Measurement and Adjustment of Resultant Graft Tension of ACL Reconstructed Knee : An in vitro Study*

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In this study, a device is developed for the measurement and adjustment of resultant graft tension of the anterior cruciate ligament (ACL) reconstructed knee in vitro. This device is attached to the tibial surface at the distal end of the drill hole for ACL reconstruction. It measures the graft tension via a suture coming from the graft and fixed at one end of the device positioned on the axis of the drill hole, by using strain gauges. A hollow bolt-nut pair at the end of suture fixation site provides a level adjusting mechanism for the initial tension adjustment of the graft. The calibration test showed a good linearity and sensitivity, and the effect of the device is examined through the knee extension test and the anterior-posterior (A-P) drawer test for four human cadaveric knees. The graft tension observed by the device showed the ACL/graft tension characteristics that is consistent with those in past reports by several authors, and it is confirmed that the developed device enables us to study the graft tension under the practical situation of ACL reconstruction quantitatively.

Key Words : Biomechanics, Knee Joint, Anterior Cruciate Ligament, Reconstruction, Graft Tension, Tension Measurement, Initial Tension, Knee Extension Test, Drawer Test

1. Introduction

The anterior cruciate ligament (ACL) of knee joint is frequently ruptured such as in sports accident, and many studies have been reported for its reconstruction^{(1),(2)}. The graft tension is considered as the critical biomechanical feature of ACL reconstruction, and different devices and methods have been

developed and used for its measurement and evaluation. For instance, buckle transducers^{(3),(4)} and arthroscopic force probe^{(5),(6)} are mounted on or inserted in ACL/graft, and conventional load cells and universal force-moment sensors⁽⁹⁾⁻⁽¹¹⁾ are mounted on the bone part. These devices are aimed at being used for measurement of the ACL/graft tension in vitro. However, their measuring setups are somewhat different from the clinical setup in which the graft tension is measured and adjusted at the distal entrance of the tibial tunnel⁽¹²⁾. Gertel et al.⁽³⁾, for example, have reported the adjustment of initial tension of ACL reconstructed human cadaveric knee by using a device with hollow bolt-nut pair placed in the tibial tunnel. It, however, is not identical to the clinical situation, since the bone tunnel is larger than the standard and the graft is placed in the tunnel of the device but not in the tunnel of tibia.

In this study, authors propose a simple device for the measurement and adjustment of the graft tension used under the condition same as the practical setup at the ACL reconstruction as much as possible. The feasibility of the proposed device is examined by means of the knee extension test and anterior-

* Received 6th May, 1999. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 65, No. 629, A (1999), p. 194-200 (Received 19th March, 1998)

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posterior (A-P) drawer test with four human cadaveric knees. Through these feasibility tests, the influence of the initial tension on the graft tension of ACL reconstructed knee is considered.

2. Method

2.1 V-shaped device

2.1.1 Basic idea and structure The basic idea of the tension measuring of the graft of the ACL reconstructed knee of human cadavers is schematically illustrated in Fig. 1. The device for tension measuring is made of stainless steel and has two plates interconnected with an acute angle making the shape of the letter "V" or "A", as shown in Fig. 2. The device is placed at the distal entrance of the tibial tunnel and is screwed down at the fixity plate P_t on the tibial surface. Two small waterproof strain gauges (KFWS-2N-120-C1-11L3M2R, Kyowa Denryo, Tokyo) are glued on both of superior and inferior surfaces of the other plate P_s , and are used to observe

Fig. 1 Tension measuring setup with V-shaped device

Fig. 2 Detail of V-shaped device

the bending deformation of the plate P_s due to the force acting on its tip-end. The shape and dimensions of the device are determined by considering the position and direction of the tibial tunnel and the fixity condition of the device by using bone screws. The detailed shape and dimension of the plate P_s is determined considering the strength under the graft tension of 200 N as the assumed maximum and the sensitivity under the graft tension smaller than 100 N for the initial tension adjustment. The position of proximal screw for device fixity to the tibia is determined so that it is identical to the suture anchoring position in the clinical reconstruction procedure.

The suture coming from the graft is connected to the tip-end of the plate P_s through the level adjusting mechanism that consists of a bolt-nut pair and a plate for the suture fixity. That is, a bolt of M6 with a tunnel of 3 mm in diameter is attached at the tip-end of the plate P_s . A square nut of M6 is placed on the hollow bolt and has a lid plate on its distal end. The lid plate has a hole and an M-shaped small knob. The suture coming from the graft is let out from the distal end of tibial tunnel, is passed through the hole of the hollow bolt-nut and the hole of the lid plate, and is terminated at the M-shaped knob. The nut rotates freely with respect to the lid plate, and the level of distal end of the suture at the lid plate is adjusted by using the bolt-nut pair. The range of level adjustment is set to be 10 mm in this study, although it is variable with the different choice of the bolt-nut stroke. This range of level adjustment of 10 mm enables us the tension adjustment of 60 N approximately in this study.

2.1.2 Calibration test The calibration test is conducted for the developed device in order to establish the relationship between the suture tension and the device deformation. The device is fixed to the test bed of 45 degrees so that the plate P_s is maintained horizontal. The vertical dead weights of different levels up to 100 N are applied to the device via a suture as shown in Fig. 3. The output of the stain

Fig. 3 Setup for calibration test

Fig. 4 Calibration curve

gauges through an amplifier is acquired into a personal computer for individual load level with the sampling frequency of 10 Hz for an interval of 10 seconds. The strains at all load levels applied are measured five times by the two-gauge method. The calibration test is also done by the single gauge method with the gauge on superior or inferior surface of plate P_s , in order to be prepared for the case of gauge trouble during experiments.

Figure 4 shows the calibrated relationship between the suture tension and the device deformation. The standard deviation of strain at individual load level is so small that the tick for standard deviation from the average is remained within the size of marks used in Fig. 3. These results confirm that the device has a good reproducibility and linearity with a sufficient sensitivity. This calibration test is carried out following to every experiment using the device in order to confirm the rationality of the measurement in this study.

2.2 Material and testing method

2.2.1 Material Four human knee joints of two right limbs and two left limbs have been derived from one male and three female healthy cadavers aged between 72 and 82 years. The materials have been frozen at -40 degrees Celsius immediately and kept until the biomechanical tests. After thawing to the room temperature and removing all peripheral tissues from the knee except the joint capsule, ligaments and quadriceps, the knee specimens have been sent to the both of the knee extension test and the A-P drawer test.

2.2.2 Knee extension test Figure 5(a) shows the experimental apparatus for the knee extension test. The apparatus have a femur holder, (A) in the figure, mounted on a tilting stage (B) of a pantograph-type mechanism. This mechanism enables the femur to be adjusted at any position between the horizontal and the vertical, and the femur is kept at the horizontal position in the case of the knee extension test. In order to compensate the distal part sectioned at the lower tibial shaft, a dead weight of 1.7 kg is attached to the tibia at its distal end.

(a) Knee extension test

(b) A-P drawer test

Fig. 5 Experimental apparatus

The knee extension is applied by pulling the quadriceps tendon manually along the femur. The ACL/graft tension is examined at the knee flexion angles between 0 to 90 degrees with an interval of 10 degrees for Case-1 of normal ACL, Case-2 of reconstructed ACL with the initial graft tension of 25 N, and Case-3 of reconstructed ACL with the initial graft tension of 50 N. It is noted here that the Case-1 of normal ACL in this study is not identical to the intact ACL in the normal knee. That is, first, the tibial end of intact ACL is removed from the tibial plateau with a small bone piece. Second, the tibial end of ACL is tied to a suture passing through the tibial tunnel of 8 mm in diameter from the antero-medial aspect of the tibia to the center of ACL tibial attachment for ACL reconstruction. Third, the sectioned end of the ACL is positioned at the original point of tibial insertion by adjusting the suture tension under the knee flexion angle of 90 degrees.

In the ACL reconstructed cases of Case-2 and Case-3, the normal ACL is sectioned at the femoral end and is removed. The drill-hole of 8 mm in diameter is prepared for the femur and the semitendinous muscle tendon in quadruple is used as an autograft by

(a) Case-1 with normal ACL (b) Case-2 and -3 with reconstructed ACL

Fig. 6 Preparation of specimen for knee extension test

means of the post screw ACL reconstruction technique. The suture tied to the proximal end of the graft is anchored at the proximal end of the femoral tunnel with an end-button, and then the initial tension of the graft is adjusted by referring to the practical reconstruction procedure. That is, the graft tension have been kept at 25 N for Case-2 and at 50 N for Case-3 for five minutes by using the level adjusting mechanism of the device, followed by the relaxation of five minutes. Figure 6(a) and (b) illustrate the preparation for Case-1 and Case-2/-3 schematically.

2.2.3 Anterior-posterior drawer test The experimental apparatus for knee extension test is again used for the A-P drawer test by combining with the tibia holder and its A-P translation mechanism as shown in Fig. 5(b). The tibia holder grips the tibial shaft at the distal site of the device, that is, approximately 90 mm distal from the tibial joint surface. The tibia holder is mounted on the A-P translation guide and is driven by using a stepping motor and ball-screw pair. A force gauge (FGC-40, Simpo Industry, Kyoto) and a linear velocity displacement transducer (LVDT) (LT1-120 C, Shinkoh Denki, Tokyo) are applied for measuring the A-P drawer force and displacement at the tibia holder.

Ten cycles of A-P displacements of ± 1 mm are enforced at the traveling speed of 1 mm/sec as the preconditioning, and then the A-P drawer test up to drawer force of ± 200 N is carried out at the same traveling speed of 1 mm/sec. This drawer test is conducted under the knee flexion angle of 30, 60 and 90 degrees for the following four cases. That is, Case-1: Intact, Case-2: ACL deficient, Case-3: ACL reconstructed knee with the initial graft tension of 20 N, and Case-4: ACL reconstructed knee with the initial graft tension of 40 N. In the A-P drawer test, Case-1 means the intact knee with normal ACL as is, and is different from Case-1 of the knee extension test. The procedure of ACL reconstruction is identical to that

Fig. 7 ACL reconstructed human knee with V-shaped device for A-P drawer test

Fig. 8 ACL/graft tension vs. knee flexion angle

used in the knee extension test. During the A-P drawer test, the tibia is kept at the vertical position regardless the knee flexion angle under testing, as shown in Fig. 7.

3. Result and Discussion

3.1 Knee extension test

The results of knee extension test by quadriceps tendon pull are illustrated in Fig. 8. The ACL or graft tension is almost constant for the angle of knee flexion between 50 and 90 degrees, regardless the cases of Case-1, -2 and -3. The tension of normal ACL of Case-1 is almost zero, and the graft tensions of ACL-reconstructed Case-2 and Case-3 are greater than the ACL

tension of Case-1. The ACL or graft tension increases as to the knee extension of flexion angle smaller than 50 degrees. This increase of tension by knee extension is observed in all cases. The difference between the graft tension of Case-2 or Case-3 and the tension of Case-1 is almost identical to the level of initial tension, and it seems that the initial tension is superposed to the graft tension as is. In fact, the ACL tension of Case-1 is 47.4 ± 4.8 N (average $\pm$ standard deviation) at the knee flexion angle of 0 degree, and the graft tensions are 71.6 ± 9.2 N for Case-2 with the initial tension of 25 N, and 97.3 ± 7.1 N for Case-3 with the initial tension of 50 N.

The relationship between the knee flexion angle and ACL/graft tension observed in this study is qualitatively consistent with the report by Markolf et al.^{(7),(8)} The observed values of tension, however, are quantitatively smaller than the values by Markolf et al. For instance at knee flexion angle of 30 degrees, the ACL tension by Markolf et al. is 25 N approximately, and it is 12 N approximately in this study. Although Markolf et al. have fixed the graft in the bone tunnel at the entrance site near the knee joint, the graft have fixed to the bone outside of the tunnel in this study. Ishibashi et al.⁽¹³⁾ have reported such an influence of the position of graft fixation along the tibial tunnel on the graft tension. The authors have also examined that the graft tension measured at the distal end of the bone tunnel is 25 to 50% smaller than the graft tension at the proximal entrance in a preliminary experiment by using the bone tunnel created in bovine vertebral body and bovine Achilles tendon graft.

3.2 Anterior-posterior drawer test

The total displacement of anterior and posterior directions is summarized in Table 1 for A-P drawer forces of ± 100 N and ± 200 N. The values in parenthesis are the ratio of total A-P displacements to that of intact knee of Case-1 for each knee flexion angle and drawer force. As is seen in Table 1, the total A-P displacement of Case-4 with the initial tension of 40

N is smaller than that of Case-3 with the initial tension of 20 N regardless the knee flexion angle. This difference in the total A-P displacement, however, is not so remarkable in comparison with the difference from Case-3 of ACL deficient. Figure 9 shows the anterior displacement under the different anterior drawer forces and knee flexion angles. At the anterior drawer force of 50 N, the anterior displacements of ACL reconstructed Case-3 and Case-4 are almost same as that of Case-1 of intact ACL. When the anterior drawer force becomes larger than 50 N, the anterior displacements of ACL reconstructed Case -3 and -4 becomes larger than that of Case-1 of intact

(a) Knee flexion angle of 30 degrees

(b) Knee flexion angle of 60 degrees

(c) Knee flexion angle of 90 degrees

■ Normal ACL (n=3, mean $\pm$ S.D.)
 ▨ ACL Deficient (n=3, mean $\pm$ S.D.)
 ▤ ACL Reconstructed 20N (n=4, mean $\pm$ S.D.)
 ▦ ACL Reconstructed 40N (n=4, mean $\pm$ S.D.)

Fig. 9 Anterior drawer force and displacement

Table 1 Total A-P displacement [mm]

Drawer Force	Flexion Angle	Intact	Deficient	Reconstructed	
				20N	40N
100N	30°	10.13 $\pm$ 4.25 (1)	23.70 $\pm$ 2.34 (2.33)	16.63 $\pm$ 3.85 (1.64)	14.69 $\pm$ 3.05 (1.45)
	60°	8.48 $\pm$ 3.34 (1)	19.53 $\pm$ 0.38 (2.30)	10.74 $\pm$ 0.44 (1.27)	9.67 $\pm$ 1.84 (1.14)
	90°	6.46 $\pm$ 1.84 (1)	14.24 $\pm$ 1.64 (2.21)	8.59 $\pm$ 3.27 (1.33)	6.47 $\pm$ 1.65 (1.00)
200N	30°	15.93 $\pm$ 4.72 (1)	30.56 $\pm$ 4.97 (1.92)	26.89 $\pm$ 3.84 (1.69)	25.75 $\pm$ 3.26 (1.62)
	60°	13.96 $\pm$ 4.09 (1)	26.99 $\pm$ 1.46 (1.93)	21.84 $\pm$ 1.64 (1.56)	21.34 $\pm$ 3.04 (1.53)
	90°	12.15 $\pm$ 1.16 (1)	23.42 $\pm$ 4.78 (1.93)	18.42 $\pm$ 5.43 (1.52)	16.64 $\pm$ 1.65 (1.37)

(mean $\pm$ S.D.)

Fig. 10 Graft tension vs. anterior displacement

ACL, regardless the angle of knee flexion. Especially at the anterior drawer force of 200 N, the anterior displacements of ACL reconstructed cases become comparable to that of ACL deficient Case-2 for the knee flexion angles of 30 and 60 degrees.

Figure 10 shows the relationship between the anterior displacement and the graft tension of reconstructed ACL. The solid circular marks indicate the anterior drawer force of 100 N and 200 N. Two short ticks on the abscissa indicate the anterior displacement at 100 N and 200 N in Case-1 of intact ACL. As the general observation, the graft tensions of Case-2 and -3 of reconstructed ACL increase approximately linearly with respect to increase of the anterior displacement. When this relationship is fitted by a

straight line, the slope is 4.75 for Case-3 of initial graft tension of 20 N and 4.39 for Case-4 of initial graft tension of 40 N at the knee flexion angle of 30 degrees. At the knee flexion angle of 60 degrees, the slope is 5.52 for Case-3 and 4.47 for Case-4. The slopes are 5.69 and 5.75 for Case-3 and Case-4, respectively, at the knee flexion angle of 90 degrees. That is, these slopes are not so clearly dependent on the initial graft tension of 20 N or 40 N. The graft tension of Case-4 is greater than that of Case-3, and the difference is 17.3, 17.7 and 17.8 N at the knee flexion angle of 30, 60 and 90 degrees, respectively. These differences are approximately corresponding to the 20 N difference of the initial graft tension between Case-3 and Case-4. These observations indicate that the initial graft tension is superposed on the graft tension almost as is.

The relationship between the graft tension and the anterior drawer force is shown in Fig. 11. The graft tension of Case-4 of initial graft tension of 40 N is larger than that of Case-3 of 20 N for every knee flexion angle of 30, 60 and 90 degrees. The graft tension increases almost linearly with respect to the increase of the anterior drawer force, although it is somewhat unclear in the case of knee flexion angle of 30 degrees. Their slopes are 0.52 for Case-3 and 0.48 for Case-4 at the knee flexion angle of 30 degrees; 0.50 for Case-3 and 0.42 for Case-4 at 60 degrees; and 0.40 for Case-3 and 0.38 for Case-4 at 90 degrees. These values do not show clear dependence on the magnitude of initial tension, and this feature is clearer within the range of anterior drawer force smaller than 100 N.

For the anterior drawer test, Ishibashi et al.⁽¹³⁾ have reported the difference between the tension of ACL and the graft tension of reconstructed ACL where the distal end of graft is anchored at the distal end of tibial tunnel. The reported graft tension has been 81% of drawer force of 110 N at the knee flexion angle of 30 degrees, 84% at 60 degrees, and 67% at 90 degrees. That is, the graft tension has been smaller than the drawer force, although the ACL tension has been almost the same as the drawer force. At the drawer force of 110 N in the cases of this study, the graft tension is 85.4% of the drawer force for Case-3 and 92.4% for Case 4 at the knee flexion angle of 30 degrees, and 77.2% for Case-3 and 84.1% for Case-4 at the knee flexion angle of 60 degrees. At the knee flexion angle of 90 degrees, it is 65.8% for Case-3 and 76.3% for Case-4 and the smallest among three different knee flexion angles.

The results of the drawer test and the knee extension test have showed the followings. The initial graft tension of the ACL reconstructed knee have not

Fig. 11 Graft tension vs. anterior drawer force

influenced largely on the A-P stability of the knee, although it had been considered as an important aspect for the stability of ACL reconstructed knee. However, the initial graft tension has been superposed on the graft tension during the knee extension and the anterior drawer of tibia, and has shown the direct influence on the graft tension. These observations may suggest that the influence of the initial graft tension should be considered not only from the knee stability but also from the graft tension as is.

4. Conclusions

In this study, a simple device has been developed for the adjustment and measurement of the graft tension of ACL reconstructed knee in vitro. This

device has been used for the knee extension test and the A-P drawer test. The developed device measures the graft tension at the distal entrance of tibial tunnel through a suture. It has a level adjusting mechanism of a hollow bolt-nut pair for the graft tension adjustment. This setup is basically identical to the clinical situation of ACL reconstruction except a point that the anchoring of the suture is not on the tibial surface but on the device on the tibia. The strain gauges have been used to measure the graft tension, and its sensitivity is sufficient with good linearity. The level adjusting for graft tension adjustment is simple and quite easy. The range of graft tension adjustment, of course, has a designed limit, but a different stroke of a bolt-nut pair can furnish a different adjusting range to the device. The results obtained by the knee extension test and the A-P drawer test are consistent with the results in the past reports. The effectiveness of the developed device is demonstrated and confirmed, while the tension measurement and adjustment at the outside of the bone tunnel via a suture may require careful treatment and consideration.

Two biomechanical tests carried out in this study have suggested followings. The pattern of graft tension of reconstructed ACL is not affected by the initial graft tension at reconstruction, but that the graft tension is elevated by the initial graft tension by its magnitude almost as is. The stability of the ACL reconstructed knee is not influenced so much by the difference of initial graft tension of 20 N or 40 N in terms of A-P displacement during the drawer test. This finding is consistent with the result by Markolf et al.⁽⁸⁾ that the initial graft tension between 11.1 N to 66.8 N results no influence on the A-P stability of ACL reconstructed knee. These observations conclude that the initial tension at the ACL reconstruction might be considered from the viewpoint of the graft tension as is, since it will be deeply related to the ligamentization of the graft in the postoperative convalescent period, rather than the anterior stability at the reconstruction operation. The device developed in this study may have basic potential to be used for the intraoperative measuring and adjustment of graft tension with improvement.

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