopy*. 2008;24(7):805-809.
28. Mehta A, Lin CC, Campbell RA, et al. Effects of anteromedial portal versus transtibial ACL tunnel preparation on contact characteristics of the graft and the tibial tunnel aperture. *Clin Orthop Surg*. 2019;11(1):52-59.
29. Moulton SG, Steineman BD, Haut Donahue TL, et al. Direct versus indirect ACL femoral attachment fibres and their implications on ACL graft placement. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(1):165-171.
30. Naghibi H, Janssen D, Van Tienen T, et al. A novel approach for optimal graft positioning and tensioning in anterior cruciate ligament reconstructive surgery based on the finite element modeling technique. *Knee*. 2020;27(2):384-396.
31. Narvy SJ, Hatch GF III, Ihn HE, et al. Evaluating the femoral-side critical corner in posterior cruciate ligament reconstruction: the effect of outside-in versus inside-out creation of femoral tunnels on graft contact pressure in a synthetic knee model. *Arthroscopy*. 2017;33(7):1370-1374.
32. Nawabi DH, Tucker S, Schafer KA, et al. ACL fibers near the lateral intercondylar ridge are the most load bearing during stability examinations and isometric through passive flexion. *Am J Sports Med*. 2016;44(10):2563-2571.
33. Niki Y, Matsumoto H, Hakozaki A, et al. Anatomic double-bundle anterior cruciate ligament reconstruction using bone-patellar tendon-bone and gracilis tendon graft: a comparative study with 2-year follow-up results of semitendinosus tendon grafts alone or semitendinosus-gracilis tendon grafts. *Arthroscopy*. 2011;27(9):1242-1251.
34. Okafor EC, Utturkar GM, Widmyer MR, et al. The effects of femoral graft placement on cartilage thickness after anterior cruciate ligament reconstruction. *J Biomech*. 2014;47(1):96-101.
35. Parkar AP, Adriaensen M, Vindfeld S, Solheim E. The anatomic centers of the femoral and tibial insertions of the anterior cruciate ligament: a systematic review of imaging and cadaveric studies reporting normal center locations. *Am J Sports Med*. 2017;45(9):2180-2188.
36. Pathare NP, Nicholas SJ, Colbrunn R, McHugh MP. Kinematic analysis of the indirect femoral insertion of the anterior cruciate ligament: implications for anatomic femoral tunnel placement. *Arthroscopy*. 2014;30(11):1430-1438.
37. Pearle AD, Shannon FJ, Granchi C, Wickiewicz TL, Warren RF. Comparison of 3-dimensional obliquity and anisometric characteristics of anterior cruciate ligament graft positions using surgical navigation. *Am J Sports Med*. 2008;36(8):1534-1541.
38. Pioletti DP, Rakotomanana LR, Benvenuti JF, Leyvraz PF. Viscoelastic constitutive law in large deformations: application to human knee ligaments and tendons. *J Biomech*. 1998;31(8):753-757.
39. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind MC. Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Register. *Arthroscopy*. 2013;29(1):98-105.
40. Robinson J, Stanford FC, Kendoff D, Stuber V, Pearle AD. Replication of the range of native anterior cruciate ligament fiber length change behavior achieved by different grafts: measurement using computer-assisted navigation. *Am J Sports Med*. 2009;37(7):1406-1411.
41. Sapega AA, Moyer RA, Schneck C, Komalahiranya N. Testing for isometry during reconstruction of the anterior cruciate ligament: anatomical and biomechanical considerations. *J Bone Joint Surg Am*. 1990;72(2):259-267.
42. Siebold R. The concept of complete footprint restoration with guidelines for single- and double-bundle ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(5):699-706.

43. Song Y, Debski RE, Musahl V, Thomas M, Woo SL. A three-dimensional finite element model of the human anterior cruciate ligament: a computational analysis with experimental validation. *J Biomech*. 2004;37(3):383-390.
44. van Eck CF, Kropf EJ, Romanowski JR, et al. Factors that influence the intra-articular rupture pattern of the ACL graft following single-bundle reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011; 19(8):1243-1248.
45. van Eck CF, Schkrohowsky JG, Working ZM, Irrgang JJ, Fu FH. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. *Am J Sports Med*. 2012;40(4):800-807.
46. Veronda DR, Westmann RA. Mechanical characterization of skin-finite deformations. *J Biomech*. 1970;3(1):111-124.
47. Weiss JA, Maker BN, Govindjee S. Finite element implementation of incompressible, transversely isotropic hyperelasticity. *Comput Methods Appl Mech Eng*. 1996;135(1-2):107-128.
48. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex: the effects of specimen age and orientation. *Am J Sports Med*. 1991;19(3):217-225.
49. Xu Y, Liu J, Kramer S, et al. Comparison of in situ forces and knee kinematics in anteromedial and high anteromedial bundle augmentation for partially ruptured anterior cruciate ligament. *Am J Sports Med*. 2011;39(2):272-278.