The Effect of Notchplasty on Tunnel Widening in Anterior Cruciate Ligament Reconstruction

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Purpose: To investigate changes in femoral tunnel diameter, dimension, and volume after anterior cruciate ligament reconstruction with notchplasty. Methods: Porcine knee specimens were divided into 2 groups of 10 specimens each. Group A did not receive notchplasty. A 2-mm notchplasty was conducted in group B. Seven-millimeter-diameter femoral tunnels were drilled and a doubled flexor digitorum profundus tendon was inserted and fixed with an EndoButton (Smith & Nephew, Andover, MA) in each knee specimen. Samples were mounted on a materials testing machine. Each group was preloaded at 10 N and subjected to 20 loading cycles (between 0 and 40 N), followed by 1,000 loading cycles in the elastic region (between 10 and 150 N). High-resolution computed tomography with 1.0-mm slices was conducted with all samples before and after testing. A 3-dimensional model was constructed to evaluate the degree of the tunnel change. Results: In group B the mean longest diameter and dimension of the femoral tunnel significantly increased after the test ($P = .005$ and $P = .001$, respectively). The volumetric loss of bony structure after the test in group B was significantly greater than that in group A ($P = .039$). Meanwhile, no significant difference was found before and after the test in terms of tunnel diameter, dimension, and volumetric loss around the tunnel in group A. Conclusions: The intra-articular orifice of the femoral tunnel was enlarged after the uniaxial cyclic loading test after notchplasty. An enlarged tunnel orifice may lead to a discrepancy between the tunnel and the graft at the tunnel aperture. Clinical Relevance: The data may have an implication that suspensory fixation with a notchplasty has a negative effect on the full graft accommodation at the tunnel aperture. Aperture widening may affect graft positioning, leading to subtle changes in graft biomechanics and laxity.

Notchplasty is performed during anterior cruciate ligament (ACL) reconstruction to improve visualization of the posterior wall, allow for easier passage of the graft, and prevent impingement of the graft. Notchplasty is especially useful in cases of a congenitally narrow notch and stenosing osteophytes in chronically unstable knees.

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knee extension.\textsuperscript{9} This biomechanical stimulation has been called “physiological impingement,” leading to functional adaptation of the ACL structure.\textsuperscript{10} These previous studies have shown that the anterior notch wall is crucial for the function of the ACL.\textsuperscript{9,10}

On the other hand, there has been concern over the effects of suspensory fixation on femoral tunnel expansion, suggesting that suspensory fixation may increase a combination of micromotion of the graft and a biological component at the graft-bone interface.\textsuperscript{11,12} Obviously, tunnel expansion can make ACL revision surgery difficult.\textsuperscript{13-15} Furthermore, widening at the tunnel aperture may lead to lack of full accommodation at the tunnel orifice.\textsuperscript{16,17}

This study investigated the effects of notchplasty on the structural change of the femoral tunnel when the graft undergoes fixation with suspensory fixation. The purpose of the study was to investigate changes in femoral tunnel diameter, dimension, and volume after ACL reconstruction with notchplasty. The study hypothesis was that notchplasty may lead to early deformation of the femoral tunnel.

Methods

Specimen Preparation

Twenty knee specimens were obtained from 6-month-old pigs slaughtered in abattoirs for human consumption. The specimens were stored at $-20^\circ$C within 5 hours after recovery and were thawed at room temperature for 24 hours before use. Dual x-ray absorptiometry scanning (GE Lunar DPX-MD; GE Healthcare Technologies, Waukesha, WI) was used to screen specimens before testing to provide specimens that closely approximated the human condition. The apparent bone mineral density (BMD) of femurs in young females was reported to range from 1.25 to 1.4 g/cm\textsuperscript{2}.\textsuperscript{18} The specimens in which the apparent BMD was less dense or more dense than that of femurs in young females were excluded before study use. The mean apparent BMD of the specimens selected was $1.4 \pm 0.5$ g/cm\textsuperscript{2}. Of 40 porcine specimens, 20 specimens that had acceptable BMD were selected, divided into 10 matched pairs with equivalent apparent BMD, and labeled group A and group B. Doubled flexor digitorum profundus tendons were harvested from the specimens and whipstitched with No. 2 Ethibond (Ethicon, Somerville, NJ). The mean length of the graft was 72 mm (range, 65 to 80 mm). The graft diameter was measured with an incremental sizing block (Smith \& Nephew, Andover, MA) to correspond to a tunnel diameter of 7 mm.

Operative Technique

Each specimen was disarticulated at the knee joint, and the femur was sectioned at the mid shaft. The soft tissue was removed to allow easy potting in cylindrical polymethyl methacrylate molds. After the ACL was resected from the notch, a 2-mm notchplasty was performed before drilling the tunnel in group B. A ruler was used to measure a 2-mm notchplasty, and a line was drawn on the femoral condyle. Several holes were drilled on the previously drawn line by use of a K-wire of 1.1 mm in diameter. Finally, notchplasty was performed by connecting the holes with an osteotome. A high-speed burr was then used to smooth the rough surface. Each notchplasty was extended to the posterior back wall, and the uniform thickness of the notchplasty was confirmed by checking the thickness of removed bone. Notchplasty was not performed in the 10 specimens comprising group A. A custom-made guide was used to locate the center of the femoral tunnel 7 mm anterior to the posterior wall in the notch, and the fluted guide hole was aimed at the native ACL femoral footprint in group A. In group B the center point of the femoral tunnel was matched with group A after notchplasty using the same custom-made guide to provide an identical point of the tunnel center between the 2 groups. The femoral tunnel captured the anteromedial bundle–oriented footprint rather than the midpoint of the native femoral footprint.

A 7-mm femoral tunnel was drilled, and the sharp edge of the tunnel was minimally chamfered with an ACL chamfer rasp to avoid graft damage. The mean tunnel length measured $36.7 \pm 3.7$ mm (range, 30 to 40 mm).

Testing Setup

As a graft fixation device, the same sized EndoButton (12 mm in length; Smith \& Nephew) and the same sized closed loop (15 mm in length) was used for each specimen. The mean length of the graft inside the tunnel was $21.7 \pm 3.7$ mm. The porcine distal femur was potted in cylindrical molds of polymethyl methacrylate and secured in custom-made cylinders, which were mounted on an Adelaide Testing Machines device (Toronto, Ontario, Canada) with a 25-kN load cell. Each femur was fixed to the base of the machine while facing backward by means of a fixation jig. The fixation jig was specially designed and made to provide detailed flexion angles. The sutured end of the graft was secured to a specially designed clamp to ensure secure fixation. A 25-mm length of the graft was preserved between the clamp and the tunnel aperture. The axis of the femur formed a 15\textdegree angle with the operational axis of the machine. The load was applied in parallel with the long axis of the graft, corresponding to uniaxial cyclic loading. The angle formed by the bisection of the longitudinal axis of the femur and the ACL was regarded to be about 45\textdegree when the knee was in full extension, based on a previous study.\textsuperscript{19} The 15\textdegree angle between the femur and the graft corresponded to 30\textdegree of...
flexion of the knee. This flexion angle is similar to that used as an angle for graft fixation at the time of ACL surgery (Fig 1). High-resolution computed tomography (CT) with 1-mm slices was applied to all samples before testing. Each group was preloaded at 10 N and subjected to 20 loading cycles in the elastic region (between 0 and 40 N) at a strain rate of 200 mm/min and a frequency of 30 cycles/min, which corresponded to the intraoperative preloading procedure. This was followed by 1,000 submaximal loading cycles in the elastic region (between 10 and 150 N), which corresponded to the early rehabilitation period, at the same strain rate and frequency. The latter test lasted about 35 minutes, during which the graft was manually hydrated every 5 minutes with a syringe containing saline solution. After the cyclic loading test was completed, samples were rechecked with high-resolution CT to evaluate the change in the degree of the tunnel shape.

**Measurement Method**

First, the morphologic changes of the tunnel orifice were grossly inspected. Thereafter the CT images were imported into a 3-dimensional (3D) modeling software program, Amira (version 3.0; TGS, Mercury Computer Systems, Chelmsford, MA). Segmentation (threshold and region growing) was used to obtain the bone contours, which were then used to generate the 3D computational model of the femur. The 3D model was imported into a reverse-engineering software program, Rapidform (INUS, Seoul, South Korea). A plane bisecting the tunnel and parallel to the direction of pull was created and used to contour the bone. The cross-sectional view was used to compute the longest diameter of the tunnel before and after the test, as well as to compute the distance of the point of deformation from the tunnel opening in the post-test femur model. The intra-articular apertures of the femoral tunnels were outlined by spline curves to determine the intra-articular tunnel morphology. The areas of these closed circumferential curves were calculated using the function of a special software program implanted in the Rapidform program. The volumetric loss was evaluated by superimposing 3D images obtained before the test and obtained after the test. This superimposition algorithm, which was already implanted in the Rapidform program, enhanced measurement accuracy. The post-test model was subtracted from the superimposed model. The volume of the remaining areas corresponded to the volume of the recessed bony structure around the femoral tunnel. The overall testing protocol is illustrated in Fig 2.

**Statistical Analysis**

On the basis of a pilot study, tunnel diameter was defined as a primary variable. The mean and standard deviation of the difference in tunnel diameter were defined as 5.2 mm and 1.7 mm, respectively. A sample size of 9 specimens for each group was estimated, accepting an α of 5% and a β of 20%, for a final power of 80%. The differences in the longest diameter and area of the intra-articular orifice of the femoral tunnel before and after the test were statistically analyzed with a paired t test. A Student t test was performed to evaluate the differences in the data measured between the testing groups. The level of significance was set at $P < .05$.

**Results**

**Visual Examination of Structural Change Around Tunnel**

In group B the structural change of the intra-articular orifice of the femoral tunnel was obvious after the loading test. In particular, the anterior margin of the tunnel...
Changes in Tunnel Diameter After Testing

Before the loading test, the mean longest diameter of the tunnel orifice was 9.4 ± 0.4 mm in group A and 9.5 ± 0.3 mm in group B, with no significant difference. For group B, the mean longest diameter (15.8 ± 1.5 mm) after the loading test was significantly greater than that for group A (9.7 ± 0.5 mm) \((P = .005)\). After the loading test, the mean longest diameter of the tunnel orifice in group A was 9.7 ± 0.5 mm, with no significant difference compared with the value measured before the test. The mean value in group B was 15.8 ± 1.5 mm, which was significantly greater than that measured before the loading test \((P = .005)\). In group B the point of structural changes in the tunnel was 5.2 ± 2.3 mm from the orifice of the tunnel. The point of the anterior margin of the tunnel orifice shifted 6.3 ± 1.7 mm to the anterior direction \((P < .001)\).

Changes in Area of Tunnel Orifice After Testing

Before the loading test, the mean area of the intra-articular orifice in groups A and B was 80.6 ± 5.9 mm² and 83.9 ± 8.9 mm², respectively, with no significant difference. After the loading test, the area in group A was 84.4 ± 3.8 mm², with no significant difference compared with that before the loading test. The area in group B significantly increased after the loading test \((125.3 ± 13.1 \text{ mm}^2, P = .001)\) compared with that before the loading test. A significant difference was noted between the area in groups A and B after the loading test \((P < .001)\).

Volumetric Loss of Bony Structure Around Tunnel

For group B, the volumetric loss of bony structure anterior to the anterior margin of the tunnel orifice was...
208.7 ± 110.7 mm³, which was significantly greater than that for group A (27.6 ± 44.6 mm³) \((P = .039)\). The overall data regarding changes in diameter, area, and volumetric loss are shown in Fig 5.

**Discussion**

In accordance with the hypothesis of this study, we have shown that the degree of widening of the femoral tunnel orifice in a group receiving notchplasty after the uniaxial cyclic loading test simulating early rehabilitation\(^{20,21}\) was significantly greater than that in a group without notchplasty. In our study the graft constructs were subjected to preloading and repetitive cyclic loading conditions. Although the experimental protocols vary widely, the preloading process is generally recommended to minimize the natural elastic creep in the graft.\(^{20-23}\) Repetitive loading cycles can be considered an early aggressive rehabilitation period because multiple loading cycles of the ACL graft occur in vivo during the period.\(^{20,21}\)

Notchplasty may lead to abnormal knee laxity by placing the femoral insertion laterally,\(^{6,7}\) and removal of the native ACL footprint in the medial wall of the lateral femoral condyle may complicate the anatomic placement of the femoral tunnel.\(^{26,27}\) Yet notchplasty is still used for a narrow intercondylar notch in chronic unstable knees and a congenitally narrow notch.\(^{28}\) When a surgeon is performing a notchplasty, the use of the procedure is left to his or her discretion. In human knees requiring a notchplasty, most surgeons remove the lateral intercondylar wall, ranging from 3 to 6 mm in width. For this study, a uniform 2-mm layer of bone was removed from the roof of the notch and wall of the lateral femoral condyle to provide a consistent and reproducible technique for specimens in group B.\(^{29}\) The results of our study may have an implication suggesting that if the thickness of the notchplasty is greater than that of the native cortical wall in the notch, this will lead to exposure of the cancellous bone bed beneath the cortical wall. The exposed cancellous bone can be a potential risk factor of deformation under external loading conditions. If the thickness of the bone removed by notchplasty is smaller than the native cortical thickness, the effect on the structural deformation at the tunnel orifice may be minimized.

Although there have been numerous reports regarding femoral tunnel widening after ACL reconstruction,\(^{13,30-32}\) little is known of the effects of notchplasty on early
 deformation of the structure of the femoral tunnel after ACL reconstruction. The biological and mechanical factors of tunnel widening have been well described. The predominant mechanical theory is graft-tunnel interface micromotion. In addition, fixation methods, stress shielding of the graft, improper tunnel position, and accelerated rehabilitation have been proposed as mechanical factors. Biologically, elevated cytokine levels in the synovial fluid, which are caused by graft swelling and a pressure effect, may stimulate osteoclastic activity, leading to bone resorption. Mechanical explanations for tunnel widening include the windshield-wiper effect as the grafts move inside the tunnel during knee motion. We believe a possible explanation for the structural change of the femoral tunnel in this study was the motion at the graft-bone tunnel interface. The cancellous bone stock could have been abraded by the graft, contacting the corresponding anterior edge of the intra-articular orifice. An anterior shift of the anterior margin of the femoral tunnel noted in this study could cause underfilling of the femoral tunnel with the graft at the intra-articular orifice because the deformed shape of the tunnel orifice was larger than the initial morphology. Discrepancies in diameter between the graft and intra-articular orifice can lead to delays in graft incorporation, resulting in potential graft failure. In addition, aperture widening may affect graft positioning, leading to subtle change in graft biomechanics and laxity.

The suspensory fixation as a fixation modality used in this study may have the potential to induce great graft-tunnel motion especially at the tunnel orifice, leading to recession of the soft cancellous bone exposed after notchplasty. However, it is still inconclusive whether the suspensory fixation method is the crucial factor contributing to tunnel widening. Previous studies suggested that a suspensory fixation method could cause great graft-tunnel motion, resulting in delayed graft incorporation and later widening of the tunnel. Meanwhile, recent studies have shown that the conventional transtibial technique resulted in significantly greater femoral tunnel expansion when compared with the anteromedial portal approach. The possible explanation for the high incidence of tunnel widening after use of the transtibial tunnel method is nonanatomic femoral tunnel placement. In our study the center of the femoral tunnel was placed in the anteromedial bundle–oriented footprint within the native femoral attachment. Our data indicate that even though the femoral tunnel was positioned in the anatomic footprint, notchplasty—which exposed cancellous bone in the intercondylar notch wall—could have led to deformation of the tunnel aperture geometry.

We used porcine knee specimens because the specimens are the preferred experimental model for ACL study. Porcine knees are similar to young human knees in terms of their shape, size, biomechanical properties of the ACL, and bone quality. If appropriately screened, porcine knee specimens can provide experimental models with uniform bone quality and similar bone density to young females whose apparent BMD in the distal femur ranges from 1.25 to 1.4 g/cm². Because osteoporotic elderly cadaveric knee specimens may yield potential bias in the data regarding deformation of the bony structure under external loading conditions, porcine knee specimens can be a reasonable alternative to cadaveric specimens. In our study 40 porcine femoral specimens were initially screened based on apparent BMD. Their relatively uniform bone quality could provide precise group matching.

**Limitations**

There are limitations in this study that we should address. First, the testing design provided application of the cyclic load parallel to the longitudinal axis of the graft. These experimental circumstances were widely applied in biomechanical tests regarding ACL reconstruction.
however, longitudinal cyclic loading is not a realistic representation of the actual physiological loading conditions. Second, the custom-made guide used in this study captured the anteromedial bundle rather than the mid position of the native ACL footprint. The femoral tunnel position is usually determined after notchplasty in clinical practice. In that situation, one is unable to determine the center of the native footprint. In this study the center of the femoral tunnel was also selected after notchplasty. Therefore, to simplify the study and try to yield better reproducibility in the technique between the groups (with and without notchplasty), a custom-made guide was used. The fluted guide hole was aimed at the native ACL femoral footprint in the group without notchplasty because the native ACL attachment could be directly observed after removal of the ACL. In the group receiving notchplasty, the center point of the femoral tunnel was matched with the group without notchplasty to provide an identical point of the tunnel center in both groups.

Conclusions

The intra-articular orifice of the femoral tunnel was enlarged after the uniaxial cyclic loading test after notchplasty. An enlarged tunnel orifice may lead to a discrepancy between the tunnel and the graft at the tunnel aperture.

References


