How Isometric Are the Anatomic Femoral Tunnel and the Anterior Tibial Tunnel for Anterior Cruciate Ligament Reconstruction?

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Purpose: The purpose of this study was to evaluate the isometry of an anatomic femoral tunnel and anterior tibial tunnel positions. **Methods:** Tibial tunnels were made at 2 different locations in 10 cadaveric knees: the conventional tunnel and a more anterior position. Three-dimensional computed tomography (CT) scanning was then performed at 0°, 30°, 60°, 90°, and 120°. After removal of the anterior cruciate ligament from its femoral attachment, the 2 different femoral tunnels were marked at (1) the vertical femoral tunnel point and (2) the anatomic femoral tunnel point. After scans were repeated for coordinate transformation, the change in length between the tunnels was calculated with imaging software (OsiriX, version 3.2; Apple, Cupertino, CA) and the center of rotation for the femoral tunnels was calculated with a least squares fitting algorithm. **Results:** The conventional tibial tunnel–vertical femoral tunnel combination showed the least excursion as knee flexion angle changed. The vertical femoral tunnel combination groups showed a trend toward increasing length as the knee flexion angle increased. In contrast, the anatomic femoral tunnel combination groups displayed a trend toward decreased length with increasing knee flexion. At less than 30° of flexion, the tibial anterior–anatomic femoral tunnel showed the least excursion. **Conclusions:** The anatomic femoral tunnel was nonisometric, and the differences in isometry for each tunnel type were explained primarily by differences in relations between the centers of rotation of tunnels and tunnel position. When a femoral anatomic tunnel is chosen for anterior cruciate ligament reconstruction, the anterior tibial tunnel offers greater isometric benefits than the conventional tibial tunnel, especially in near full extension. **Clinical Relevance:** The distance between anatomic femoral and tibial tunnels is greatest in full extension and decreases with flexion. This would result in graft laxity. The surgeon should give consideration to a more anterior tibial tunnel position, which shows less excursion in early flexion.

Over the last several years, there has been growing interest in anatomic reconstruction of the anterior cruciate ligament (ACL) instead of isometric reconstruction using a proximal, deep femoral tunnel.[1-4] In addition, because the transtibial tunnel technique has been replaced by the anteromedial (AM) portal technique to

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construct these anatomic femoral tunnels, the tibial tunnel position may also be varied to offer potential biomechanical benefits. Furthermore, because the femoral tunnel shifts to a more horizontal position, the tibial tunnel can be made in a more anterior position than the classic tibial tunnel without roof impingement. Theoretically, a more anteriorly placed tunnel offers a more horizontal graft to resist anterior displacement.

There is great enthusiasm for ACL reconstruction using anatomic femoral tunnels because such tunnels are believed to confer increased rotational stability and tensioning patterns that are more consistent with the native ACL,[1,2,4-7] but little has been described about the isometry of these new tunnel positions, which is closely related to the graft tension throughout the range of motion.

The purpose of this study was to evaluate the isometry of an anatomic femoral tunnel and anterior tibial tunnel positions compared with a vertical femoral tunnel and conventional tibial tunnel positions. We analyzed the relative length changes of different tunnel combinations for 2 different femoral and 2 tibial tunnel points using 3-dimensional (3D) computed tomography (CT) scans. To predict and explain the different patterns of isometry, we determined the center of rotation (COR) of each femoral tunnel using coordinate transformation and a least squares circle-fitting algorithm. We hypothesized that the anatomic femoral tunnel would be better than a vertical femoral tunnel in terms of isometry.

METHODS

Specimen Preparation and Testing Protocols

We analyzed the isometry of different tunnel combinations of an anatomic versus vertical femoral tunnel and a conventional versus anterior tibial tunnel using 3D CT scans and a spatial coordinate system. Ten fresh-frozen, nonpaired human cadaveric knees, ranging in age from 48 to 77 years (mean, 59 years), were used in this study. All knees were macroscopically intact and showed no evidence of previous surgeries, pre-existing arthritis, or ligamentous instability by clinical examination. The specimens were kept frozen at −20°C before testing and were thawed at room temperature for 24 hours before the experiments were conducted. The femur and tibia were sectioned at approximately 30 cm from the joint line. After making an 8-cm AM arthrotomy, we made transosseous tibial tunnels at 2 different locations using a 2.5-mm ACL guide pin: (1) the conventional site, that is, the center of the ACL stump on the imaginary extended line of the posterior margin of the lateral meniscus anterior horn (conventional tibial tunnel), and (2) a more anterior position, that is, the center of the ACL stump on an imaginary line between the posterior margin of the lateral and medial meniscus anterior horns (anterior tibial tunnel) (Fig 1). After 3 reference points were made for coordinate transformation (2 points on medial femoral condyle and 1 on lateral epicondyle) (Appendix 1, available at www.arthroscopyjournal.org), the incisions were closed in layers before CT scanning to minimize any effects on knee mechanics. We used a 64-line spiral CT system (General Electric, Waukesha, WI) with a slice thickness of 0.6 mm. All specimens were scanned by CT at 0°, 30°, 60°, 90°, and 120° with premolded fabric braces at each flexion angle. After removal of the ACL from the femoral attachment, the femoral tunnel position was marked on a knee at 90° of flexion with a 2.5-mm guide pin at 2 different locations: (1) The vertical femoral tunnel was marked at 5 mm medial to the center of the notch (11 o'clock) and 5 mm distal to the posterior cortex. (2) The anatomic femoral tunnel was marked at 6 mm anterior to the articular surface and 6 mm distal to the posterior cortex

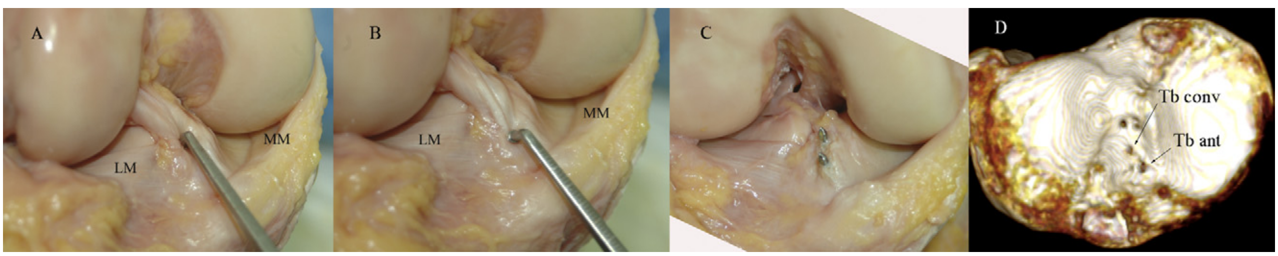

Figure 1. Tibial tunnel locations: conventional tibial tunnel (A), more anterior tibial tunnel (B), tunnel position after removal of ACL (C), and tibial tunnel location on 3D CT image (D). (LM, lateral meniscus; MM, medial meniscus; Tb ant, anterior tibial tunnel; Tb conv, conventional tibial tunnel.)

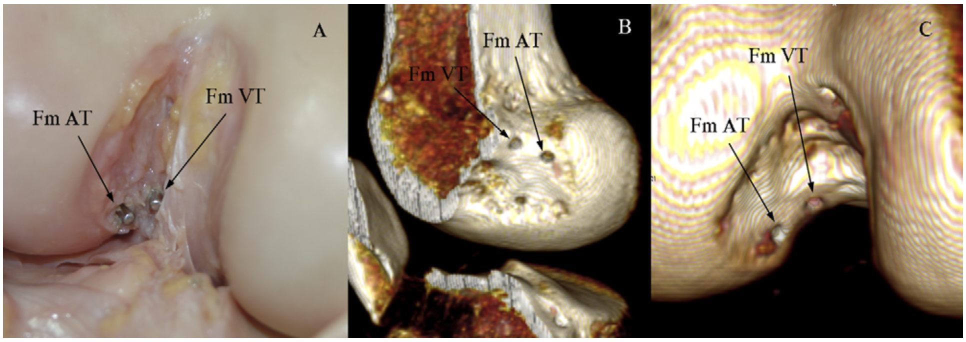

Figure 2. Varying femoral tunnel locations: femoral tunnel location in specimen (A) and tunnel location on 3D CT image (B, C). (Fm AT, anatomic femoral tunnel; Fm VT, vertical femoral tunnel.)

using a 6-mm offset guide with the knee in 90° of flexion (Fig 2).[8] Afterward, the knees were rescanned in a fully extended position to obtain a relative coordinate for each tunnel point. A coordinate transform method was used to obtain the femoral tunnel coordinates. The coordinates of the femoral tunnel points from the final scan data acquired after removal of the ACL were transformed to the local coordinate system of the CT scan at each knee flexion angle as defined by 3 reference points on the femoral bone (Appendix 1). By use of this method, the femoral tunnel location could be identified at each knee flexion angle before removal of the ACL fibers. The lengths between the inner orifices of the femoral tunnels and tibial tunnels were calculated from 3D coordinates that were obtained with medical imaging software (OsiriX, version 3.2; Apple, Cupertino, CA) and a coordinate system. OsiriX software provided multiplanar reconstructed images of the axial, sagittal, and frontal planes. The coordinate values of 3D space were taken to the nearest 0.01 mm (Fig 3). The lengths between the inner orifices of the femoral and tibial tunnels were calculated using coordinate values from each tunnel aperture. The length in full extension (0° of flexion) was used as a reference length and subtracted from each length at each flexion point. Accordingly, a positive value indicates an increase in the length compared with

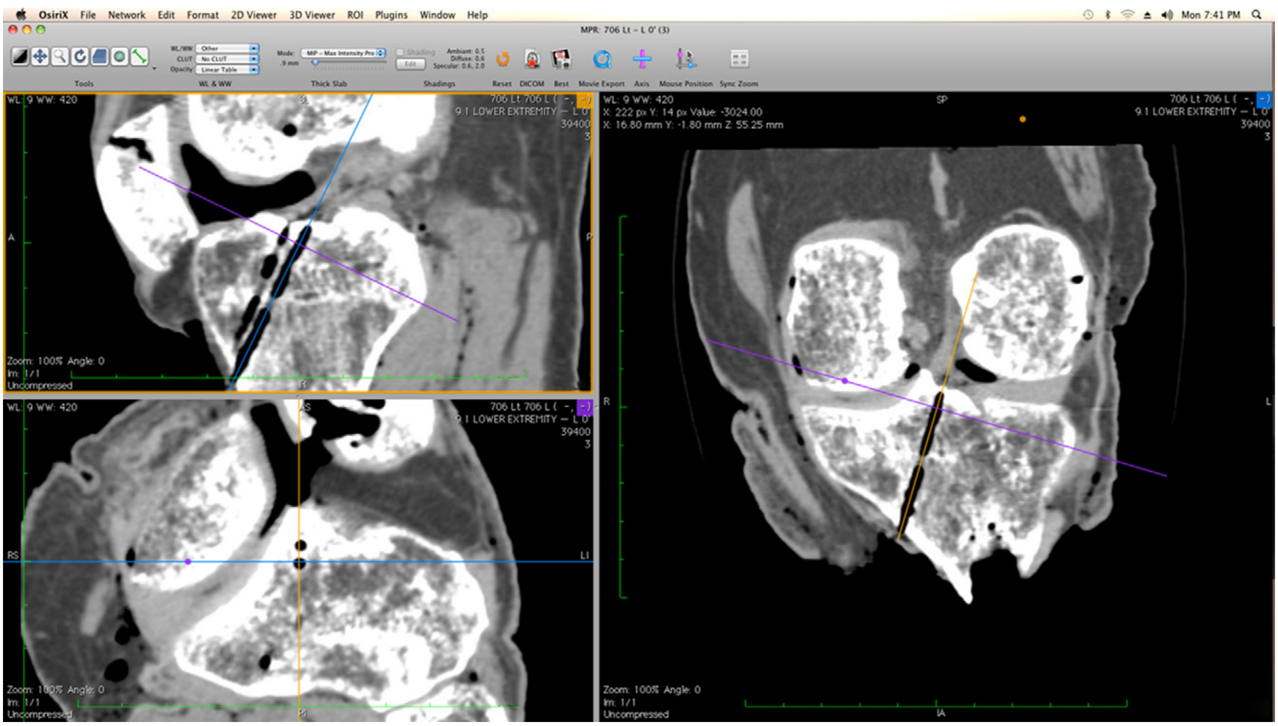

Figure 3. Measurement of tunnel points in OsiriX imaging program in multiplanar reformatting mode.

full extension, and vice versa. Thus a positive value at any given flexion point would suggest relative tension on an ACL graft, and a negative value would suggest increased slack over the condition at full extension.

Finally, to assess the CORs for femoral tunnels, the coordinate value of each tunnel at varying flexion angles was transformed to a coordinate system of full extension. The CORs for the femoral tunnels were calculated from 5 different coordinates from each flexion angle using a least squares cylinder-fitting algorithm along a fixed axis vertical to the sagittal plane according to the method of Kasa[9] (Fig 4, Appendix 1).[10] The sagittal plane was defined as the plane perpendicular to the femoral epicondylar axis and parallel to the anterior-posterior plane of the tibial plateau.

Calculated CORs were plotted to the sagittal plane with a 10-unit grid system based on the Blumensaat line, with the femoral trochlear groove and the posterior and anterior borders of the lateral femoral condyle.[11] The geometric points of CORs were described as units of the grid and percentage ± standard deviation of the x-y orientation in the sagittal-plane 3D CT–reconstructed image.

Statistical Analysis

A priori power analysis performed with G*Power software, version 3.01 (Franz Faul, Christian-Albrechts-Universität Kiel, Kiel, Germany), indicated that 9 specimens would be needed per group to detect an effect size of 0.8 with an overall $\alpha = .05$ and a power of 0.8.[12] The data were confirmed to be normally distributed by a Kolmogorov-Smirnov test. The distance measurements at each flexion angle for each combination and in each combination for each flexion angle were compared by a 2-way repeated-measures analysis of variance. To determine statistical differences among groups, the Tukey test for post hoc analysis was performed. Statistical significance was set at $P < .05$. All statistical analyses were performed with SigmaStat (version 2.0; SPSS, Chicago, IL). The reliability of measurements was assessed by intraobserver and interobserver variability. All measurements were repeated and recorded by the principal observer, as well as a secondary observer, at intervals of 2 weeks. Repeatability and reproducibility of our measurements were evaluated by calculating the intraclass and interclass correlation coefficients using SPSS software (version 12.0; SPSS). The intraclass and interclass correlation coefficients were interpreted as poor if less than 0.4, marginal if greater than or equal to 0.4 but less than 0.75, and good when greater than or equal to 0.75.

RESULTS

Isometry

Flexion of the knee had a significant effect on the length of the path between the femoral and tibial tunnels in all combinations except conventional tibial tunnel–vertical femoral tunnel (Table 1, Fig 5). The

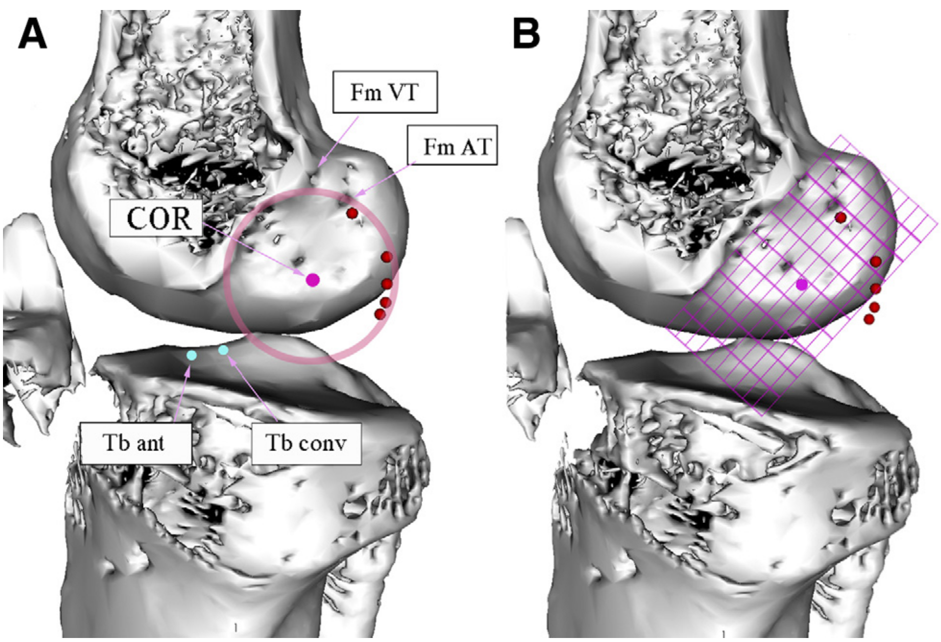

FIGURE 4. (A) Plot of COR using least squares circle-fitting algorithm. (B) Plot of COR using 10-unit custom grid. Red dots represent each tunnel point at each knee flexion angle. (Fm AT, anatomic femoral tunnel; Fm VT, vertical femoral tunnel; Tb ant, anterior tibial tunnel; Tb conv, conventional tibial tunnel.)

TABLE 1. *Length Changes for Different Tunnel Combinations Through Range of Motion (mm)*

Tunnel Combination	0° of Knee Flexion	30° of Knee Flexion	60° of Knee Flexion	90° of Knee Flexion	120° of Knee Flexion	Maximum Excursion*
Tb conv–Fm VT	0	0.4 ± 0.4	0.3 ± 0.3	1.1 ± 1.1	0.6 ± 0.6	1.1
Tb conv–Fm AT	0	−0.9 ± 1.7	−2.7 ± 1.8	−2.8 ± 2.0	−4.4 ± 1.8	4.4
Tb ant–Fm VT	0	1.5 ± 1.6	1.8 ± 1.5	2.7 ± 1.6	2.7 ± 2.2	2.7
Tb ant–Fm AT	0	−0.1 ± 1.7	−1.6 ± 1.5	−1.8 ± 1.5	−3.2 ± 1.6	3.2

NOTE. Values are given as mean ± standard deviation.
Abbreviations: Fm AT, anatomic femoral tunnel; Fm VT, vertical femoral tunnel; Tb ant, tibial anterior tunnel; Tb conv, conventional tibial tunnel.
*Maximum excursion = Maximum mean value – Minimum mean value.

conventional tibial tunnel–vertical femoral tunnel showed the least excursion over the range of motion except at less than 30° of flexion. Overall, the conventional tibial tunnel–vertical femoral tunnel group showed the least excursion in terms of isometry.

The femoral vertical tunnel combination groups (anterior tibial tunnel–vertical femoral tunnel and conventional tibial tunnel–vertical femoral tunnel) showed a trend toward increased length as the knee flexion angle increased. In contrast, the anatomic femoral tunnel combination groups displayed a trend toward shorter lengths with increasing knee flexion. In other words, femoral tunnel positions exerted greater effects than tibial tunnel positions in terms of isometry (Table 1, Fig 5).

Among the vertical femoral tunnel combination groups, the anterior tibial tunnel group showed significantly greater length changes than the conventional tibial tunnel group (Fig 6).

Among the anatomic femoral tunnel combination groups, the conventional tibial tunnel group showed a significant length reduction at 30°, 60°, and 120° compared with the anterior tibial tunnel group (Fig 7). Although the conventional tibial tunnel group showed no significant length change from 0° to 30° of knee flexion, the anterior tibial tunnel group displayed significantly less change than the conventional tibial tun-

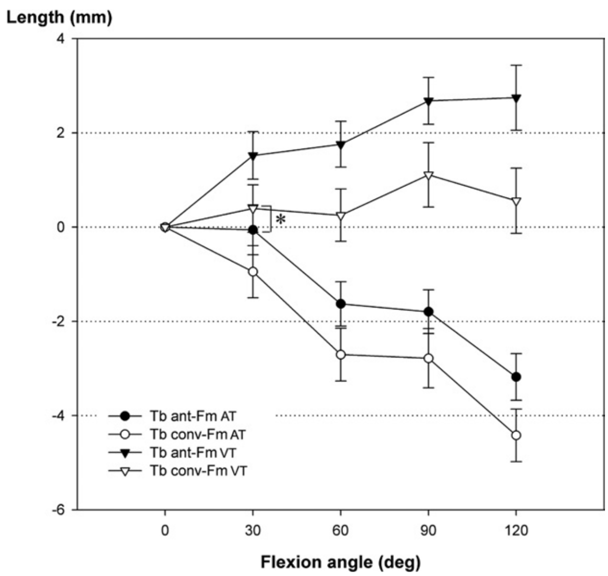

FIGURE 5. Mean length changes with changes in flexion angle in 4 different tunnel combinations. There are significant differences for all comparisons between different tunnel combinations at each knee flexion angle, except the comparisons between the conventional tibial tunnel (Tb conv)–vertical femoral tunnel (Fm VT) and anterior tibial tunnel (Tb ant)–anatomic femoral tunnel (Fm AT) combinations at 30° (*P = .525).

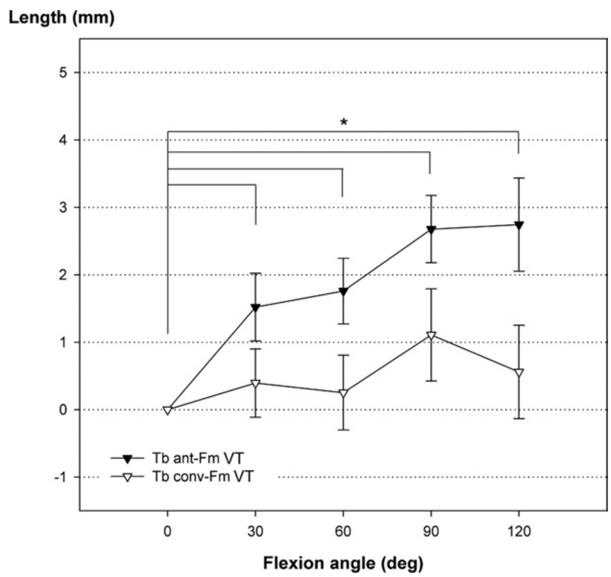

FIGURE 6. Length changes in vertical femoral tunnel combination. The asterisk indicates a significant difference ($P < .05$) between different knee flexion angles. (Fm VT, vertical femoral tunnel; Tb ant, anterior tibial tunnel; Tb conv, conventional tibial tunnel.)

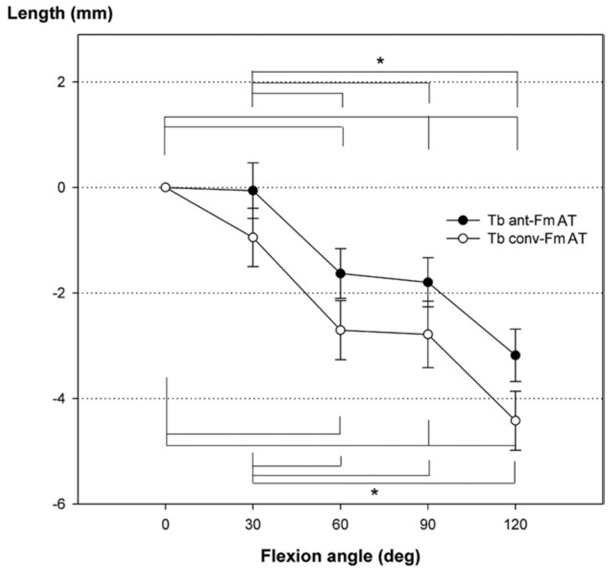

FIGURE 7. Length changes in anatomic femoral tunnel combination. The asterisks indicate significant differences ($P < .05$) between different knee flexion angles. (Fm AT, anatomic femoral tunnel; Tb ant, anterior tibial tunnel; Tb conv, conventional tibial tunnel.)

nel group (-0.06 ± 1.67 mm and -0.94 ± 1.75 mm, respectively; $P = .044$).

Both intraobserver reliability and interobserver reliability for measurements of the imaging program data were very high (intraclass and interclass correlation coefficients of 0.95 and 0.96, respectively, with 95% confidence intervals).

COR for Femoral Tunnel

The mean anatomic and vertical femoral tunnels were located on the grid at x = 23% ± 9%, y = 32% ± 11% and at x = 26% ± 14%, y = 5% ± 8%, respectively (Fig 8).

The CORs of both types of femoral tunnels were located in different positions. The CORs of anatomic and vertical femoral tunnels were located on the grid at x = 52% ± 9%, y = 53% ± 13% and at x = 66% ± 8%, y = 47% ± 13%, respectively (Fig 8).

DISCUSSION

It has been reported that the native ACL is not isometric but has a complex, double-bundle fiber anatomy; in addition, an in vitro study has suggested that placement of the femoral graft in the femoral footprint of the native ACL resulted in closer knee joint kinematics than the isometric femoral position.[3] However, theoretically, isometry is relevant to graft tension during the early postoperative phase and related to graft slackening.[13] So, reported biomechanical study cannot solve this mismatch between isometry and graft tension to justify the anatomic ACL reconstruction to obtain better kinematics in the whole range of motion. Our study shows that an anatomic AM single-bundle reconstruction is nonisometric and unlikely to prevent anterior tibial displacement through a full range of knee motion, because the distance between anatomic femoral and tibial tunnels is greatest in full extension and decreases with flexion. This would result in graft laxity. The surgeon should give consideration to modification of the initial fixation angle, viscoelastic properties of graft, or perhaps, additional bundle reconstruction to achieve stability throughout the range of motion.

With respect to ACL graft isometry, most research has focused on the native ACL bundle itself.[14-19] More recently, however, the preferred femoral tunnel position has changed to a more anatomic location from the classical isometric location (over-the-top position). At the same time, different descriptions of tunnel location in published reports have made it difficult to compare

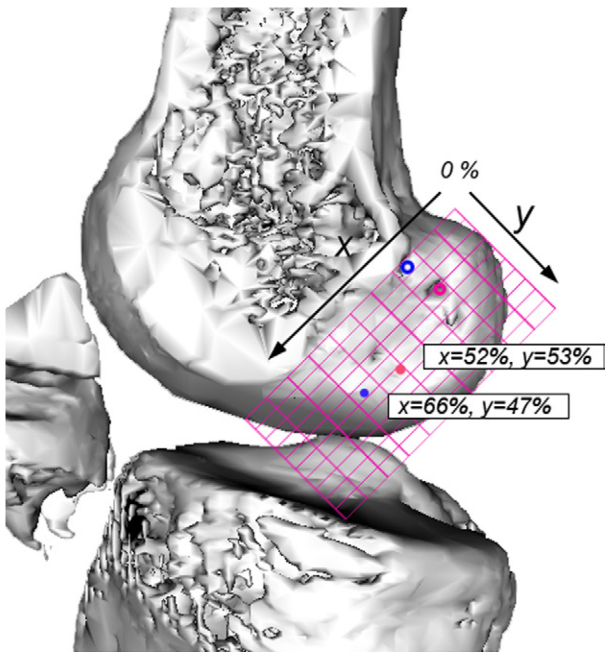

FIGURE 8. COR for each femoral tunnel. The pink and blue hollow circles represent the mean locations of the anatomic and vertical femoral tunnels, respectively. The pink and blue solid dots represent the mean CORs for the anatomic and vertical femoral tunnels, respectively. (x, line parallel to Blumensaat line; y, line perpendicular to Blumensaat line.)

results. We chose to focus instead on the impact of tunnel position, using 3D CT scans and a volume-rendering program to present the location of tunnel positions more objectively.

We also used a coordinate transform algorithm to plot the ACL femoral tunnel position on a local coordinate system for each knee flexion angle without an ACL removal procedure. This method can reduce bias from graft fixation conditions such as tension and knee flexion angle, as well as changes in knee biomechanics derived from ACL removal.[20]

The location of the anatomic femoral tunnel in our study was very similar to the locations of anatomic AM bundles in other studies.[3,21,22] It has been reported that the anatomic AM bundle was located at 20% to 25% along the Blumensaat line and 25% to 35% along the line perpendicular to the Blumensaat line in quadrant methods. So, the anatomic femoral tunnel of our study can represent the anatomic femoral tunnel.

Early anatomic studies showed that the 2 bundles function in a reciprocal manner, with the posterolateral bundle reaching maximal length and tension in extension whereas the AM bundle reaches maximal length in the flexed position.[14,16,23] Recently, however, Li and colleagues[24,25] reported that both bundles were longest at low flexion angles and shortened significantly with increasing flexion. We observed that when the femoral tunnels were made at a vertical position (close to the over-the-top position), length tended to increase with flexion, especially when the tibial tunnel was made on the anterior side. The differences in these results may be because of the femoral tunnel position. In the earlier study of Li and colleagues,[24] the AM bundle of the femoral tunnel was defined closer to the over-the-top position compared with their later study.[25] When the femoral tunnel was defined closer to the over-the-top position, there was a slight increase in length in early flexion (0° to 30°).[24]

These findings, as well as ours, can be explained by the relation between tunnel position and the COR. When the knee moved from the zero position (full extension) to a flexed position, the length between the tunnels changed according to the relation between the COR and the femoral tunnel position. (The tibial bone was assumed to be fixed during rotation.) The vertical femoral tunnel moved farther from the COR in initial to mid flexion, increasing the length (Fig 9A). When the tunnel passed the COR, the change in length was reduced because it moved according to the radius of the rotation arc. For the anatomic femoral tunnel, which was already located close to or below the COR in the zero position, length decreased as the knee flexed (Fig 9B). This method can predict isometry problems in ligament reconstruction if 3D coordinate data or volume-rendered images using CT scan or magnetic resonance imaging are available.

Because the CORs were calculated based on just 5 different tunnel points for each angle and the knee

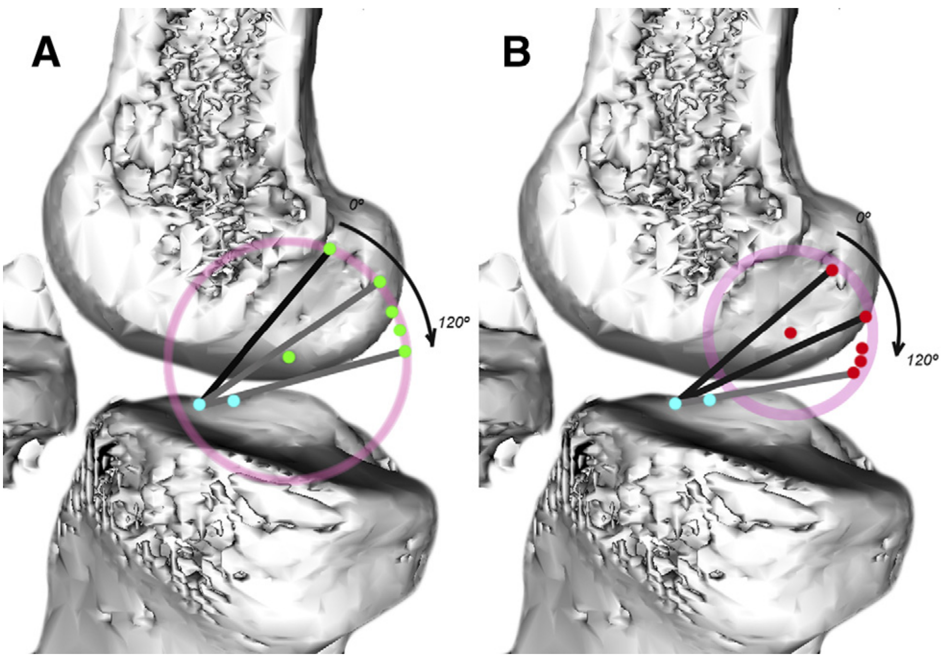

FIGURE 9. Relations between COR and length change. (A) The vertical femoral tunnel (over-the-top position, green dot) moved far from the COR in initial to mid flexion, with increasing length until it passed the COR (central green dot). Length was then reduced because it moved following the radius of the rotation arc. (B) Because the anatomic femoral tunnel (red dot) is already located close to or below the COR (central red dot) in the zero position, the length between the tunnels decreased as the knee flexed. (Blue dots, tibial tunnels.)

flexion movement was the combination of rolling and gliding, as well as the instant COR,[26] the calculated CORs were located at different points according to the femoral tunnel position, even in the same knee. Although they were different according to the femoral tunnel points, the aforementioned relation between isometry and the COR was the same in all knee specimens.

Our results suggested several clinically relevant findings for ACL reconstructions. First, when an anatomic femoral tunnel is chosen for ACL reconstruction, the graft length will be longest in full extension (Fig 7). This information can be considered when one is evaluating knee flexion angles for graft fixation and rehabilitation. Austin et al.[27] reported that the tensioning of the graft at 30° of knee flexion was associated with loss of knee extension when the anatomic femoral tunnel was chosen. Our results can offer supportive data for this phenomenon. Second, our data suggest that an anatomic AM single-bundle reconstruction cannot prevent anterior displacement in the entire range of motion, because the graft will become looser in flexion when it is initially fixed in a fully extended position. To achieve stability throughout flexion, modification of the initial fixation angle, or perhaps double-bundle reconstruction, should be considered. Third, our data show that isometry of an ACL graft is affected by femoral tunnel position more than by tibial tunnel position. This has not previously been proven. Finally, although the conventional method (conventional tibial tunnel–vertical femoral tunnel) yielded the best isometry, when an anatomic femoral tunnel is chosen because of increased rotational stability,[1-4,6] a more anterior tibial tunnel might be preferred over a conventional tibial tunnel in terms of isometry. The more anterior tibial tunnel–anatomic femoral tunnel combination showed little excursion in a near-extension position (0° to 30°), which is known to be an important factor in functional results and avoiding postoperative flexion contracture. In addition, this combination can create horizontally directed graft to resist anterior translational force without impingement than the conventional tibial tunnel position.[28-30]

Our study had some limitations. First, because we used cadavers, we could not exactly simulate in vivo biomechanics. The second limitation was that the measured length was the distance between the tunnel apertures and not the real length along the course followed by the ligament or tendon. Although this method can represent the trends of length changes and the ACL has a straighter course than the posterior cruciate ligament or posterolateral ligament structures, validations of the observed correlations are needed. The third limitation was that we assessed real distance instead of strain (length change relative to original length). Real distance can be affected by biases related to individual variation (i.e., knee size), but we found that the real length change (regardless of strain change) was directly related to the final clinical results. In addition, intraoperative isometric analyses and measuring systems that assess knee instability such as the KT-1000 (MEDmetric, San Diego, CA) also assess real length regardless of patient size. Accordingly, we chose real lengths to provide more comprehensive data for use in clinical situations. Finally, we only considered the sagittal plane for COR and excluded other axes. Although frontal- and axial-plane variation of the tunnel point was minimal, further studies could include multiplane movement to analyze the relation between isometry and rotational movement.

CONCLUSIONS

Contrary to our hypothesis, the anatomic femoral tunnel was nonisometric, and the differences in isometry for each tunnel type were explained primarily by differences in relations between the CORs of tunnels and tunnel position. When a femoral anatomic tunnel is chosen for ACL reconstruction, the anterior tibial tunnel offers greater isometric benefits than the conventional tibial tunnel, especially in near full extension.

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APPENDIX 1

Coordinate Transformation System

A local coordinate system can be determined from 3 points in space. Another point in space can be described using the local coordinate system through a coordinate transformation from the global coordinate system to the local coordinate system.

If there is a body in 3D space and there are 3 points on the body whose coordinate vectors are A, B, and C in a global coordinate system, then a local coordinate system on the body can be determined using the coordinate vectors of the 3 points.

Unit vectors from A to B (V_{ab}) and from A to C (V_{ac}) are as follows:

$$V_{ab} = (B - A)/norm(B - A)$$
$$V_{ac} = (C - A)/norm(C - A)$$

Setting A as the origin, V_{ab} as the x-axis ($V_x = V_{ab}$), and V_{ac} as a temporary y-axis ($V_y' = V_{ac}$) of the local coordinate system yields the following:

$$V_z = V_x \times V_y' = V_{ab} \times V_{ac}$$

The y-axis (V_y) can be determined from V_x and V_z as

$$V_y = V_z \times V_x = V_{ab} \times V_{ac} \times V_{ab}$$

Here, *x* and *norm* represent the cross product and vector length, respectively. The body's local coordinate system ($V_xV_yV_z$) whose origin is at A has been determined.

If there is another point, D, on the body, then its coordinate (T_x, T_y, T_z) in the body's local coordinate system can be calculated as follows:

$$T_x = V_x \cdot (D - A)$$
$$T_y = V_y \cdot (D - A)$$
$$T_z = V_z \cdot (D - A)$$

Here, a dot represents dot product.

Then, the coordinate vector of D in the local coordinate system is

$$V_{ad} = T_xV_x + T_yV_y + T_zV_z$$

Least Squares Circle-Fitting Algorithm

A 2-dimensional (2D) circle can be fit to 3D points through the following steps:

1. Calculate a fitting plane to 3D points.
2. Project the 3D points to the plane.
3. Determine a 2D coordinate system on the plane, and calculate the coordinates of the projected points in this coordinate system.
4. Fit a circle to the projected points.
5. Calculate the coordinates of the circle in the original 3D coordinate system.

The plane equation in 3D space can be defined by the equation z = Ax + By + C + e, where *e* is residual. If we fit this plane to *n* sample points, the square sum of the residuals is

$$E(A, B, C) = \sum_{i=1}^{n} (e_i)^2 = \sum_{i=1}^{n} (Ax_i + By_i + C - z_i)^2$$

To minimize E(A, B, C), the following 3 equations should be met:

$$\frac{\partial E}{\partial A} = 2\sum_{i=1}^{n} x_i(Ax_i + By_i + C - z_i) = 0$$
$$\frac{\partial E}{\partial B} = 2\sum_{i=1}^{n} y_i(Ax_i + By_i + C - z_i) = 0$$
$$\frac{\partial E}{\partial C} = 2\sum_{i=1}^{n} (Ax_i + By_i + C - z_i) = 0$$

These equations can be written in a matrix format:

$$\begin{bmatrix} \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_iy_i & \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_iy_i & \sum_{i=1}^{n} y_i^2 & \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} y_i & \sum_{i=1}^{n} 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} x_iz_i \\ \sum_{i=1}^{n} y_iz_i \\ \sum_{i=1}^{n} z_i \end{bmatrix}$$

The solution of the matrix equation provides a plane equation that fits the *n* sample points in 3D space.

In the second step, the sample points in 3D space should be projected onto the plane along the normal vector of the plane N(A, B, −1); then, each sample point (x_i, y_i, z_i) is moved to x_i', y_i', z_i' as follows:

$$x_i' = x_i - A\frac{Ax_i + By_i - z_i + C}{A^2 + B^2 + 1}$$
$$y_i' = y_i - B\frac{Ax_i + By_i - z_i + C}{A^2 + B^2 + 1}$$
$$z_i' = x_i + 1\frac{Ax_i + By_i - z_i + C}{A^2 + B^2 + 1}$$

The third step is to determine a coordinate system in the plane from the projected points. Two arbitrary points are selected, $P_1(x_1', y_1', z_1')$ and $P_2(x_2', y_2', z_2')$, among the sample points. The 2D coordinate system with the origin at P_1 and the x-axis along P_1P_2 can then be determined as follows:

$$V_x = (P_2 - P_1)/norm(P_2 - P_1)$$
$$V_y = N \times V_x$$

If the projected points are $P_i(x_i', y_i', z_i')$, then the coordinates of the projected points in this 2D system (x_i'', y_i'') can be determined as

$$x_i'' = V_x \cdot P_i$$
$$y_i'' = V_y \cdot P_i$$
$$z_i'' = 0$$

There are a number of 2D circle-fitting methods.[9,10,31,32] By applying the method of Kasa[9] to the projected points in the 2D coordinate system, a formula to fit a circle can be described.

If we have n sample points (x_1'', y_1''), (x_2'', y_2''), . . ., (x_n'', y_n''), then the intermediate values (K_1, K_2, K_3) used to calculate the center and radius of a fitting circle can be obtained from the following matrix equation:

$$\begin{bmatrix} x_1'' & y_1'' & 1 \\ x_2'' & y_2'' & 1 \\ \vdots & \vdots & \vdots \\ x_n'' & y_n'' & 1 \end{bmatrix} \begin{pmatrix} K_1 \\ K_2 \\ K_3 \end{pmatrix} = \begin{bmatrix} (x_1'')^2 + (y_1'')^2 \\ (x_2'')^2 + (y_2'')^2 \\ \vdots \\ (x_n'')^2 + (y_n'')^2 \end{bmatrix}$$

If the matrix on the left side is A, the vector on the right side is B, and A is not a square matrix, then the least squares solution of the matrix equation (K1, K2, K3) can be obtained as

$$K = (A^T A)^{-1}(A^T B)$$

The center (C_x'', C_y'') and the radius (R) of the fitting circle can be calculated as

$$C_x'' = K_1/2$$
$$C_y'' = K_2/2$$
$$R = \sqrt{(K_1)^2/4 + (K_2)^2/4 + K_3}$$

The coordinates of the circle center in a global coordinate system can then be calculated as

$$C_g(C_x, C_y, C_z) = P_1 + V_x C_x'' + V_y C_y''$$