Load and length changes in an artificial ligament substitute

10 cases of anterior cruciate ligament reconstruction

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In 10 patients who had reconstruction of the anterior cruciate ligament, the load and length changes in an artificial ligament substitute were measured during passive knee motion. Using a special drill guide, the ligament was placed within ±2 mm of the normal anatomic center on the femur. With the femoral end fixed with a bicortical screw the ligament was preloaded to 40 N at the flexion angle with the shortest intraarticular ligament length, usually 45°. The change in load was then registered from 90° of flexion to full extension. In 2/10 cases loads of > 200 N were registered in full extension, but the mean load was 160 N. There was a higher loss of load during the first extension/flexion cycle than during the 4th cycle. The load change correlated to the length change, but the degree of length change could not predict the maximum load level. There was a large variation in load levels between different knees, even with similar ligament placements, but the least change in load and length was obtained by an anatomic placement. Isometer readings did not predict the load level in the ligament substitute, but could indicate the angle of flexion with minimum load. Therefore, the isometer can be used to control the placement of the attachment points for the substitute. After fixation, fiber settling and stretching the ligament, as well as adaptation of the tissues, will tend to reduce the load levels.

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Substitute placement has become increasingly important in reconstructive surgery for anterior cruciate insufficiency. The concept of isometry has been introduced as constant intraarticular length of anterior cruciate substitutes in all knee positions (Odensten and Gillquist 1985, 1986, Hefzy and Grood 1986, Good et al. 1987, Hefzy et al. 1989, Sapega et al. 1990). Since a change in distance between attachment points with knee motion will change the substitute load, placement precision is important. To find the best substitute placement, the use of a spring-loaded isometer has been proposed (Odensten and Gillquist 1986, Graf et al. 1987). It is assumed that a small change in length also reduces the load in the substitute. In this study we analyzed whether length changes recorded by a spring-loaded isometer can be used to predict load levels in artificial substitutes during passive knee motion. The load levels reached during clinical implantation of an artificial ligament were also related to ligament placement.

Patients and methods

In 10 patients (Table 1) the anterior cruciate ligament was reconstructed because of symptomatic, chronic anterior instability. Associated injuries were repaired after all measurements were completed. A notchplasty to 20 mm width (Odensten and Gillquist 1985) was performed when necessary. A braided polyethylene ligament prosthesis (stiffness: 216 N/mm, creep <1 percent, 5 mm in diameter; Smith & Nephew Richards, Memphis, TN, U.S.A.) was placed with a drill guide (Stryker Corp. Kalamazoo, MI, U.S.A.) through femoral and tibial tunnels in a straight line in the frontal plane (Odensten and Gillquist 1986). The ligament was fixed to the femur with a bicortical screw and length changes during passive knee motion, with the foot supported, were recorded at the tibial end with a spring-loaded isometer (stiffness 4 N/mm, Stryker Corp.) fixed to the tibia with 1 mm steel pins. The ligament was preloaded with 40 N. The flexion angle was measured in 10° increments with a liquid goniometer. After the length measurements, the 40 N preload was reapplied to the ligament at the flexion angle, with the shortest intra-articular ligament length.

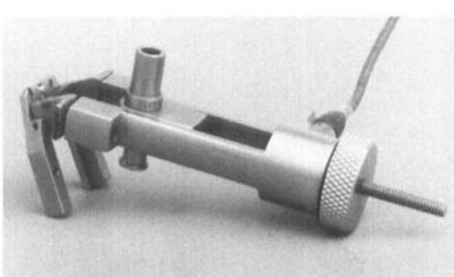
Table 1. Observations in 10 cases of anterior cruciate ligament reconstruction

Case	Sex	Age	Injury[a]	Position		Change in		Corr[d]	A–P translation[e]		Load[f]
				Femur	Tibia	Length[b]	Load[c]		Pre	Post	
1	M	48	L,M,LL,OA	0.67	0.43	–2	108	0.77	4	–5	40
2	M	25	–	0.66	0.42	–1.5	170	0.98	4	–1	40
3	M	36	–	0.66	0.39	–3	223	0.94	11	0	40
4	M	31	M	0.64	0.49	–2	87	0.96	6	1	60
5	F	26	LL	0.67	0.33	–3.5	125	0.87	5	–1	20
6	M	30	–	0.66	0.48	–1	131	0.94	4	–2	20
7	M	30	M	0.66	0.46	–3.2	190	0.99	7	–2	40
8	M	31	M	0.68	0.40	–2.6	170	0.97	3	–2	40
9	F	23	M,L,OA	0.72	0.31	–4.3	59	0.60	4	–2	20
10	M	26	L	0.64	0.43	–2.8	189	0.92	6	0	40
Mean		31		0.67	0.41	–2.5	145	0.9	5.4	–1.4	36
SD		*7*		*0.02*	*0.06*	*0.9*	*52*	*0.03*	*2.3*	*1.7*	*13*

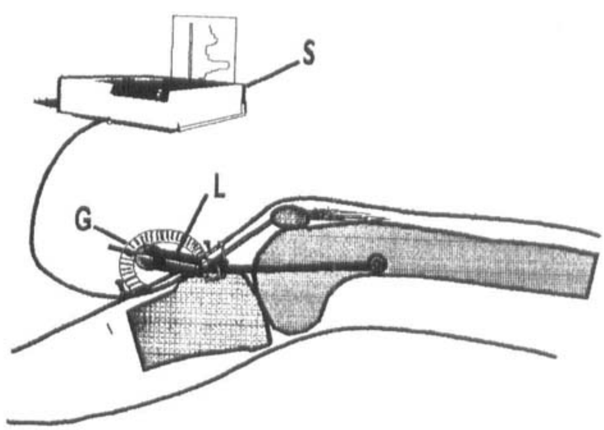
[a] L/M Lateral/medial meniscectomy; LL/ML Lateral/medial ligament reconstruction; and OA Degenerative changes in joint cartilage with fragmentation
[b] Change in length (mm) from full extension to shortest intraarticular length
[c] Change in load (N) from full extension to minimum load
[d] Correlation coefficient between the individual length and load values
[e] A–P displacement difference (injured–normal knee) at the beginning and at the end of surgery
[f] Preload used on the individual ligament to produce the postoperative A-P displacement

After 4–5 motion cycles for conditioning, starting at 90°of flexion, the preload was adjusted to 40 N and the change in load recorded on an x–y recorder during 4 cycles of extension and flexion with a Kistler piezo-electric load cell (9001 Kistler Instrument Corp., NY, U.S.A.) fixed to the anterior tibia by four K-wires (Figure 1). Between each extension and flexion cycle the ligament tension was reset to 40 N at the flexion angle with the shortest intraarticular ligament length. There was no appreciable drift in the load cell between recordings or patients. The load output was calibrated by applying 90 N to the load cell with a spring-loaded handle before and after the measurements. The data sampling was always done from 90° of flexion to full extension and then back to 90° and the load levels were read from the load curves for every 10°. The effect of friction in the tunnels was estimated in a few cases by using a polyethylene ligament of 2 mm diameter through the 5 mm drill channels. There was no appreciable difference in length/load changes or curve shapes. The position of the drill channels was evaluated on intraoperative x-ray films according to Good et

Figure 1. The load cell.



Details of the load cell assembly.



The load cell (L) was connected to the ligament which was fixed to the femur by a bicortical screw. The flexion angles were measured by a liquid goniometer (G). The signals from the load cell were recorded on a strip chart recorder (S).

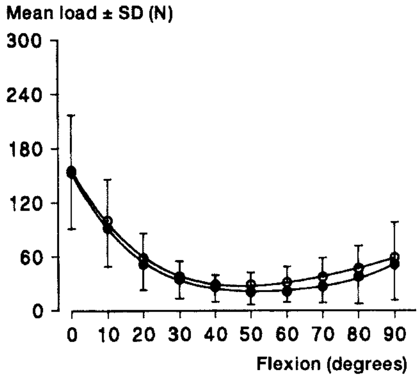


Figure 2. Mean load curves from the 4th cycle of extension ○ and flexion ●. The bars denote SD.

al. (1987). On the lateral films the position of the center of the femoral drill channel was expressed as a fraction of the condyle depth along Blumensaat's line. The same technique was applied to the tibial attachment. These measurements have a coefficient of variation for double determinations of 9.5 percent. The accuracy of the drillguide system is within ± 2 mm of the center of the anatomic attachment on the femur (Good et al. 1987). The A-P displacement of the tibia in the normal and injured knees was measured at 20° of knee flexion intraoperatively with a test device (OSI, Hayward CA, U.S.A.) before and after fixation of the ligament. At the end of the operation, the ligament was loaded to 40 N in 20° of flexion and the AP displacement measured at 90 N force in order to match the displacement of the injured knee to that of the normal knee. If necessary, the load was adjusted to reach the desired AP displacement. This procedure has been previously shown to produce a desired knee stability (Gillquist and Odensten 1992).

The Student's *t*-test was used for independent samples.

Results

The mean *(SD)* ligament positions on the femur and tibia were 0.67 *(0.02)* and 0.41 *(0.05)*, respectively, which represent areas within the attachments of the normal ACL (Good et al. 1987). The mean change in length recorded with the isometer was 2.5 *(0.9)* mm. The isometer curves had a maximum in full extension and a minimum around 45°.

Ligament preload was always lost during the first extension and flexion cycles but it was maintained during the last cycles. Load dissipation was lower during the last cycles than the first cycle (*P* 0.001). The maximum load, 160 *(63)* N, was always obtained in full extension and the minimum was around 45° (Figure 2). In 2 cases loads between 200 and 250 N were registered in full extension. There was a good correlation between the shape of the isometer curves and the load curves (mean r 0.9 *(0.03)*, *P* 0.01). However, the individual length changes could not predict the magnitude of load change. The change in load/mm length change was 55 *(23)* N for 0–45° and 29 *(28)* N (0.1) for 45–90° of knee flexion. In the mean, 80 *(23)* percent of the maximum load in extension was lost during the last flexion cycle from 0 to 90°. Variation in the ligament position on the tibia was significantly related to the length change (*r* –0.74, *P* 0.02), more anterior positions leading to a greater length change. The variation in the femoral position was smaller but did influence the load change during knee motion with greater loss of load in more posterior positions (*r* 0.75, *P* 0.01). A more anatomic femoral insertion improved the correlation between the length and the load curves as compared to a position outside the anatomic area ($P < 0.01$). The mean total AP displacement of the injured knees changed from 11 *(1.5)* mm to 4.3 *(1.3)* mm after fixation of the ligament. The mean total AP displacement of the normal knees was 5.7 *(1.6)* mm. The AP displacement difference (injured – normal knee AP displacement) changed from 5.4 *(2.3)* mm before surgery to –1.4 *(1.7)* mm (*P* 0.001). The mean ligament preload used to achieve this was 36 *(13)* N (range 20–60 N).

Discussion

Our study confirms that high loads in knee joint extension can occur in artificial ligament reconstructions, as was demonstrated experimentally by More and Markolf in 1988. Loads between 200 and 250 N were recorded in full extension in 2/10 cases in spite of anatomic placement. The load range in extension in this study corresponds well to the 50–240 N range demonstrated in the natural anterior cruciate ligament under experimental conditions by Markolf et al. 1990. The shapes of the mean load curves in our study are also comparable to the findings of Markolf et al. 1990. At the lowest point (45° of flexion) only the preload of 40 N remained and there was very little increase in the mean load during the last degrees of flexion. This shows that the implantation resulted in a near-normal load pattern in the ligaments. It has been shown that the loads generated are dependent on the preload in the ligament and the angle of knee flexion where the ligament is tensioned, whereas the ligament insertion site influences the shape of the curve (Bylski-Austrow et al. 1990). This tallies with the relation between attachment points and the length and load change that we could demonstrate. It seems that an anatomic placement on the femur will minimize the load change and the loads in a particular substitute will then depend mostly on the preload. On the other hand, different substitutes will result in different load levels for the same placement and pretension, dependening on their material characteristics. In the experiment the preload was applied in the flexion angle where the lowest intraarticular length was recorded. This was necessary to ensure some tension in the substitute throughout the whole range of motion. Since the ligaments were finally tensioned at 20° of flexion, the maximum loads reached were probably lower than what was recorded during the experiment. Our previous clinical experience shows that 40 N preload in an artificial ligament in 20° of knee flexion usually results in normal knee AP displacement measured at the same flexion angle (Gillquist 1987). In the present study 6/10 cases showed acceptable values with that preload, but in 3 cases 20 N was used and in one case 60 N. In the mean we achieved a slight overtightening of the knees but, considering the measurement error, it was felt safer to be on the tight side. The recorded length changes were generally within accepted limits for isometry ($\leq$ 2.5 mm). The tibial placement had a large variation and an anterior position seemed to increase the length change which is an undesirable effect. We have previously found that an anterior tibial placement results in a higher failure rate for artificial ligaments from impingement in the notch with the knee in extension (Gillquist and Odensten 1992). Impingement of an autologous ligament has also been shown to occur with an anterior tibial position (Clark and Howell 1990). Therefore, a position anterior to the anatomic attachment on the tibia should be avoided. Other authors have suggested that malpositioning of the ligament substitute may be responsible for limitations in knee motion (Bylski-Austrow et al. 1990) or failure of a reconstructed ligament (Clark and Howell 1990, Gillquist and Odensten 1992).

The shape of the length curves generally correlated well to the load curves but the length changes did not reflect the magnitude of load change. The load change per mm length change varied widely between patients. Since gross changes in femoral placement will produce characteristic length change curves (Odensten and Gillquist 1985, Sidles et al. 1988, Bylski-Austrow et al. 1990, O'Brien et al. 1990) the spring loaded isometers can be used to avoid gross errors in ligament placement and to predict the shape of the load curve and the flexion angle with the lowest load, but not to predict the actual load levels in an individual patient. The load changes will probably be minimized if the substitute is placed within the anatomic area. Even with similar placement the load levels will vary with knee joint anatomy, substitute characteristics and preload. During the initial motion cycles the applied preload was more or less lost. With several cycles the load dissipation diminished indicating stretch out and fiber settling of the ligament and adjustment of the joint soft tissues. It is a well known fact that viscoelastic structures become stiffer when loaded repeatedly. Therefore, cycling of the knee under ligament load with repeated adjustment of the tension may be necessary to maintain the desired load level and stability. A similar procedure has been described for the Goretex ligament in vitro by More and Markolf (1988).

In clinical practice the use of an isometer is recommended. Length changes should be read for every 15° from full extension to 110° of flexion. To avoid overtensioning of the substitute, the final preload should be applied midway between full extension and the flexion angle with the shortest intraarticular length (minimum load). A preload of 40 N on the substitute seems to restore A-P displacement to normal in most cases (Gillquist and Odensten 1992). Before final fixation 3–5 motion cycles under load seem to ensure that the ligament substitute is under tension. Due to viscoelastic changes in the tissues it is probable that the applied tension will diminish with time after surgery. We have previously demonstrated that the A-P displacement increases during the first years after reconstruction (Gillquist and Odensten 1992).

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