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ORIGINAL ARTICLE

Comparison of anterior cruciate ligament reconstruction methods between reverse "Y" plasty reconstruction and traditional single-bundle technique—A cadaveric study

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KEYWORDS
Anterior cruciate ligament reconstruction;
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Double bundle reconstruction;
Single bundle reconstruction

Summary *Background:* In 2009, a reverse "Y" plasty anterior cruciate ligament (ACL) reconstruction technique was proposed, with double-tibial tunnel and single-femoral tunnel, and the result obtained proved that the reverse "Y" plasty technique was satisfactory. This cadaveric study was designed to compare the reverse "Y" plasty reconstruction method with the conventional single-bundle technique for the first time.
Methods: In this study, 30 cadaveric knees were used and were randomly divided into five groups with six knees each. Six cadaveric knees with intact ACL were treated as the control group, and another six knees with ruptured ACL were treated as the rupture group. In group A, the single-bundle technique was used. In groups B and C, reverse "Y" plasty technique was used, and the grafts were fixed with absorbable biointerference screws in tibiae and absorbable biointerference screws (Group B) or Endobutton (Group C) in femora. Five groups were tested with an MTS material testing machine (MTS-858) by the use of a cyclic loading of 134 N at 15°, 30°, 60° and 90° of knee flexion and a combined 7-Nm valgus torque and 5-Nm internal tibial rotation torque at 15°, 30°, 45° and 60° of knee flexion.
Results: Both single-bundle and reverse "Y" plasty groups demonstrated similar anterior–posterior stability compared with the control group, whereas the single-bundle group showed

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inferior rotational stability tested at 30° and 45° of knee flexion than the reverse "Y" plasty group and control group. These two different fixation methods at the femoral site (Group B and C) showed no difference in anterior—posterior and rotational stability.
Conclusions: The new reverse "Y" plasty ACL reconstruction method may restore normal knee stability, especially rotational stability, better than single-bundle reconstruction.
The translational potential of this article: This study provides strong support for the new reverse "Y" plasty ACL reconstruction technique and is expected to propose a new surgical approach with good biomechanical features.

Introduction

Anterior cruciate ligament (ACL) rupture is one of the most common injuries in the knee [1], and it may result in many secondary injuries, such as torn meniscus and cartilage damage, which lead to knee degeneration [2]. ACL reconstruction, with a success rate >90% [3], has been the most effective way to treat ACL rupture. Surgeons refined surgical approach with many reconstructive techniques over the past years, such as the single-bundle technique, anatomic double-bundle reconstruction technique [4,5], triple-bundle reconstruction technique [6,7], plasty reconstruction technique [8], etc.

In 2009, Ping et al [18] proposed a reverse "Y" plasty ACL reconstruction technique with double-tibial tunnel and single-femoral tunnel by using the hamstrings as autografts and fixing graft with absorbable biointerference screws or Endobutton in the femora and with absorbable biointerference screws in the tibiae. This study derives from the previous result that the new technique is reliable and satisfactory, and the clinical efficacy of both kinds of fixation in the femur is similar. The purpose of this study is to further evaluate the new technique and compare it with the traditional single-bundle technique. In addition, we hypothesised that there would be no significant differences in anterior—posterior stability among the single-bundle technique, double-bundle techniques and the intact knee, but the reverse "Y" plasty reconstruction technique may be superior in rotational stability than single-bundle reconstruction technique.

Materials and methods

Specimen preparation

In the study, 30 human cadaveric knees were dissected. The specimens were stored in the refrigerator at −80°C and then were allowed to defrost in isotonic saline (0.9% NaCl solution) for an hour before the test.

All were male with a mean age of 38.5 years (range: 18—55 years). Each knee was removed with all tissues, except skin and subcutaneous tissues, of 15—25 cm proximal and distal to the joint. In this study, specimen preparation and surgical operation were performed by one experienced surgeon. All specimens were dissected by removing muscles, vasa and nerves, but all ligaments, including medial collateral ligament, lateral collateral ligament, anterior collateral ligament, posterior collateral ligament, medial patellafemoral ligament and the capsules, were preserved. X-ray and magnetic resonance imaging were used for scanning the specimens to ensure the absence of osseous and soft tissue abnormalities or deformity that might affect ACL reconstructive surgery and testing results. The distal tibia and the proximal femur were fixed to the embedding cassette with the polymethyl methacrylate bone cement. To secure the knee activity, the vertical axis of the embedding cassette must be kept parallel (Fig. 1). Specimens were then randomly divided into five groups with a sample size of n = 6 for each group. The ACLs of the three experimental groups and rupture group were resected for ACL reconstruction surgery. The ACLs of the control group remained intact. At the same time, 36 flexor tendons were obtained from the same cadaveric upper limbs for ACL reconstruction. The grafts were prepared according to the grouping and then were left to defrost in isotonic saline (0.9% NaCl solution) for an hour before the test (Fig. 2). A tensile load of 70 N was applied to the grafts for 15 minute for preconditioning and used as an initial graft tension. The specimen preparation protocol had been approved by the ethics committee of Sun Yat-Sen Memorial Hospital, Sun Yat-Sen University, Guangzhou, China.

Figure 1 The cadaveric knee of 15—25 cm, proximal and distal to the joint centre, was prepared and fixed to the embedding cassette with the polymethyl methacrylate bone cement.

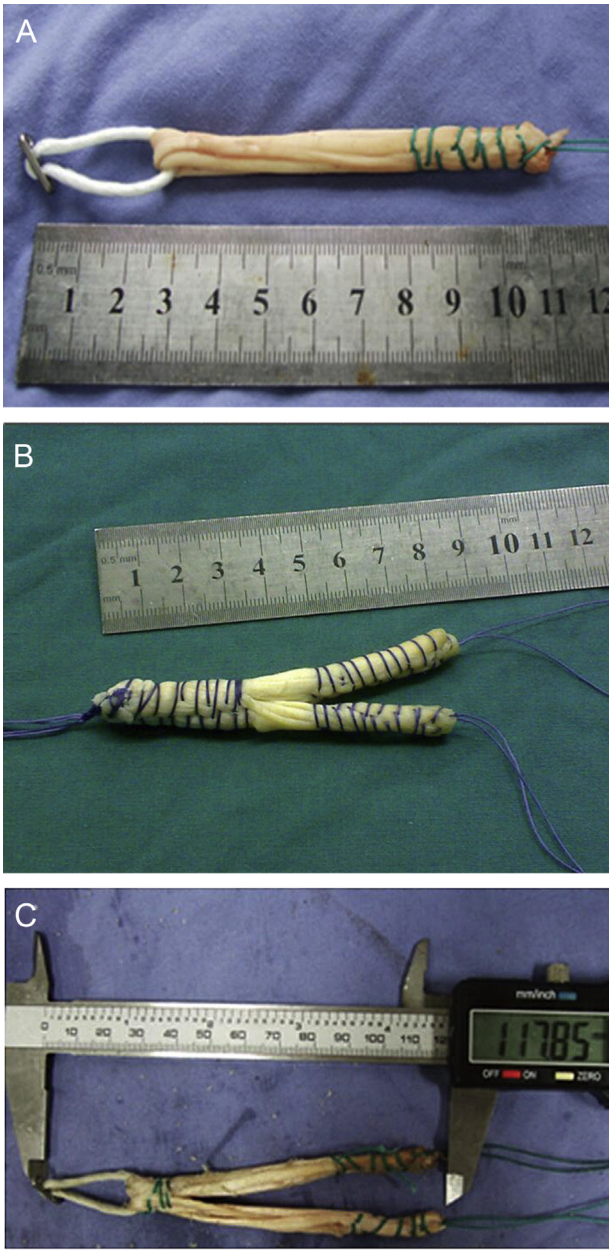

Figure 2 (A) Two tendons were folded to become a single bundle with a four-strand tendon graft, with the diameter of 8 mm and length of 8.5 cm. (B) Two bundles of tendons were folded and woven together for 0.5 cm in one end, and the other two ends of the graft were woven separately for 3.5 cm with the total length of 8.5 cm. (C) Two bundles with tendons threaded through the loop over the Endobutton. The two ends of the graft were woven separately for 3.5 cm.

In group A, ACL reconstruction was performed with traditional single-bundle technique and with the Endobutton method. Two tendons were folded into a four-strand tendon graft, with the diameter of 8 mm and length of 8.5 cm. The tibial end of the graft was woven separately for about 3.5 cm. Using a 55° tibial drill guide, a trained surgeon advanced a guide wire into the centre of the tibial footprint, and an 8-mm tibial tunnel was drilled over the guide wire. On the femoral tunnel side, the tunnel with the diameter of 8 mm was drilled into the lateral wall of the intercondylar notch, leaving a 2-mm posterior wall within the footprint. The graft passed through the tibial and femoral tunnels, and the tibial end was fixed with absorbable biointerference screws under tension with the knee at 30° of flexion.

In groups B and C, a reverse "Y" plasty technique was used, and the tendons were woven to a reverse "Y" plasty graft. In group B, two tendons were folded and woven together for 0.5 cm in one end, and the other two ends of the graft were woven separately for about 3.5 cm with the total length of 8.5 cm. In group C, two tendons were threaded through the loop over the Endobutton, and the two ends of the graft were woven separately for about 3.5 cm.

In group B, the tibial tunnel was created by the traditional double-bundle reconstruction technique, with two separate tibial tunnels at the footprint of the ACL tibial segment. A bone bridge ranging from 2 mm to 3 mm was left. The diameter of the anteromedial (AM) tunnel was 6 mm, and the diameter of the posterolateral (PL) tunnel was 7 mm. The femoral tunnel was drilled into the femoral footprint, 2 mm anterior to the posterior wall. The guide pin was drilled with the knee flexed over 120°. An 8-mm tunnel extending for 3.5 mm was created using a reamer. The grafts were passed through the tunnels. The femoral tunnel was fixed at 120° of knee flexion, the PL tunnel at 10° and the AM tunnel at 70°, all with absorbable biointerference screws.

In group C, the same double-bundle technique as in group B was used in the tibial tunnel. In the femoral side, the location of the bone tunnel was the same except for different methods. The femoral tunnel was created by the Endobutton method. A 4.5-mm tunnel passing through the femoral cortical bone was made first; then, the tunnel was enlarged using an 8-mm reamer for about 2.5–3.5 cm, reserving a distance of 6 mm to the lateral femoral cortex. The graft was guided to the corresponding tunnels. The graft at the femoral side was fixed with an Endobutton (Smith & Nephew, USA). Tibial sides were fixed with absorbable biointerference screws similar to that for the group B.

Biomechanical testing

All tests were performed with an MTS-858 (MTS 858 Mini Bionix; MTS Corp, Minneapolis, USA) servohydraulic testing machine. Eight heat sensors were mounted to the femur and tibia with cortical pins and were used to measure the knee kinematics (with an accuracy of $<0.1°$) and displacements (with an accuracy of <0.01 mm) according to the manufacturer, and five signal receptors were put around the machine (Fig. 3).

The femur and tibia were mounted onto the tensile tester of the machine. In the testing, two kinds of loading conditions were involved. The first load was a cyclic anterior tibial load from 0 N to 134 N (at the speed of 10 N/s) at full extension and 15°, 30°, 60° and 90° of knee flexion. The second load was a combined 7-Nm valgus torque and 5-Nm internal tibial rotation torque at 15°, 30°, 45° and 60° of knee flexion. The anterior tibial translations (ATTs) during the anterior tibial load and the combined rotatory load were measured at different angles of knee flexion.

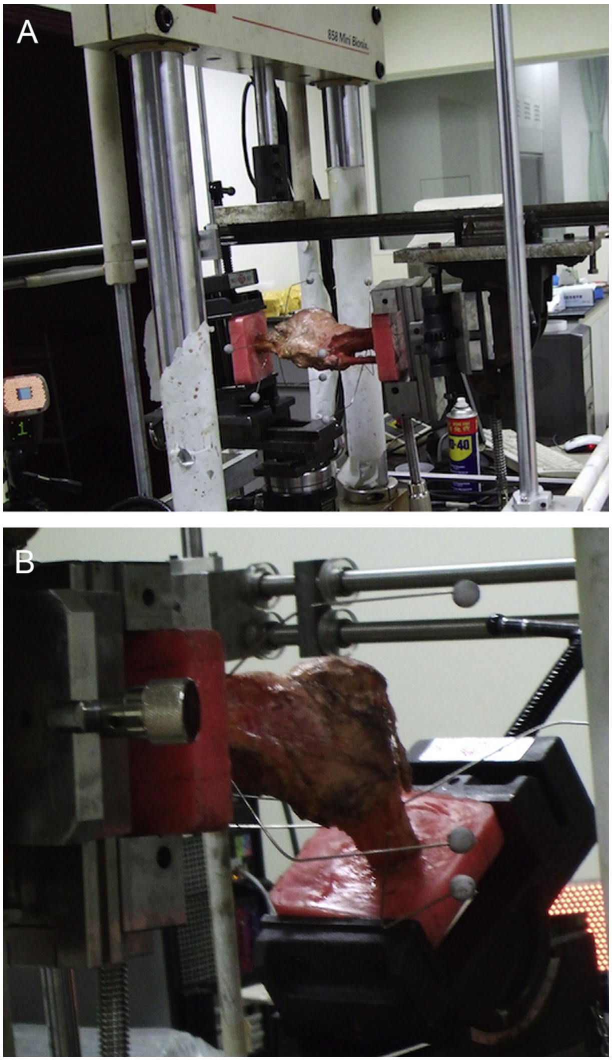

Figure 3 (A) Biomechanical testing of cadaveric operated knees operated with different surgical techniques was performed with an MTS-858 servohydraulic testing machine. (B) Eight heat sensors were mounted to the femur and tibia with cortical pins and used to measure the knee kinematics and displacements.

Statistics

Statistical analysis was performed with the SPSS version 20.0 (IBM Corp, Armonk, NY, USA). All data were described by mean $\pm$ standard deviation. One-way analysis of variation and Least Significance Difference-*t* test were used to compare differences between groups. A *p* value less than 0.05 was interpreted as statistically significant.

Results

Anterior tibial translation at 134-N anterior load

The results of ATT were summarised in Table 1. The mean values were used for comparison. Similar to intact knees, all three bundling techniques (A, B and C) show significant treatment efficacy compared with knees with ruptured ACL ($p > 0.01$), yet without a difference in the ATT among each other ($p > 0.05$) although all show significance. After the ACL was transversely cut, the anterior–posterior translation increased significantly at all flexion angles ($p < 0.05$). For the single-tunnel reconstruction technique (group A), the ATT was 5.50 $\pm$ 0.48 mm at 15° of flexion and 5.80 $\pm$ 0.55 mm at 90° of flexion. For the reverse "Y" reconstruction technique (group B and C), these values showed no statistical significance compared with the single-bundle technique ($p > 0.05$) (Fig. 4).

Table 1 Anterior tibial translation at 134-N anterior load.

Group	N	Knee flexion angle	Mean	Standard deviation
Intact	6	15°	5.40	0.33
		30°	5.63	0.50
		60°	5.77	0.62
		90°	5.53	0.41
Ruptured	6	15°	11.05	0.91
		30°	12.26	0.84
		60°	12.04	0.94
		90°	11.47	0.83
Single Bundle (A)	6	15°	5.47	0.78
		30°	5.82	0.29
		60°	5.95	0.40
		90°	5.79	0.55
Double Bundle-bioscrew (B)	6	15°	5.40	0.50
		30°	5.78	0.41
		60°	5.84	0.50
		90°	5.76	0.40
Double Bundle-Endobutton (C)	6	15°	5.50	0.58
		30°	5.84	0.27
		60°	5.84	0.54
		90°	5.73	0.41

Anterior tibial translation at combined valgus (10 Nm) and rotatory (5 Nm) load

The results of the coupled ATT at combined valgus (7 Nm) and rotatory (5 Nm) load were summarised in Table 2. ACL rupture increased the coupled ATT at both flexion angles ($p < 0.05$). For single-bundle reconstruction technique, the coupled ATT was 6.62 $\pm$ 0.68 mm and 8.09 $\pm$ 0.96 mm at 30° and 45° of flexion, respectively. These values were higher than those of the intact knee at both flexion angles ($p < 0.05$). With the reverse "Y" reconstruction technique using absorbable biointerference screws (Group B) and Endobutton (Group C), their mean values were significantly less than those of single-bundle reconstruction method at both flexion angles ($p < 0.05$) (Fig. 5).

Discussion

The newly improved technique of the ACL reconstruction in the study is similar to that proposed by George Papachristou [8] in 2008. In their biomechanics study, they used "Δ" plasty technique to reconstruct ACL, with two separate

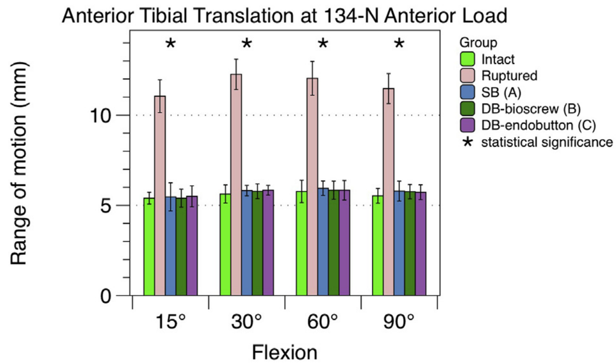

Figure 4 Anterior tibial translation in response to an anterior load of 134 N. The mean values are used for data comparison. Similar to intact knees, all three bundling techniques (A, B and C) show significant treatment efficacy compared with knees with ruptured ACL ($p > 0.01$), yet without a difference in the anterior tibial translation among each other ($p > 0.05$) although all show significance.
ACL = anterior cruciate ligament.

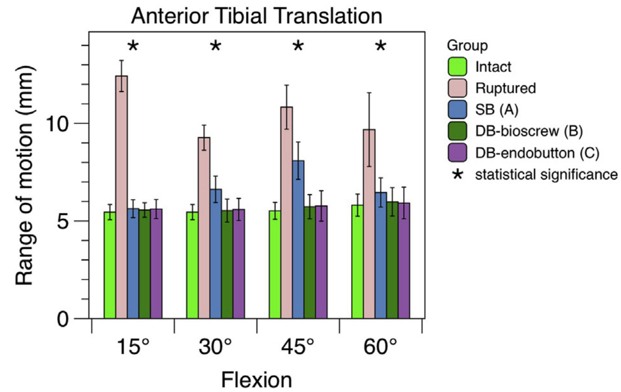

Figure 5 Anterior tibial translation in response to combined 7-Nm valgus torque and 5-Nm internal tibial rotation torque. The mean values are included in the figure. The level between A and B or C of significance was $p < 0.05$. No statistical significance between B and C ($p > 0.05$) was observed.

Table 2 Anterior tibial translation at combined valgus (10 Nm) and rotatory (5 Nm) load.

Group	N	Knee flexion angle	Mean	Standard deviation
Intact	6	15°	5.45	0.39
		30°	5.45	0.39
		45°	5.52	0.43
		60°	5.81	0.57
Ruptured	6	15°	12.43	0.80
		30°	9.27	0.64
		45°	10.83	1.13
		60°	9.68	1.89
SB (A)	6	15°	5.63	0.46
		30°	6.62	0.68
		45°	8.09	0.96
		60°	6.46	0.75
DB-bioscrew (B)	6	15°	5.56	0.37
		30°	5.53	0.59
		45°	5.73	0.62
		60°	5.98	0.73
DB-Endobutton (C)	6	15°	5.61	0.49
		30°	5.59	0.57
		45°	5.77	0.78
		60°	5.92	0.81

tibial tunnels and a femoral tunnel. Our technique was similar to this. We also used two tibial tunnels and one femoral tunnel, and the method of choosing the tunnel was the same. The femoral tunnel was at the centre of the footprint, and a double-bundle technique was used with the two tibial tunnels. But there are two main differences between two studies. First, we used a new graft preparation method. They retained the natural attachment of hamstring tendons to overpass the phase of revascularisation, whereas we used free autografts. Second, the fixation was different: In "Δ" plasty study, the tendon end was sutured with two Dexon 2 bi-colour sutures and was tied to femoral and tibial cancellous screws. In our study, the grafts were fixed with Endobutton or absorbable bio-interference screws in the femur and with absorbable bio-interference screws in the tibia.

At present, the techniques for double-bundle reconstruction of the ACL described in the literature vary greatly based on tunnel locations. Some favour drilling one tibial tunnel for both the AM and PL bundles and two femoral tunnels [10—14]. Others are inclined towards drilling both two tibial and femoral tunnels for AM and PL bundles [15—17]. Ping et al [18] adopted another technique in which two tibial tunnels and single-femoral tunnel for double-bundle ACL reconstruction were drilled. The justification for this is that we consider that the double-tunnel technique may result in frequent intercondylar fossa impact because the double-bundle technique increases the diameter of the grafts particularly in cadaver whose bone mineral density is changed [19]; Previous studies concluded that double-bundle technique shows much better anterior or rotational stability than single-bundle technique [20—23]. Furthermore, anatomic literature [24] has shown that the tibial insertion of the ACL is the broadest portion of the ligament. Anatomic ACL can be approached better by using two tibial tunnels than using only one tunnel. Most importantly, the reverse "Y" plasty is in a way superior to other two methods of fixation [25,26]. Therefore, we chose the reverse "Y" fixation technique which is easier to handle in clinical settings.

The most commonly known test in ACL injury assessment is the Lachman's test, which aimed to evaluate the anterior laxity of the joint (anterior tibial translation at 10—30° flexion knee). We tested the ATT load at full extension and 15°, 30°, 60° and 90° of knee flexion, and no difference was found among three experimental groups. The pivot-shift manoeuvre is widely used for objective assessment of the joint laxity in clinical scores [9], which made a combination of axial load and valgus force during knee flexion from an extended position. We also performed a similar manoeuvre that anterior tibial translation at combined valgus (7 Nm) and rotatory (5 Nm) load for assessment. We found that the new reverse "Y" plasty ACL reconstruction technique displayed better rotational stability than single-bundle reconstruction technique. We concluded that single-bundle reconstruction technique could easily bring about the failure to restore translational stability just as central single-bundle ACL reconstruction had an altered rotational axis. For anatomic double-bundle studies [27], the posterolateral bundle originates more distally and posteriorly relative to the anteromedial bundle on the wall of the intercondylar notch. When the knee is extended, the posterolateral bundle is under tension, and the anteromedial bundle is moderately lax; therefore, based on our evidence, we believe that the double-bundle technique effectively improves rotational stability both in 30° and 45° flexion knee. However, double-bundle tunnel position in the tibia and femur [28] and the knee flexion angles for graft fixation [29], even graft fixation sequence [30], can be the factors affecting the whole reconstruction and give rise to errors in our study. Correspondingly in the clinical result [18], the range of rotation between the single-bundle and double-bundle groups may be regarded as evidence that the different surgical reconstruction techniques provided distinction in knee rotational restraints. As regard to absorbable biointerference screws and Endobutton in the femoral double-bundle reconstruction technique, no difference was observed between two groups, which is similar to Ma et al's clinical follow-up evaluation [31], even if they used single-bundle ACL reconstruction.

Under the inadequacies of experimental conditions, our study has such following limitations: (1) For our MTS-858 testing machine, when we tested rotational examination, the displacement distance was calculated by formula manipulation involved in flexion angle and constant. Although this procedure was made by a same experienced operator, there might still be personal errors and bias. (2) The fresh frozen cadavers this study used were stiffer than the normal tissue of patients who undergo ACL reconstruction. The reduction of bone mineral density in cadavers would result in fixation loosening that caused an increase in shift distance. (3) We have no midpoint as the standard for accurate displacement, which may also produce errors.

Conflicts of interest statement

There is no conflict of interest.

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