

Can an Isometer Predict the Tensile Behavior of a Double-Looped Hamstring Graft during Anterior Cruciate Ligament Reconstruction?

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Summary: An isometer, a highly compliant spring-scale device for measuring suture displacement, has been used intraoperatively by surgeons to select the optimal placement of the femoral tunnel for an anterior cruciate ligament graft. The isometer measures the displacement of a suture centered in a tibial tunnel and attached to an intraarticular location on the femur before the femoral tunnel is drilled. Because the placement of the femoral tunnel strongly impacts the tensile behavior of an anterior cruciate ligament graft and because surgeons have used the amount of suture displacement to guide the placement of the femoral tunnel, the objective of this study was to determine the ability of an isometer to predict graft tension. In 14 patients undergoing reconstructive surgery of the anterior cruciate ligament, an isometer was used to measure suture displacement during passive knee motion for a provisional femoral tunnel location. An electrogoniometer recorded the flexion angle of the knee. The femoral tunnel was drilled. A double-looped semitendinosus and gracilis autograft was inserted around a post in the femoral tunnel, and the tension in the four limbs of the graft exiting the tibial tunnel was measured during passive knee motion. Graft-tension versus knee-flexion-angle curves revealed that each knee exhibited one of two distinct curve shapes: L-shaped, characterized by the maximum tension occurring at full extension and a nearly flat profile from 35 to 90° of flexion, or U-shaped, with elevated tensions at 80-90° of flexion ($p < 0.001$) reaching at least half of the tension in full extension. Because the shapes of the suture-displacement versus flexion-angle curves were more consistently L-shaped, the intraoperative measurement of suture displacement was not a useful predictor of either the increase in tension in the graft with flexion or the maximum tension in the graft.

Excessive tension in an anterior cruciate ligament graft during the early postoperative period should be avoided because fixation, remodeling, and maturation of the graft may be adversely affected (13). It is widely agreed that changes in the placement of the femoral tunnel have a larger effect on relative displacement and tension in the graft than do changes in the placement of the tibial tunnel (1,2,7,8,15,19). Consequently, a methodology that would enable the surgeon to predict tensile behavior and maximum tension in the graft for a selected placement of the femoral tunnel prior to drilling the definitive femoral tunnel would be useful.

One method that has been proposed to check the placement of a provisional femoral tunnel is isometry. The principle behind isometry is that the measurement of the relative displacement of a trial suture or wire can be used to predict the tensile behavior and,

hence, the maximum tension of an anterior cruciate ligament graft. Because the isometer is used to measure suture displacement before the definitive femoral tunnel is drilled, the surgeon may be able to rely on the magnitude of the suture displacement to locate the optimal placement for the femoral tunnel, thus avoiding the complications associated with high graft forces.

The usefulness of isometry is controversial (1). Using a bone-patellar tendon-bone graft, one study observed that large graft tensions could be avoided by utilizing isometer measurements to adjust the placement of the femoral tunnel (13). Other studies have found measurements of suture displacement to be a poor predictor of either the tensile behavior (5) or the maximum tension (4,6,15) of the graft.

Because the literature is inconclusive on the value of isometry, the objective of this study was to evaluate *in vivo* the ability of an isometer measurement of suture displacement to predict tensile behavior and hence the maximum tension of a double-looped semitendinosus and gracilis graft inserted arthroscopically by an endoscopic technique.

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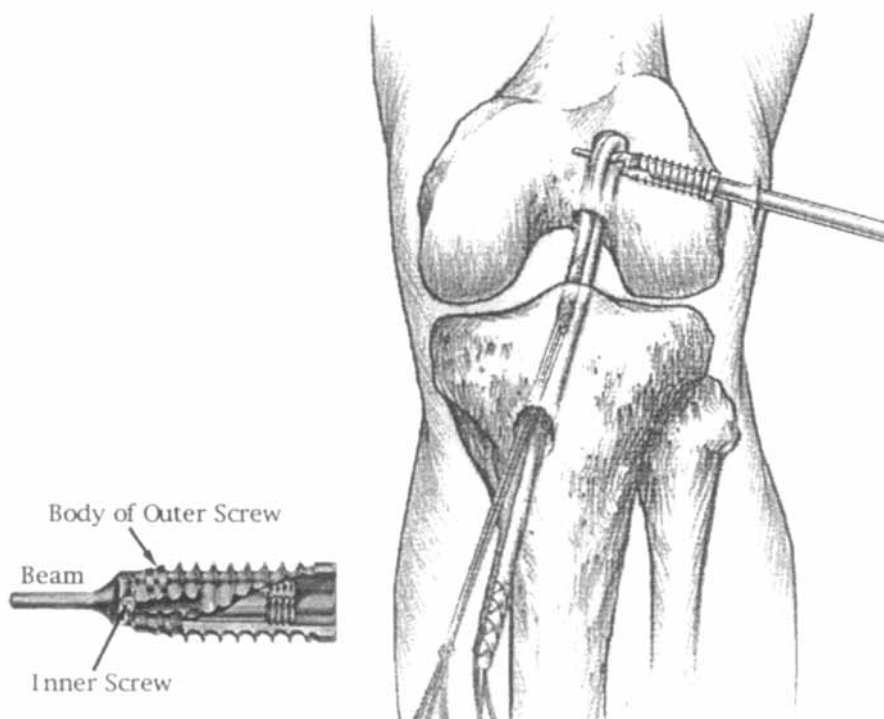


FIG. 1. Diagram of the shape and location of the femoral fixation device. The device was inserted through the lateral femoral condyle. The post, extending from the hollow body of the screw, bisects and spans the femoral tunnel and functions like a pulley. The two tendons were drawn up the tibial tunnel around the post and back down the tibial tunnel by the sutures sewn to the ends of each tendon. The midpoint of each tendon was centered on the post. (Adapted with permission from Wallace MP: "In Vivo Tensile Behavior of a Four-Bundle Hamstring Graft as a Replacement for the Anterior Cruciate Ligament" *Journal of Orthopaedic Research* 15:540, 1997.)

METHODS AND MATERIALS

From December 1994 to March 1995, suture displacement and graft tension were measured intraoperatively in 14 patients requiring repair of a torn anterior cruciate ligament. All patients agreed to participate in the study and signed a consent form approved by the Human Subjects Review Boards. There were 13 men and one woman, with an equal representation of right and left knees. The average age was 26 years old (range: 14-33 years). Four patients had an isolated injury to the anterior cruciate ligament, whereas the remainder had additional pathologies primarily to the meniscus (20).

The semitendinosus and gracilis tendons were harvested, muscle was removed, and each tendon was sutured (Vicryl 3-0; Ethicon, Somerville, NJ, U.S.A.) into a compact tube. A stiff, polyester, braided suture (no. 5 Ticron; Davis and Geck, Danbury, CT, U.S.A.) was sewn to each end of each tendon. The length of the prepared tendons averaged 27 ± 0.5 cm. The double-looped semitendinosus and gracilis graft, formed by looping the middle of the semitendinosus and gracilis tendons over a suture, was sized by pulling it through a series of calibrated cylinders (Arthrotek, Ontario, CA, U.S.A.). The tibial and femoral tunnels were drilled to match the diameter of the cylinder that provided the snugest fit.

The knee was inspected arthroscopically, and unstable meniscal tears were either repaired or partially excised. The tibial tunnel was drilled after customizing the position and angle of the tibial tunnel to account for variability in knee extension and roof angle (9-12). An endoscopic femoral aimer, sized specifically for the diameter of the graft (Arthrotek), was inserted through the tibial tunnel to place a guide wire 5-7 mm distal to the proximal edge of the intercondylar roof at approximately 11 o'clock for the right knee or 1 o'clock for the left knee (11). With the provisional femoral site identified, the guide wire was removed and isometric testing was conducted.

A modified screw (Isotac; Smith and Nephew, Andover, MA,

U.S.A.), in which a no. 2 silk suture (Ethicon) was passed through an eyelet, was screwed into the femoral pilot hole created by the guide wire. The two ends of the suture were passed through a spring isometer (Smith and Nephew), which was inserted into a size-specific centering sleeve (Smith and Nephew) within the tibial tunnel. The leg was flexed to 30° , and the suture was hitched to the isometer with the spring compressed 7 mm. The tension in the suture was calculated to be 28 N on the basis of a spring stiffness of 4 N/mm.

An electrogoniometer was attached to the lateral side of the femur with a molded, polyethylene cuff and Velcro strap, and to the tibia with a Velcro strap to continuously measure the flexion angle of the knee (20). The electrogoniometer was specially built for this application and used a potentiometer with infinite resolution to make the angular measurements. The flexion angle of the knee was measured, and the data from the electrogoniometer were stored on a personal computer. The 0° flexion angle was established with the knee fully extended (20).

The isometer was preconditioned by passively flexing and extending the knee three times. Because the thigh was oriented parallel to the floor, the surgeon compressed the joint to eliminate distraction by gravity during passive flexion of the knee (18). The position of the spring was read at 15° intervals during passive flexion from 0 to 90° . Suture displacement could not be measured past 90° of flexion because the operating table prevented full flexion of the knee. Data were collected for four cycles and averaged at each flexion angle.

The results from the isometer were not used to alter the placement of the femoral tunnel. The isometer and modified screw were removed, and the guide wire was reinserted through the tibial tunnel and into the original femoral pilot hole. A closed-end femoral tunnel was drilled to a depth of 25 mm by means of a cannulated endoscopic femoral reamer.

The double-looped semitendinosus and gracilis graft was se-

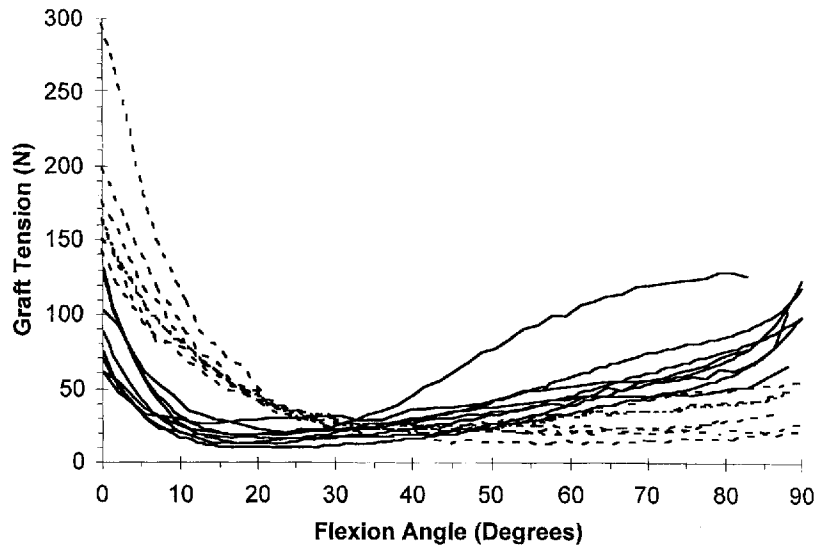


FIG. 2. Graph of the tensile behavior of the double-looped semitendinosus and gracilis graft versus flexion angle for all 14 patients. The tension-flexion curve was classified as either U-shaped (solid line) in eight patients or as L-shaped (dotted line) in six patients.

cured inside the femoral tunnel by looping the midpoint of each graft around a post that bisected the femoral tunnel (bone mulch screw; Arthrotek) (Fig. 1). The post, which functioned like a pulley, extended from a hollow, threaded screw that was introduced through a tunnel drilled transversely through the lateral femoral condyle (11).

Graft tension and flexion angle were simultaneously measured with an instrumentation and a data acquisition system previously described (20). Briefly, a frame containing four load cells was rigidly fixed to the tibia. Each of the four graft bundles was connected to one of the load cells. A personal computer recorded tension in each bundle and the flexion angle of the knee.

The flexion angle for pretensioning the graft was chosen so that the bundles did not become slack during passive motion of the knee. To locate this flexion angle, each bundle was initially pretensioned to 20 N at 30° of flexion and the knee was passively cycled three times. The flexion angle at which the graft tension was minimum was used as the flexion angle to set the graft tension. Each bundle was tensioned to 5 N at this selected flexion angle, which ranged from 25 to 40°. The graft was then preconditioned by passively cycling the knee 10 times. Data were acquired at 100 Hz while

the knee was cycled eight times from 0 to 80-90° of flexion (20).

Statistical Analysis

The tension-flexion curve from each cycle was constructed by summing the tension in all four bundles at flexion angle increments of 1° and plotting the total (i.e., summed) tension as a function of flexion angle. In each patient, the tension-flexion curve of the graft became reproducible by at least the fourth cycle. Therefore, steady-state data from the eighth cycle were used for analysis (20). The tension-flexion curves did not appear to be the same shape among the patients. The representative curve from each patient had either a U or L-shaped profile (Fig. 2). By grouping the two sets of curves and using flexion angle as the covariate, an analysis of covariance was used to determine whether the two graft tension-flexion curves were significantly different.

To determine whether the suture displacement-flexion curve shape predicted the graft tension-flexion curve shape, a one-factor repeated-measures analysis of variance was used at each flexion angle at which the suture displacement was measured. The independent variable was the measurement device (isometer or load cell), and the dependent variable was the quantity measured by

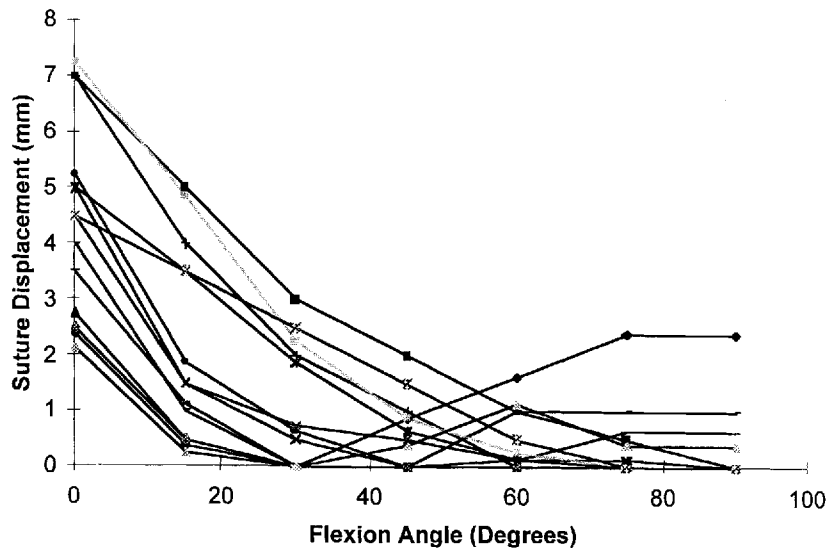


FIG. 3. Graph of suture displacement versus flexion angle for all 14 patients. Suture displacement was measured at 15° intervals.

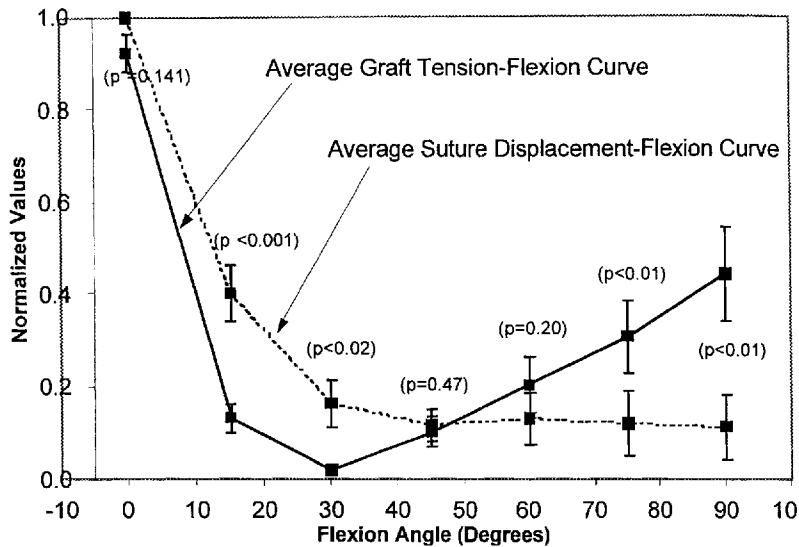


FIG. 4. Graph of the normalized suture displacement-flexion curve compared with the graft tension-flexion curve. The shape of the suture displacement-flexion curve was not predictive of the shape of the graft tension-flexion curve for the patients as a group. There were significant differences between the normalized suture displacement and graft tension curves at 15, 30, 75, and 90° of flexion ($p < 0.05$).

each device. Because the output from the graft load cell (Newtons) produced a different measurement than did the isometer device (millimeters) and because a comparison of the shapes of the two curves was of interest, the data produced by both devices were normalized at 0, 15, 30, 45, 60, 75, and 90° with use of the following equations: $\text{normalized tension} \times \text{degree} = (\text{tension} \times \text{degree} - \text{pretension}) / (\text{maximum tension} - \text{pretension})$, and $\text{normalized displacement} \times \text{degree} = (\text{displacement} \times \text{degree} - \text{minimum displacement}) / (\text{maximum displacement} - \text{minimum displacement})$. By means of the normalization, the shapes of the two curves were isolated from the scaling effects and analyzed separately. The shape of the suture displacement-flexion curve was considered to be the same as that of the graft tension-flexion curve if no significant difference existed between the normalized suture displacement and normalized graft tension at any flexion angle.

Because the shape of the suture displacement-flexion curve did not predict the shape of the graft tension-flexion curve when the patients were analyzed as a group, an additional analysis was performed to determine whether the suture displacement-flexion

curve shape was predictive of the graft tension-flexion curve shape within a patient. A regression analysis used a second-order polynomial on the normalized data to model the relation between suture displacement and graft tension for each patient over the range of flexion tested. The correlation coefficient was used to determine how strongly the shape of the suture displacement curve predicted the shape of the graft tension curve.

Inasmuch as the normalization isolated the curve shape from the scaling effects but the scaling effects were also of interest, a second type of analysis focused on the scaling effect. Specifically, a simple regression analysis was conducted to determine whether the maximum suture displacement was predictive of the maximum total graft tension.

Error Analysis

Three sources of error were analyzed that may have affected the tension measurement, including friction between graft bundles and between the graft and tibial tunnel, compliance of the suture, and slippage of the suture sewn to the tendon. The details of this

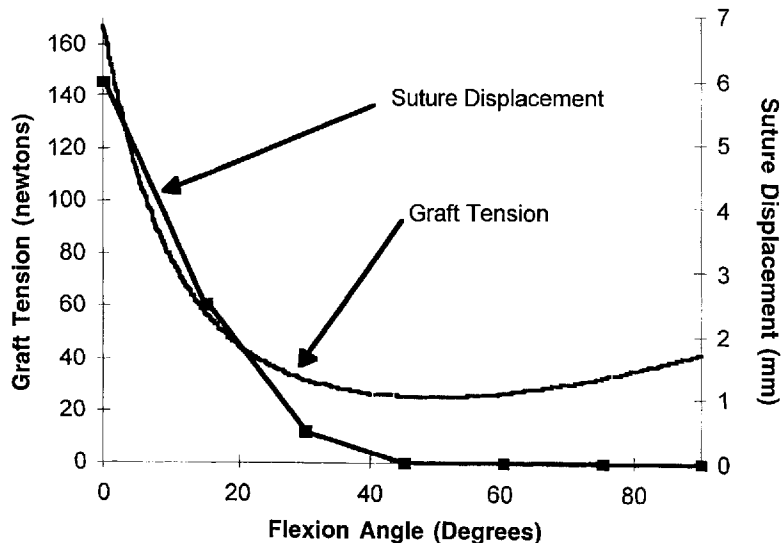


FIG. 5. Graph of suture displacement versus flexion angle compared with an L-shaped graft tension pattern. The suture displacement predicted the tension in the graft in the six patients with L-shaped tension-flexion curves ($r^2 = 0.95-0.99$, $p = 0.005-0.001$) (Table 1).

TABLE 1. Second-order polynomial regression model of suture displacement and graft tension, and maximum graft tension and maximum suture displacement for each patient

Patient	Pattern of tension-flexion curve	Suture displacement vs graft tension (r^2)	Statistical significance	Maximum graft tension	Maximum suture displacement (mm)
1	U shape	0.69	$p = 0.173$, NS	125	2.5
2	L shape	0.99	$p = 0.001$	150	7.0
3	U shape	0.65	$p = 0.206$, NS	89	2.5
4	U shape	0.88	$p = 0.043$	131	5.0
5	L shape	0.97	$p = 0.001$	175	5.0
6	L shape	0.96	$p = 0.002$	164	5.0
7	L shape	0.99	$p = 0.001$	198	7.0
8	U shape	0.44	$p = 0.319$, NS	98	4.0
9	U shape	0.66	$p = 0.117$, NS	129	3.5
10	U shape	0.75	$p = 0.061$, NS	102	2.5
11	L shape	0.99	$p = 0.001$	279	7.5
12	U shape	0.29	$p = 0.579$, NS	98	2.0
13	U shape	0.78	$p = 0.048$	70	4.5
14	L shape	0.95	$p = 0.005$	145	4.5

NS = not significant.

analysis were given previously (20). The conclusions from this analysis were that neither the friction nor the slippage affected the measured tension. Although the compliance of the suture caused the tension to be underestimated by as much as 11%, this error was systematic and hence does not affect the interpretation of the results.

RESULTS

The graft tension-flexion curve for each patient followed one of two distinct profiles (Fig. 2). An L-shaped curve, characterized by the maximum tension occurring at full extension and a nearly flat profile from 35 to 90° of flexion, was observed in six patients. A U-shaped curve, with elevated tension in 80-90° of

flexion reaching at least half the tension in full extension, was observed in eight patients. The analysis of covariance confirmed that these two curve profiles were significantly different ($p < 0.001$).

The maximum suture displacement for all 14 patients averaged 4.5 ± 1.7 mm, with a range of 2.0-7.0 mm. The maximum displacement occurred at full extension for all patients, whereas the minimum occurred anywhere at 30-90° of flexion (Fig. 3).

The shape of the suture displacement-flexion curve was not predictive of the shape of the graft tension-flexion curve for the patients as a group. There were significant differences between the normalized suture

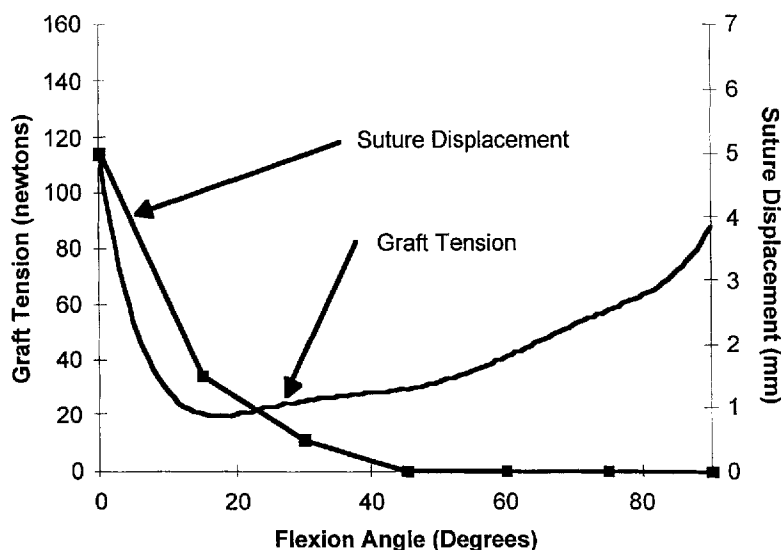


FIG. 6. Graph of suture displacement versus flexion angle compared with a U-shaped graft tension pattern. The suture displacement did not predict the tension in the graft in six of eight patients with U-shaped tension-flexion curves ($r^2 = 0.29-0.88$, $p = 0.579-0.043$).

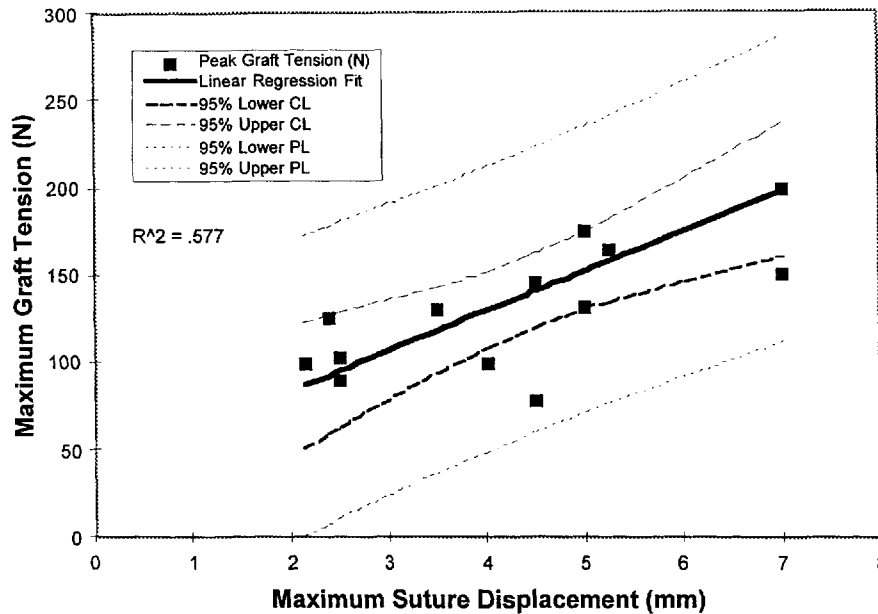


FIG. 7. Graph of maximum suture displacement versus maximum graft tension for 14 patients. The predictive relationship between maximum suture displacement and maximum graft tension ($r^2 = 0.577$, $p < 0.0014$) was relatively inaccurate. The slope of the regression curve is flat, and the 95% confidence interval of ± 25 N and predictive interval of ± 80 N were relatively broad. For example, there is considerable overlap in the predicted range of maximum graft tension for a knee with a 3-mm (20-180 N) or 6-mm (80-260 N) maximum suture displacement. CL = confidence limit, and PL = predictive limit.

displacement and graft tension curves at 15, 30, 75, and 90° of flexion ($p < 0.05$) (Fig. 4).

When the displacement-flexion curve of the normalized suture was compared with the tension-flexion curve of the normalized graft using regression within a patient, the behavior of the suture was found to be predictive of the tensile behavior of the graft in only eight of the 14 patients. The normalized suture displacement predicted the normalized tension in the graft in the six patients with L-shaped tension-flexion curves ($r^2 = 0.95-0.99$, $p = 0.005-0.001$) (Table 1 and Fig. 5). It did not predict the normalized tension in the graft in six of eight patients with U-shaped tension-flexion curves ($r^2 = 0.29-0.88$, $p = 0.579-0.043$) (Table 1 and Fig. 6).

The predictive relationship between maximum suture displacement and maximum graft tension ($r^2 = 0.585$, $p < 0.0014$) was relatively inaccurate. The slope of the regression curve was flat, with a broad 95% confidence interval of ± 25 N and an even wider 95% predictive interval of ± 80 N. For example, there was considerable overlap in the predicted range of maximum graft tensions for a knee with a 3-mm (20-180 N) or 6-mm (80-260 N) maximum suture displacement (Fig. 7). The 95% predictive intervals of maximum graft tension were wide at every 1-mm increment of maximum suture displacement; this limited the ability of a specific suture displacement to predict maximum graft tension.

DISCUSSION

Our investigation demonstrated that the measure-

ment of suture displacement with a highly compliant spring isometer was a poor predictor of the tensile behavior (i.e., shape of the tension-flexion curve) and maximum tension of a double-looped semitendinosus and gracilis graft; therefore, the question of whether such devices are worthwhile instruments for the surgical procedures described is raised. A displacement of the trial suture of 3 mm or less did not predict the tensile behavior of a double-looped semitendinosus and gracilis graft. The grafts in these patients had U-shaped tension profiles in which the tension increased from 30 to 90° of flexion even though the displacement of the trial suture predicted that the tension in the graft would remain constant (Fig. 6 and Table 1).

The poor predictability of the trial suture in our study does not support the recommendations made by other authors that a reasonable intraoperative goal is to choose a location for the femoral tunnel that limits suture displacement to 3 mm as the knee is moved from 30° to full extension (3,13,16,17). Although a statistically significant relationship existed between the maximum suture displacement and maximum graft tension, the flat slope of the regression curve, the wide confidence interval, and the even wider predictive interval prevent the measurement of suture displacement from being a reliable method to predict the maximum tension of a graft (Fig. 6).

The relatively flat slope of the graph comparing maximum suture displacement with maximum graft tension (Fig. 7) was probably the result of use of a highly compliant spring isometer (4 N/mm). The spring isometer was more elastic than the modified screw and

the loop of no. 2 silk suture. These three components are connected in series; therefore, the compliance of the system used to measure suture displacement was determined by the most elastic component, the spring isometer. The development of a stiffer isometer with sufficient resolution and accuracy for measuring changes in suture length may improve the ability of a measurement by an isometer to predict graft tension.

The inability of the displacement of a trial wire to predict an increase in graft tension with knee flexion has also been observed with a bone-patellar tendon-bone graft. In the study by Markolf et al. (13,14), four of 17 specimens had an increase in the tension of a bone-patellar tendon-bone graft with knee flexion without a corresponding increase in the displacement of the trial wire. Although the authors believed that the cause of the increase in graft tension with flexion was anterior placement of the femoral tunnel (13,14), an evaluation of this hypothesis was not performed; this suggests that other causes could be responsible for the inconsistent behavior of the trial wire.

We do not believe that the cause of the increase in graft tension with flexion was anterior placement of the femoral tunnel. In our study, a femoral aimer was used that consistently centered the femoral tunnel 5-6 mm anterior or distal from the posterior or proximal ridge of the intercondylar roof. The thickness of the posterior wall of the femoral tunnel was measured arthroscopically and never exceeded 2 mm. Because the femoral tunnels were consistently placed as far posteriorly as possible without cutting out the posterior wall of the tunnel, it can be inferred that anterior placement of the femoral tunnel was probably not the cause of the increase in graft tension with flexion.

Although the placement of the tibial tunnel is recognized as being less important to the tension of the graft than the femoral tunnel, variations in the placement of the tibial tunnel may be predictive of the increase in graft tension with flexion. We plan to study this possibility and report the results in a future article.

The effect of increasing the pretension in each bundle in 5-N increments to 20 N per bundle on the tension-flexion curve was evaluated in the last patient who was studied. Increasing the pretension caused a proportional increase in the total graft tension at each flexion angle. The shape of the tension-flexion curve did not change. Therefore, it was concluded that intraoperative measurement of suture displacement did not predict the tensile behavior and that maximum tension of an anterior cruciate ligament graft was independent of the load for pretensioning the graft.

The double-looped semitendinosus and gracilis graft was chosen for evaluation in this study because of its increased use as a replacement for the torn anterior cruciate ligament. Because the shape and biomechanical properties of a multi-bundled graft such as the

double-looped semitendinosus and gracilis graft are different from those of a single-bundled graft such as the bone-patellar tendon-bone graft, there is a possibility that the ability of an isometer measurement of suture displacement to predict maximum graft tension and tensile behavior may be dependent on the tissue or construct of the graft, or both.

The greater cross-sectional area of a double-looped semitendinosus and gracilis graft and bone-patellar tendon-bone graft compared with that of a single suture may explain why tension in the graft increases in flexion while the displacement of the suture does not. The suture, with its small diameter, may not impinge on the posterior cruciate ligament. However, when the broader graft is inserted in place of the suture, impingement with the posterior cruciate ligament may occur. Regardless of the cause, the surgeon cannot rely on *in vivo* isometric measurements to predict the tensile behavior of a double-looped semitendinosus and gracilis graft and bone-patellar tendon-bone graft (5).

Other factors, in addition to the differences in shape, dimension, and mechanical properties between the suture and anterior cruciate ligament graft, affect the ability of isometric measurements to predict the tensile behavior and maximum tension in the graft (1). The maximum suture displacement is dependent on the loading conditions across the knee. Allowing gravity to distract the knee increases the suture displacement compared with when the joint is compressed (18). Furthermore, the kinematics of the knee are different during the isometer measurement of suture displacement than with the knee with the graft in place, pretensioned, and fixed (5). Because isometric testing is performed in an anterior cruciate ligament-deficient knee with abnormal kinematics and the tensile behavior of the graft is measured in a stable, reconstructed knee, it was not surprising that little agreement existed between these two measurements.

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