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Quadriceps Load Aggravates and Roofplasty Mitigates Active Impingement of Anterior Cruciate Ligament Grafts Against the Intercondylar Roof

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Summary: Because of the complications of impingement of anterior cruciate ligament grafts on the intercondylar roof and because current surgical procedures locate the tibial tunnel such that impingement is avoided during passive but not active extension, the objectives of this study were to determine if (a) active extension precipitates and aggravates roof impingement, and (b) a roofplasty mitigates the effects of impingement. The tibial translation, flexion angle defining the onset of roof impingement, graft-roof contact pressure, and graft tension were measured for six cadaveric specimens. In each specimen, two tibial tunnel positions were studied: one customized for the slope of the intercondylar roof, and the other translated 6 mm anteriorly from the customized position. For a quadriceps load of 1,500 N, the flexion angle defining the onset of impingement, the peak contact pressure, and the graft tension increased significantly for both tunnel positions. The increases occurred because of the anterior tibial translation caused by the active load. Although a roofplasty decreased the onset of the angle of impingement, the graft tension remained unaffected. Thus, to mitigate the effect of impingement during active rehabilitative knee extension exercises, the position of the tibial tunnel must be customized to the angle of the intercondylar roof and a roofplasty must be performed. The extent of bone removed must be customized as well and can be determined by removing bone from the intercondylar roof in excess of that required to freely pass a rod, the same diameter of the graft, through the tibial tunnel into the intercondylar notch with the knee in full passive extension.

Patients with anterior cruciate ligament grafts that impinge against the intercondylar roof complain of intermittent effusions, pain, inability to fully extend the knee, and instability (3,10,12,15,17,26). These complications occur because the graft impinges (i.e., contacts) and also abrades against the intercondylar roof before the knee reaches terminal extension (9,10).

The operative technique of verifying that clearance exists between the graft and intercondylar roof with the knee in full passive hyperextension may not be sufficient to prevent roof impingement during active knee extension. Knee extension exercises can produce quadriceps forces of 1,500 N (20,21), which translate the tibia anteriorly (7,8,24). Roof impingement may occur during active knee extension because the tibia and tunnel move anteriorly with respect to the intercondylar roof.

The objectives of this study were 2-fold. The first objective was to determine if a physiologic quadriceps force could precipitate and aggravate roof impingement by increasing the flexion angle at which impingement occurs, the pressure between the graft and intercondylar roof, and the tension in the graft. The second was to determine if a roofplasty is effective at mitigating these effects of impingement.

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MATERIALS AND METHODS

Experiments

Six fresh-frozen lower limbs (five of which were used in a previous study [5]), obtained from one female and five male cadavers that were 34-82 years old (mean: 61 years old), were tested. Each knee was aligned, preconditioned, and tested in a six-degree-of-freedom, computer-controlled load application system designed and built in our laboratory (2). The knee was preconditioned by applying a 50-N, step-wise load to 200 N in both the anterior and posterior directions to the tibia for six cycles at 0, 30, 60, 90, and 120° of flexion. Zero degrees of knee extension was defined as the position of the knee with an extension moment of 2.5 Nm (16). The neutral anterior-posterior position of the tibia relative to the femur was the relative position that the bones of the intact knee assumed when aligned in the load application system with use of the functional axes approach (2). The anterior tibial displacement of the intact knee was measured from the neutral position at 30° of flexion by applying three cycles of anterior load of 200 N (1,4,18). The anterior tibial displacement of the intact knee measured during the third cycle was used to match the anterior tibial

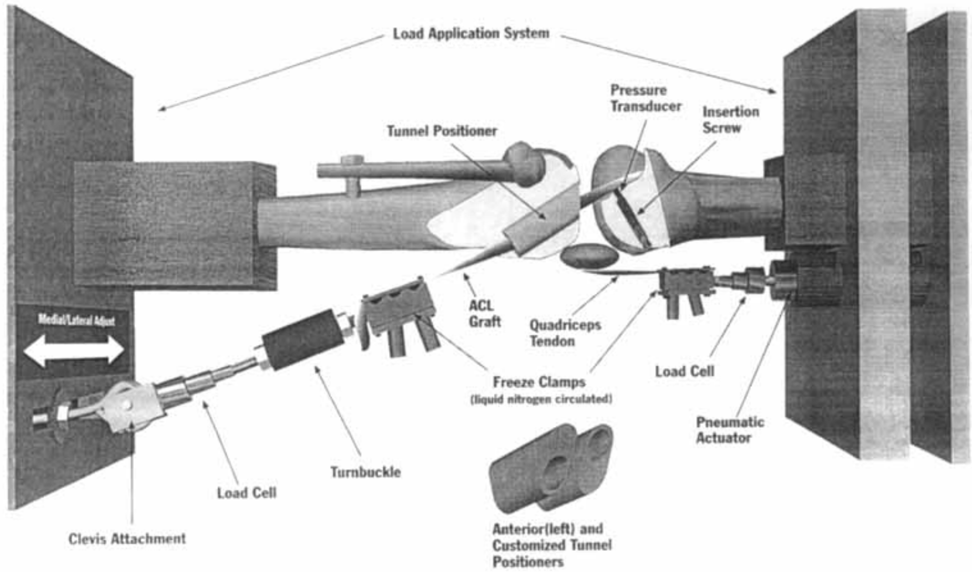

FIG. 1. Schematic diagram showing the anterior cruciate ligament (ACL) graft as it traversed from the femoral attachment through the tunnel positioner in the tibial tunnel and connected to the tension load cell. Each tunnel positioner was tapered to match the slope of the tibial plateau that had been created from drilling the oversized tunnel. Tunnel positioners were interchangeable and could be affixed within the tibial tunnel. A secure interface with the load cell was accomplished with use of a liquid nitrogen cooled freeze clamp. The turnbuckle enabled pretensioning of the graft. A miniature pressure transducer measured the contact pressure between the graft and the intercondylar roof. A pneumatic actuator with freeze clamp enabled quadriceps loading to 1,500 N.

displacement of the knee after it was reconstructed. The neutral position of the intact knee at 30° of flexion served as a common reference for measuring the anterior displacement of the tibia for both the intact knee and the reconstructed knee.

Following the procedures described in greater detail by Goss et al. (5), the anterior cruciate ligament reconstruction was performed. After the joint was exposed and the anterior cruciate ligament was excised, the tibial tunnel was placed with use of a guide (Impingement-Free Tibial Guide; Arthrotek, Warsaw, IN, U.S.A.) that customized both the position of the tibial tunnel for variability in knee extension and the slope of the intercondylar roof (11,13). An offset drill guide was used to create an oval, oversized tibial tunnel that was 12-mm wide and 23-mm deep in the anterior-posterior dimension. Two tunnel positioners, made of polytetrafluoroethylene (Teflon; E. I. DuPont, Wilmington, DE, U.S.A.) to minimize friction, were built to fit into the oversized tibial tunnel. One positioner centered the graft in the customized location while the other centered the graft in the anterior location (5). With the aid of a femoral drill guide (Endoscopic Size-Specific Femoral Aimer; Arthrotek), the location of the femoral tunnel was determined (5) and the tunnel was drilled 10-mm deep to the same diameter (9 mm) as the Teflon bushing. The femoral tunnel was completed by drilling from the anterolateral femur with use of a larger diameter (12-mm) drill until it met the smaller tunnel. Made from the Achilles tendon harvested from each specimen, the 9-mm-diameter graft was inserted into one of the tunnel positioners selected at random and the calcaneal bone plug was press-fit and cemented inside the femoral tunnel with use of polymethylmethacrylate (G. C. America, Chicago, IL, U.S.A.).

Contact between the intercondylar roof and graft and changes in pressure were measured with a miniature pressure transducer (Precision Measurement, Ann Arbor, MI, U.S.A.). Placed in a tunnel located at the apex of the notch at the junction of the intercondylar roof and articular cartilage (5), the tip of the transducer was adjusted until it was flush to the intercondylar roof.

The reconstructed knee was reinstalled in the load application system, and the graft was attached to a load cell (A.L. Design, Buffalo, NY, U.S.A.) with use of a freeze clamp attached to a turnbuckle (Fig. 1). The anterior tibial displacement of the reconstructed knee at 30° of flexion under 200 N of anterior load was matched to the normal knee by adjusting the pretension in the graft with use of the turnbuckle. The graft was preconditioned by passively cycling the knee 10 times from hyperextension (flexion angle with a 10-Nm extension moment) to 120° of flexion and then applying a 2,000-N quadriceps load over the same range of flexion angles. The pretension in the graft was readjusted so that the anterior tibial displacement of the reconstructed knee matched that of the normal knee.

The angle at which the graft contacted the intercondylar roof, the anterior-posterior position of the tibia, the pressure between the graft and roof, and the tension in the graft were measured at randomly selected flexion angles from 120° of flexion to hyperextension during passive extension and 1,500 N of quadriceps load. The tibial tunnel positioner was changed, and the entire testing protocol was repeated. The anterior tibial displacement of the knee was remeasured at the completion of each of two testing sequences.

A roofplasty was performed to determine if the effects of roof impingement caused by a 1,500-N quadriceps load could be eliminated. Ten millimeters of bone was removed from the apex of the intercondylar notch. The graft was positioned with use of the anterior tunnel positioner, which was chosen instead of the customized position because roof impingement was more severe for the anterior tunnel. The testing protocol, including the adjustment of pretension to match the anterior tibial displacement, was repeated.

Statistical Analysis

A two-factor repeated measures analysis of variance (ANOVA) was used to determine if quadriceps load caused the graft to contact the intercondylar roof earlier in the flexion arc. The two factors were quadriceps load at two levels, 1,500 and 0 N (i.e., passive), and tibial tunnel placement at two levels, customized and anterior. The flexion angle at which the pressure increased from 0 kPa was defined as the angle at which the graft first contacted the intercondylar roof.

Three three-factor repeated measures ANOVAs were used to

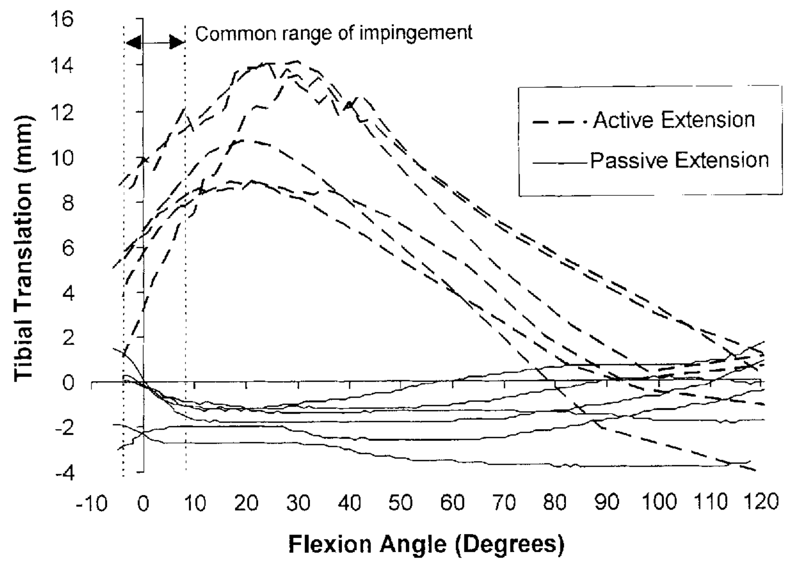

FIG. 2. Tibial translations for six specimens with use of the customized tibial tunnel with either passive extension or active quadriceps load of 1,500 N. Positive values indicate anterior tibial translation, and negative values indicate posterior tibial translation. The quadriceps load significantly increased the anterior tibial displacement ($p < 0.001$).

determine if quadriceps load increased the pressure between the graft and roof, the graft tension, and the anterior position of the tibia. The three factors were quadriceps load, tibial tunnel placement, and flexion angle with seven levels: 8, 6, 4, 2, 0, −2, and −4°. Impingement occurred in a different motion arc for each knee. To permit comparisons between specimens, the analysis was limited to the motion arc where impingement occurred for all specimens: 8° of flexion to 4° of hyperextension (Fig. 2).

A one-factor repeated measures ANOVA was used to determine if a 10-mm roofplasty eliminated roof impingement during a 1,500-N quadriceps load with the graft in the anterior tibial tunnel. The tunnel factor had two levels: no roofplasty and a 10-mm roofplasty. Three two-factor repeated measures ANOVAs were used to determine if a roofplasty and the angle of knee flexion affected the pressure between the graft and roof, the graft tension, and the anterior position of the tibia.

RESULTS

Under the application of the 1,500-N quadriceps force, the anterior tibial translation increased throughout the motion arc (Fig. 2). In the motion arc in which impingement occurred, the anterior tibial translation increased significantly when the 1,500-N quadriceps load was applied ($p < 0.001$). With the graft in the anterior tibial tunnel, the tibia translated anteriorly 9.6 ± 0.6 mm at 8° of flexion (range: 8.3-12.0 mm) and 5.5 ± 0.5 mm with the knee in 4° of hyperextension (range: 3.8-7.2 mm). The tibia translated anteriorly 10.5 ± 0.7 mm with the graft in the customized tibial tunnel at 8° of flexion (range: 8.7-13.1 mm) and 6.0 ±

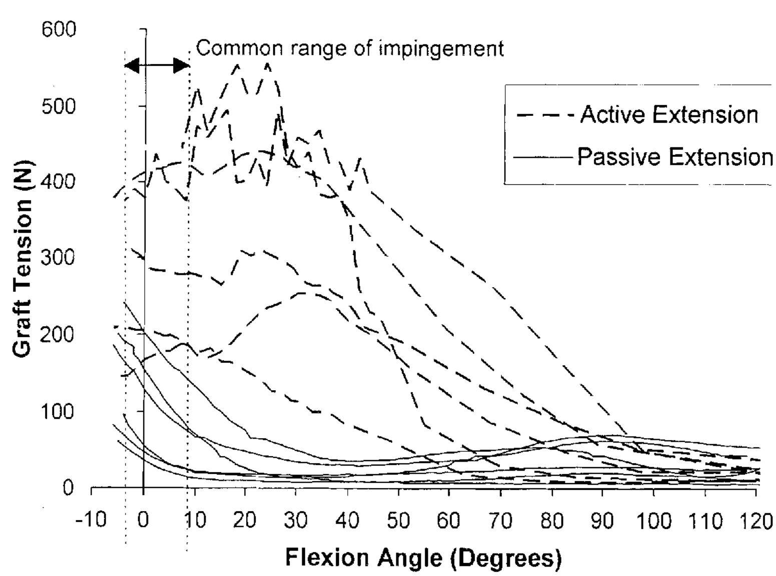

FIG. 3. Tension in six anterior cruciate ligament grafts with use of the customized tibial tunnel with passive extension and active quadriceps load of 1,500 N. The quadriceps load significantly increased the tension in the graft ($p < 0.001$).

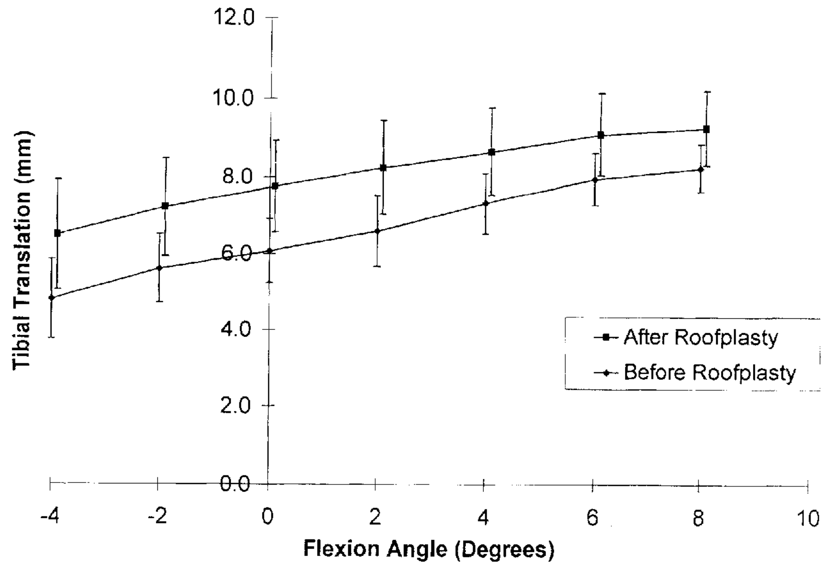

FIG. 4. Mean anterior tibial translation (±1 SE) with use of the anterior tibial tunnel, before and after a 10-mm roofplasty, during quadriceps load (n = 6). A 10-mm roofplasty resulted in an increase in the anterior tibial translation during quadriceps load ($p = 0.021$).

0.7 mm with the knee in 4° of hyperextension (range: 3.8-8.3 mm).

Because of the increased anterior tibial translation precipitated by the active quadriceps force, the flexion angle at which roof impingement occurred increased significantly as well ($p = 0.005$). With the graft in the anterior tibial tunnel, the onset of impingement occurred at 16 ± 3.5° of flexion (range: 7-28°) during the quadriceps load instead of at 3 ± 3° during passive extension (range: −6-12°). With the graft in the customized tibial tunnel, the onset of impingement occurred at 8 ± 4° of flexion (range: −6-22°) during the quadriceps load instead of at −4 ± 1° of hyperextension (range: −6- 0°) during passive extension. The range of motion at which the graft contacted the intercondylar roof during the quadriceps load was 20° for the anterior tunnel and 12° for the customized tunnel when a roofplasty was not performed.

The contact pressure between the anterior cruciate ligament graft and the intercondylar roof increased significantly under the application of the 1,500-N quadriceps load ($p < 0.001$). The maximum pressure occurred with the knee in hyperextension. With the graft in the anterior tunnel, the pressure increased on average from 433 kPa at 0 N to 1,647 kPa (3.8 times) when the quadriceps load was applied with the knee in hyperextension. At this same flexion angle, the pressure increased on average from 90 kPa at 0 N to 1,056

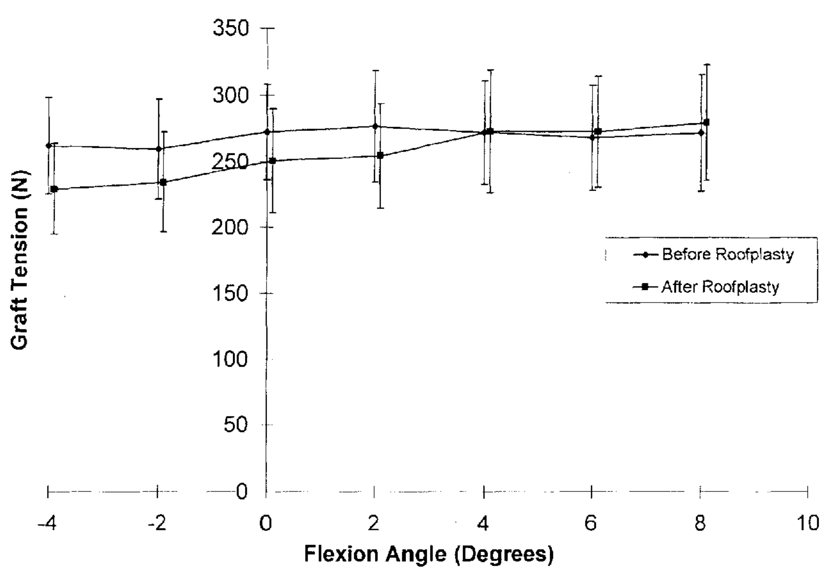

FIG. 5. Mean tension (±1 SE) in the anterior cruciate ligament graft with use of the anterior tibial tunnel, before and after a 10-mm roofplasty, during quadriceps load (n = 6). A 10-mm roofplasty had no significant effect on the tension in the graft during active knee extension ($p = 0.388$).

kPa (11.7 times) with the graft in the customized tunnel when the quadriceps load was applied.

Concomitant with the increase in contact pressure, the tension in the anterior cruciate ligament graft increased significantly for the 1,500-N quadriceps load ($p < 0.001$). With the graft in the anterior tibial tunnel, the quadriceps load caused the graft tension to increase 235 ± 37 N when the knee was in 8° of flexion (range: 107-336 N) and 152 ± 25 N when it was in 4° of hyperextension (range: 58-208 N) (Fig. 3). With the graft in the customized tibial tunnel, the quadriceps load caused the graft tension to increase 250 ± 32 N when the knee was in 8° of flexion (range: 168-350 N) and to increase 160 ± 23 N when it was in 4° of hyperextension (range: 81-222 N).

With the graft in the anterior tunnel and the 1,500-N quadriceps load applied, the roofplasty allowed the tibia to translate an average of 1.7 ± 0.5 mm (range: 0.1-3.3 mm) more anteriorly with the knee in 4° of hyperextension ($p = 0.021$) (Fig. 4). As a result, the roofplasty significantly decreased the angle at which the graft contacted the intercondylar roof from 16 ± 3.5° of flexion (range: 7-28°) to −1 ± 2° of hyperextension (range: 7-−6°) ($p < 0.005$). Although the roofplasty did not completely eliminate the pressure between the graft and roof, it did decrease the pressure on average from 1,703 to 473 kPa (3.6 times) at 4° of hyperextension ($p < 0.005$). The roofplasty did not change the tension in the graft ($p = 0.388$) (Fig. 5).

DISCUSSION

Because of the complications of roof impingement and because current surgical procedures avoid impingement for passive but not for active knee extension, the objective of this research was to quantitatively study the effect of quadriceps force on impingement. For this study, experiments were performed on cadaveric knees. Inherent to the experiments were several methodological issues that should be critically examined before the findings are interpreted. Because this examination has been made previously for the graft pretension, the measured graft tension, and the measured contact pressure (5), only a summary will be given here. The method of pretensioning was appropriate for this study because it was based on restoring the anterior tibial displacement of the reconstructed knee to that of the knee with the normal anterior cruciate ligament. Also, although the measured tension in the graft may not have been intraarticular (because of friction in the tibial tunnel) or the same as the tension that occurs *in vivo* (because the graft was not constructed from commonly used tendons), the interpretation of results is not affected because the analyses were based on the differences in tension and not on the absolute tension. Similar reasoning holds for the pressure measurement.

One issue unique to this study concerned the small increase in anterior tibial displacement of 0.7 ± 0.2 mm following quadriceps loading. This increase indicated that either the joint had not been sufficiently preconditioned or that the graft had slipped at its points of fixation. Slippage of the graft inside the freeze clamp was unlikely. A pilot study demonstrated that the freeze-clamp connection did not slip with graft loads as high as 450 N. Slippage may have occurred within the femoral tunnel where bone cement was used to fix the bone plug to the osteopenic femur. Regardless of the source of the increased anterior tibial displacement, the associated variability was randomly distributed by performing the quadriceps loading tests at randomly selected flexion angles.

Inasmuch as the methodology was appropriate for the goals of this study, the results can be discussed meaningfully. The key results were that active translation of the tibia caused by a 1,500-N quadriceps load precipitated and aggravated impingement of the graft by allowing the graft to contact the roof earlier in the flexion arc, increasing the contact pressure and increasing the tension in the graft relative to the corresponding changes for passive motion. Furthermore, although a 10-mm roofplasty did not reduce graft tension, it reduced, but did not eliminate, the range of contact and the contact pressure with the graft in the anterior tibial tunnel. Finally, placing the graft in a customized tibial tunnel without performing a roofplasty still resulted in contact between the graft and roof and increases in pressure.

The increase in the graft tension was caused by the quadriceps load and not by roof impingement. The quadriceps load translated the tibia anteriorly, which strained the anterior cruciate ligament graft (23). The roofplasty did not decrease the tension in the graft, because the tibia translated nearly 2 mm more anteriorly after the roofplasty (Fig. 4). This increase in tibial translation allowed the tension in the graft to remain equal at the same flexion angle whether or not the graft was impinged on by the intercondylar roof. Because roof impingement did not cause an increase in the tension of the graft, the tension in the graft cannot be affected by changing the position of the tibial tunnel or by performing a roofplasty. Tension increases in the graft can be controlled only by limiting the magnitude of the quadriceps load and applying the lowest possible pretension to the graft that still restores normal laxity at a specified flexion angle.

Arthroscopic evaluation of grafts subjected to roof impingement indicates that abrasion is the principle mechanism of graft injury (25). Abrasion occurs when pressure develops between the graft and intercondylar roof and the tibia translates. Our study supports abrasion as a mechanism for graft injury. As the knee was extended under the action of the active quadriceps force, the graft contacted the intercondylar roof well before the knee was fully extended, the contact pressure increased, and the tibia translated.

Damage to an anterior cruciate ligament graft from roof impingement is more likely to occur during knee extension exercises than during passive motion. For the customized tibial tunnel, impingement does not occur during passive motion until the knee is hyperextended (5). However, studies have shown that quadriceps loads of 1,500 N occur during active knee extension exercises (6,21,22). Co-contraction of the hamstring muscles, which can reduce anterior tibial translation with the knee in flexion, does not limit anterior translation from 22° of flexion to hyperextension (19) at which roof impingement during quadriceps loading occurs. Avoiding knee extension exercises from hyperextension to 28° of flexion can eliminate active impingement, but this will compromise rapid rehabilitation of the reconstructed knee.

Proper placement of the tibial tunnel and a roofplasty have the potential to eliminate active roof impingement while allowing knee extension exercises. Although a 10-mm roofplasty was effective at reducing the effects of roof impingement when the graft was routed through an anterior tibial tunnel, the effects were not eliminated. Also, a customized tibial tunnel without a roofplasty did not prevent active impingement. Therefore, a roofplasty is required even for the more posterior, customized tibial tunnel. However, the amount of bone removed from the intercondylar roof will have to be individualized for each patient. Variability in notch geometry, graft dimensions, stiffness of the graft and its fixation, tunnel placement, knee hyperextension, and joint laxity between patients precludes a standard-sized roofplasty for all knees.

To customize the amount of bone removed from the intercondylar roof, a technique that has been shown to be effective is to remove bone from the intercondylar roof in excess of that required to freely pass a rod, the same diameter of the graft, through the tibial tunnel and into the intercondylar notch with the knee in full passive extension (12,14). With use of this technique, contact between the graft and roof can be shifted into the range of hyperextension, offering the possibility of avoiding impingement during active extension exercises. Although this technique will consistently retard the onset of impingement, it has not yet been demonstrated to avoid impingement.

The requirement that a roofplasty prevent active impingement of a graft, when not necessary for preventing abrasion of the normal anterior cruciate ligament, may be explained by the difference in shape between the distal half of the normal anterior cruciate ligament and a graft. The normal anterior cruciate ligament has a broad anterior flare that contours to the distal outlet of the intercondylar notch, increasing the contact area and lowering the pressure between the graft and roof. The anterior fibers of the normal anterior cruciate ligament also relax with knee extension, which lowers the tension in the graft. This anterior flare of the normal ligament cannot be replicated by either a cylindrical or a rectangular graft. Contact between the graft and intercondylar roof may occur over a smaller surface area, increasing pressure, and either nonisometric graft placement or excessive pretensioning may allow the tension in the anterior fibers in the graft to remain high with the knee fully extended; this provides ideal conditions for graft abrasion.

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