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ORIGINAL ARTICLE

Biomechanical Evaluation of Modified ACL Reconstruction with Over-the-Top Augmentation Technique

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Abstract

Background Modified ACL reconstruction with over-the-top augmentation technique (OA-ACLR) was designed to allow one-stage revision regardless of tunnel conditions as well as to offer firm stability by hybrid double-fixation. Thus, the purpose of the study is to biomechanically evaluate its effect on knee stability by comparing it with single-bundle ACL reconstruction (SB-ACLR).

Methods Ten porcine knees were sequentially tested using a custom testing system for intact ACL, ACL deficiency, SB-ACLR and OA-ACLR. First, 134-N anterior tibial load was applied, and anterior tibial translation was measured at 30°, 60°, and 90°. Then, anterior tibial translation and relative tibial rotation were measured in a combined rotatory load of 5-Nm of internal tibial torque and 10-Nm of valgus torque.

Results Under anterior tibial load or combined anterior and rotatory loads, SB-ACLR and OA-ACLR resulted in no significant increase in anterior tibial translation at all flexion angles compared with an intact ACL group, and no significant difference was noted in anterior tibial translation between the two ACL reconstruction groups. In combined rotatory load, OA-ACLR resulted in enhanced rotational stability compared with SB-ACLR, and it more closely restored relative tibial internal rotation to the intact ACL group.

Conclusions Our study showed that modified ACL reconstruction with over-the-top augmentation technique resulted in enhanced rotational stability compared to the conventional single-bundle ACL reconstruction, especially at lower flexion angle in a porcine model. Therefore, with several potential advantages as well as biomechanical superiority, our new technique could be clinically applicable in primary and revision ACL reconstruction.

Level of Evidence. Experimental.

Keywords Knee · Anterior cruciate ligament · ACL reconstruction · Triple bundle · Over-the-top

Introduction

ACL rupture is one of the most common sports injuries. Because ACL insufficiency causes knee joint instability leading to arthritis or meniscus injury [1, 2], there have been countless efforts to find better methods of ACL reconstruction to regain knee joint stability. The success rate of conventional isometric single-bundle ACL reconstruction is as high as 80–90%, but patients report lasting knee tenderness with rotational instability [3–7]. It is of utmost importance to recover rotational instability when performing ACL reconstruction because it accelerates the degenerative change of the knee joint [8–10].

The double-bundle ACL reconstruction technique to achieve normal knee joint biomechanics has continued its progress based on the research on anatomy and biomechanics

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since its first introduction by Mott [11] in 1983 [12–18]. Yagi et al. [16] reported that the double-bundle ACL reconstruction technique is superior to the single-bundle technique in biomechanical results regarding rotational forces. Morimoto et al. [13] reported that the double-bundle ACL reconstruction technique can reduce the degenerative change of knee joint by recovering near-normal tibiofemoral contact area and pressure at lower flexion angles.

In the 1970s, over-the-top fixation ACL reconstruction technique was introduced by MacIntosh. The advantage of this technique was that one could easily anticipate the femoral fixation site for tendon graft, and that one does not need a femoral tunnel which prevents problems caused by inappropriate tunnel position. However, there were also concerns regarding over-the-top fixation because of the non-isometric graft position, tightening the graft at knee extension and loosening it at knee flexion, making the technique incompatible as a means for ACL reconstruction. Over-the-top fixation technique was only limitedly performed in revision ACL reconstruction as a salvage procedure and was anticipated to be biomechanically inferior to other techniques because of the non-anatomical graft position. Recently, Asai et al. [19] reported that according to their biomechanical study with triaxial accelerometry, ACL reconstruction with over-the-top passage fixation technique has rotational stability comparable to the ACL reconstruction with anatomical single-bundle technique.

In this study, we assumed if isometric ACL reconstruction is combined with over-the-top graft fixation, we could achieve not only anterior but also rotational stability as well. With this, we devised modified ACL reconstruction with extra-articular augmentation technique using Achilles tendon allograft with two bundles, the shorter of which is used in transcondyle ACL reconstruction and the longer is used as augmentation with over-the-top fixation method. In this study, we tried to evaluate the recovery of stational and rotational stability in conventional single-bundle ACL reconstruction and modified ACL reconstruction with over-the-top augmentation technique, through biomechanical comparative experiment.

We hypothesized that modified ACL reconstruction with over-the-top augmentation technique, which combines transcondyle ACL reconstruction with augmentation by over-the-top fixation, would enhance postoperative knee joint rotational stability. Our purpose was to biomechanically evaluate the effect our technique has on knee joint stability when compared with single-bundle ACL reconstruction.

Materials and Methods

Specimen Preparation

The study was performed at the cell therapy center of our institution. All surgical procedures were performed by one orthopedic surgeon with over 10 years of clinical experiences in order for the uniformity of techniques regarding this study. Ten porcine left knee joints, fresh-frozen at the average age of 5 months were used as specimens. The knee joint specimens were kept at 20 °C below zero and brought out to room temperature for defrosting 8 h before measurement. Skin and soft tissue around the knee were removed except for the popliteus muscle, joint capsule, ligament, and joint supporting structures. The distal fibula was removed and to keep proximal fibula at the anatomical position, one 3.5 mm cortical screw was inserted to fix fibula to the tibia. Femur and tibia were cut at 25 cm from the knee joint and attached to the Instron testing machine (Instron 850I, MTS, Minneapolis, Minnesota), a universal testing machine, through a cylinder-shaped connecting socket made of resin, 10 cm in length and 4.5 cm in diameter. To protect the specimens from the high-temperature increase when the resin hardens, we continuously sprayed normal saline onto the specimens.

Kinematic Measurements

To measure the kinematics of the knee joint, each specimen was attached to a Customized Jig which was fixed to the Instron testing machine. The femoral end was rigidly fixed, while the tibial end was set to have 5 degrees of freedom (anterior–posterior, superior-inferior, valgus-varus, internal–external rotation, and flexion–extension) (Fig. 1). Using a load cell with a pneumatic actuator attached, the process to apply anterior and valgus load of set value was automatized. The testing machine was set to control and measure joint kinematics at various flexed angles. The anterior–posterior and medial–lateral translation of the Customized Jig fixed to the tibial end was measured with a Digital caliper, while valgus–varus and relative internal–external rotation angle of the tibia was measured with an optical encoder. We could check the relaxation of the specimen knee joint by measuring the tibial anterior–posterior translation and tibial internal–external rotation angle relative to the femur, after applying the external force (Fig. 2).

Testing Protocol

For each of the 10 porcine knee joints, (1) normal ACL, (2) ACL removal, (3) modified ACL reconstruction with over-the-top augmentation technique, (4) single bundle ACL reconstruction were performed consecutively. At each process, anterior tibial translation was measured at 30°, 60°, and 90° knee flexion, respectively, while applying 134 N of an anterior tibial load. Anterior tibial translation and relative tibial internal rotation angle were also measured while applying 5 Nm of internal tibial torque with 10 Nm of a valgus load. The width of the tibial plateau of each specimen knee joint was measured. The anterior translation of

Fig. 1 Porcine knee specimens mounted on the Instron testing machine (Instron 8501, MTS, Minneapolis, Minnesota)

the tibial lateral compartment could be expressed as the following.

$$\text{Anterior translation of tibial lateral compartment (mm)} = A + r/2 \times \text{Sin}\theta.$$

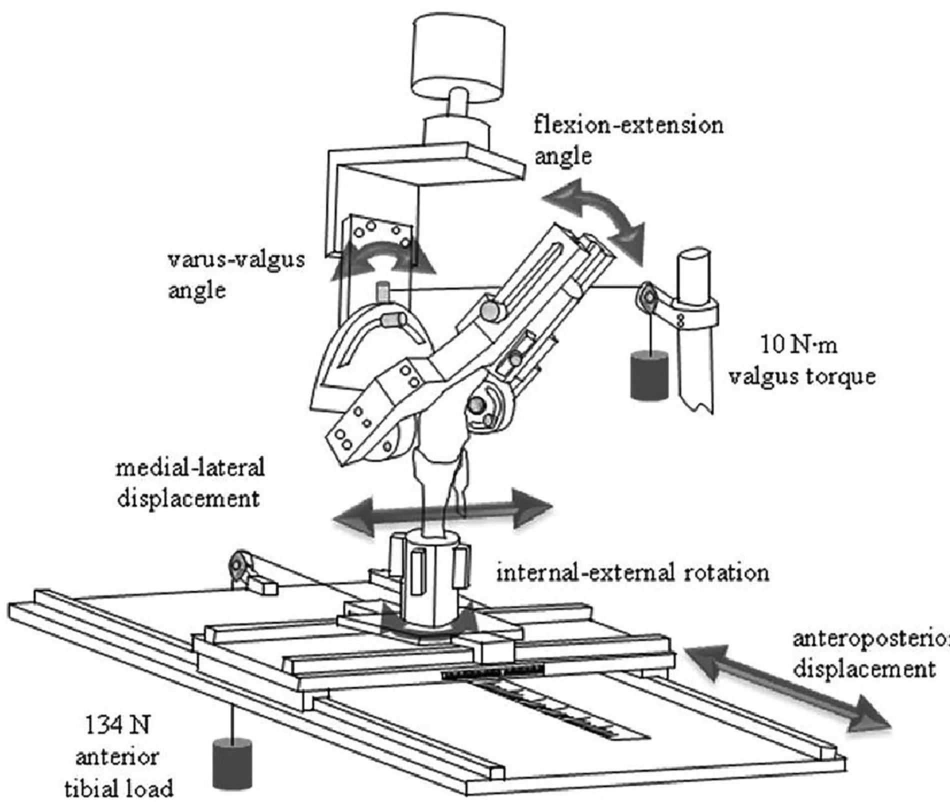
A is the anterior translation of tibia (mm), r is the width of the tibial plateau (mm), θ is the relative tibial internal rotation angle.

Surgical Technique

Modified ACL Reconstruction with Over-the-Top Augmentation Technique

A 3 cm skin incision was made at the medial and inferior aspect from tibial tuberosity and 11 mm sized tibial tunnel reaming was done targeting the isometric point. Then, 10 mm sized femoral tunnel reaming was done at the posterolateral point from over-the-top at the lateral condyle of femur, directed toward the isometric point which is 7 mm anterior from the posterior corner of the intra-articular medial wall. Tendon graft was prepared by harvesting Achilles tendon with two bundles, 15 cm and 20 cm in length respectively, and containing bone insertion site from the lower extremity of porcine. To position, the tendon graft, one of the 3 leading suture loops was passed through the tibial tunnel into the intercondylar space and again into the

Fig. 2 Freedom of motions



posterolateral aspect of over-the-top at the femoral lateral condyle. The other two loops were passed through the tibial tunnel and femoral tunnel, respectively, but in opposite directions. The short bundle of tendon graft was passed through the tibial tunnel and femoral tunnel consecutively using the suture loop positioned at the two tunnels, and the long bundle was passed alongside the suture loop that passed through the tibial tunnel into the intercondylar space and the posterolateral aspect of over-the-top at the femoral lateral condyle (Fig. 3). The rest of the long bundle which passed through the over-the-top and out of the lateral condyle is passed again through the femoral tunnel and tibial tunnel consecutively alongside the suture loop of the opposite direction. While maintaining the knee flexed at 30°, we applied maximum tension with prepared sutures to the fixation site of tendon graft and anchored it with washer and cortical screw. The short bundle of tendon graft was placed to overlap with the long bundle of tendon graft which passed through over-the-top while maintaining moderate tension, and the two bundles were fixed using two staples with a spike. Additional fixation was applied with a bioabsorbable interference screw at the external exit site of the femoral tunnel. Another bioabsorbable interference screw was inserted into the entry point of the tibial tunnel for double fixation (Fig. 4).

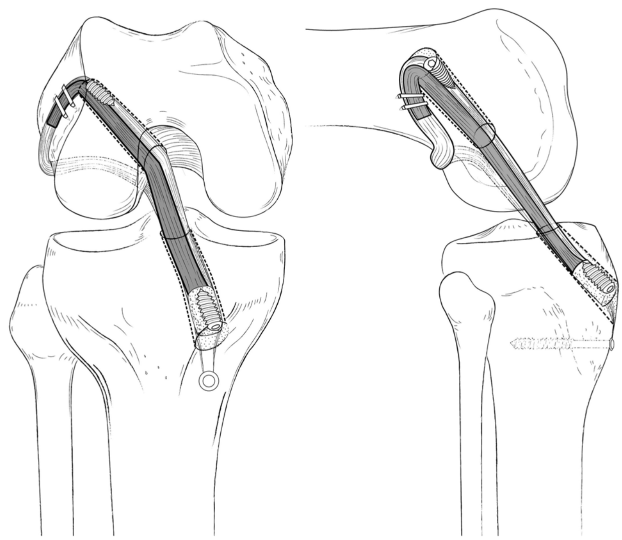


Fig. 4 The long bundle (white) is introduced back to the femoral tunnel outside in forming over-the-top sling structure of the allograft in modified ACL reconstruction with over-the-top augmentation technique. Fixation is performed as described in the text

Single Bundle ACL Reconstruction

For single bundle ACL reconstruction, the anterior tibialis tendon was harvested from the lower extremity of porcine and folded to form 2 layers and was sutured with No.2 ethibond in a whipstitch method except for the intraarticular part. From the specimen that underwent modified ACL reconstruction with over-the-top augmentation technique, we removed the tendon graft and interference screw to obtain vacant tibial and femoral tunnel. Anterior tibialis tendon graft was inserted two-pronged side first into the lateral entrance of the femoral tunnel until 1 cm from the folded part remains and then, was fixated with bioabsorbable interference screw inserted into the lateral entrance of the femoral tunnel. The two-pronged side of tendon graft which passed through the femoral tunnel went into the tibial tunnel through the knee joint. While maintaining the knee flexed at 30°, the two-pronged sutures were pulled to maximum tension and tied to a cortical screw. A bioabsorbable interference screw was inserted into tibial tunnel entrance for double fixation.

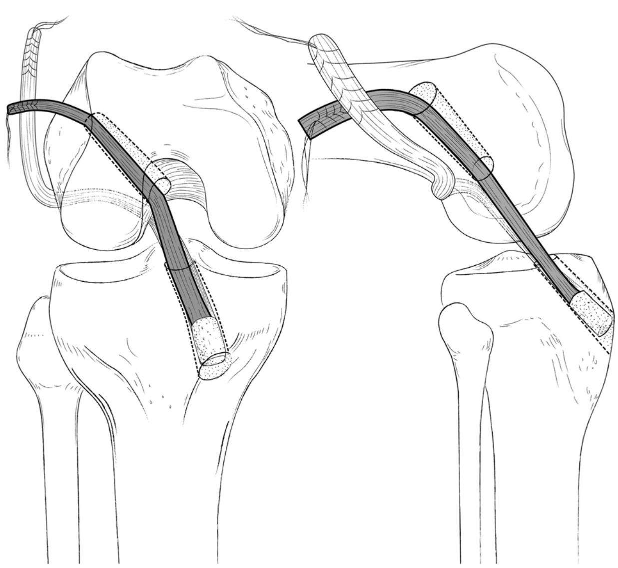


Fig. 3 Illustration of the passage route of the graft. The short bundle (shaded grey) passes through the femoral tunnel, and the long bundle (white) encases lateral femoral condyle via over-the-top

Statistical Analysis

We performed the Kruskal–Wallis test to compare the anterior translation of tibia under anterior tibial load and the anterior translation of the tibial lateral compartment under internal tibial torque with a valgus load between 4 different states of ACL. For analysis between the groups, we performed the Mann–Whitney *U* test. All statistical analysis was done with SPSS ver. 18.0, and when the *P*-value was less than 0.05, the result was assumed to be statistically significant.

Results

Anterior Tibial Translation Under Anterior Tibial Load

After ACL resection, anterior tibial translation showed a statistically significant increase at all flexed angles ($P<0.05$). In addition, the anterior tibial translation at all flexed angles in knee joints that underwent ACL reconstruction was significantly lower than those of ACL deficient joints. The anterior tibial translation showed a statistically significant increase in the single-bundle ACL reconstruction group at 60° and 90° of flexion when compared with the normal ACL group. The anterior translation of the single-bundle ACL reconstruction group at all flexed angles was relatively larger than those of the modified ACL reconstruction with over-the-top augmentation technique group, but the result was not statistically significant (Table 1, Fig. 5).

Table 1 Anterior tibial translation under anterior tibial load

Knee flexion angle	Anterior tibial translation (mm)		
	30°	60°	90°
ACL-intact	10.8 ± 3.5	10.7 ± 3.2	10.3 ± 2.2
ACL-deficient	28 ± 4.3	26.8 ± 8.0	23 ± 6.4
SB	13.3 ± 2.3	14.8 ± 3.9	13.7 ± 3.3
OA	11.8 ± 2.1	12.3 ± 2.2	12.8 ± 1.9

Mean ± SD, *SB* single-bundle ACL reconstruction, *OA* modified ACL reconstruction with over-the-top augmentation

Anterior Tibial Translation Under Anterior Tibial Load and Combined Rotatory Load

At all flexed angles, ACL deficient group showed significantly larger anterior tibial translation than normal ACL group and both ACL reconstruction groups ($P<0.05$). In addition, at all flexed angles, the anterior tibial translation of the single-bundle ACL reconstruction group was significantly larger than those of the normal ACL group ($P<0.05$). While the anterior tibial translation of the modified ACL reconstruction with over-the-top augmentation technique group was relatively larger than that of the normal ACL group, the result was not statistically significant. The anterior tibial translation of the modified ACL reconstruction with over-the-top augmentation technique group at 30° of flexion was significantly lower than that of the single-bundle ACL reconstruction group ($P<0.05$). At 60° of flexion, the anterior tibial translation of the modified ACL reconstruction

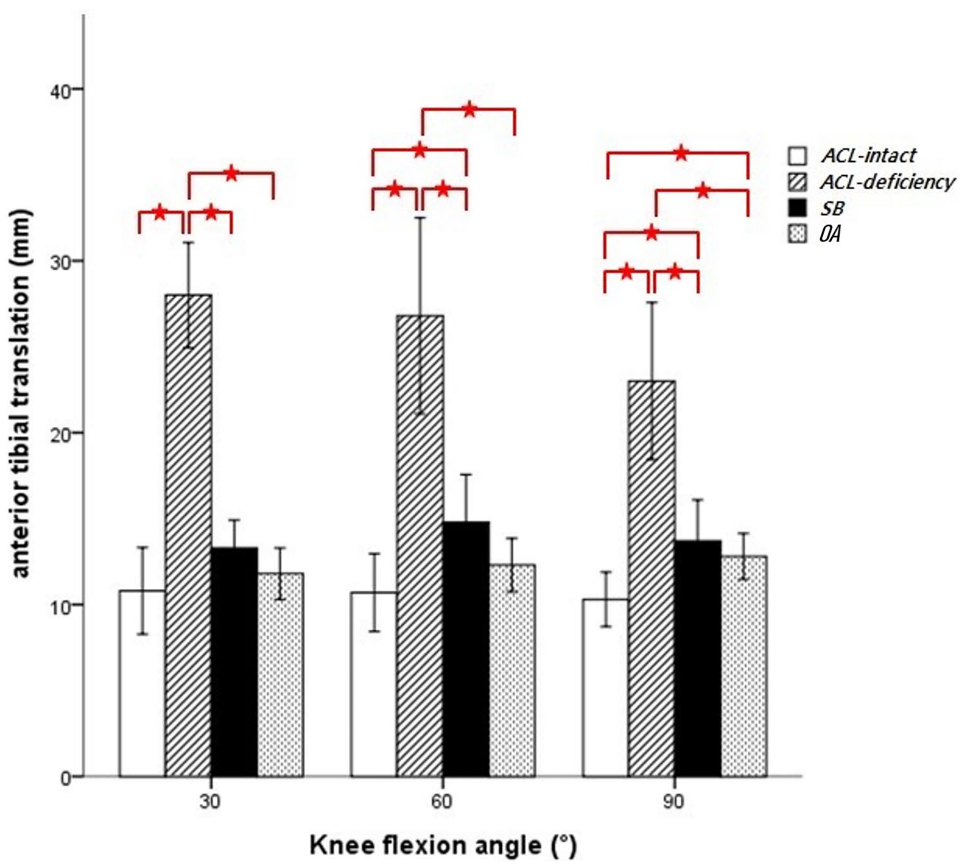


Fig. 5 Comparison of anterior tibial translation under anterior tibial load. The asterisk indicates statistically significant difference (*$P<0.05$) (*SB* single-bundle reconstruction, *OA* modified ACL reconstruction with over-the-top augmentation)

with over-the-top augmentation technique group was lower than that of the single-bundle ACL reconstruction group, but the result was not statistically significant. (Table 2, Fig. 6).

Anterior Translation of Tibial Lateral Compartment Under Anterior Tibial Load and Combined Rotatory Load

The anterior translation of the tibial lateral compartment of the normal ACL group and both ACL reconstruction groups at 30° and 60° of flexion were significantly lower than those of the ACL deficient group ($P < 0.05$). There was no statistically significant difference between the anterior translation of the tibial lateral compartment in the normal ACL group and the modified ACL reconstruction with over-the-top augmentation technique group at all flexed angles. The anterior translation of the tibial lateral compartment was significantly lower in the modified ACL reconstruction with over-the-top augmentation technique group at 30° of flexion than in the single-bundle ACL reconstruction group ($P < 0.05$) (Table 2, Fig. 7).

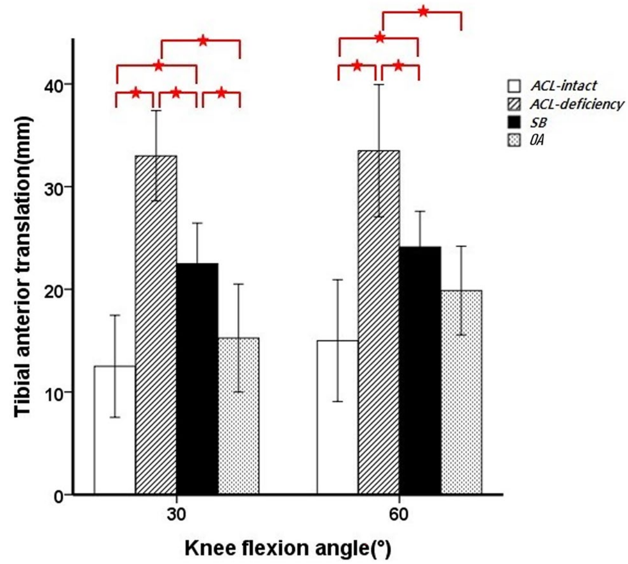


Fig. 6 Comparison of anterior tibial translation under combined rotatory load. The asterisk indicates statistically significant difference (*$P < 0.05$) (*SB* single-bundle reconstruction, *OA* modified ACL reconstruction with over-the-top augmentation)

Discussion

The important point we are to make in this study is that a novel ACL reconstruction technique with extra-articular augmentation by forming a sling structure at over-the-top enhances knee joint rotational stability. Previously, reconstruction with lateral plasty was reported to lengthen the lever arm to prevent subluxation of the lateral compartment and to increase the recovery of rotatory motion [20]. Maracacci et al. [21] introduced the ACL reconstruction technique of over-the-top single bundle fixation with external tenodesis and reported after an average of 11 years of follow-up study that, extra-articular fixation technique enhances rotational stability. In addition, Maracacci et al. [22, 23] introduced double-bundle ACL reconstruction with intra-articular graft going through the over-the-top passage into the femoral tunnel, and then into the tibial tunnel via the knee joint before it is fixed. This technique is reported to provide functional motion stability as the position of the tendon graft is similar to that of anatomical double-bundle ACL reconstruction.

The initial motivation for designing this technique was to devise an ACL reconstruction method that can enhance graft strength and fixation regardless of bone tunnel conditions such as in the cases of revision ACL reconstruction. We assumed if conventional ACL reconstruction is combined with over-the-top graft fixation, we could achieve not only anterior but also rotational stability as well. The new ACL reconstruction technique we introduced in this study uses the long bundle of Achilles tendon with bone plug and also, adds a short bundle of Achilles tendon graft fixed inside the joint after passing through the femoral tunnel, to the double-bundle ACL reconstruction via over-the-top passage introduced by Marcacci et al. [22, 23] Although there is no advantage from longer lever arm, the over-the-top sling structure provides rotational stability through complementary effects of intra-articular tendon graft and

Table 2 Anterior tibial translation, relative tibial internal rotation, and lateral tibial compartment anterior translation under combined rotatory load

Knee flexion angle	Anterior tibial translation (mm)		Relative tibial internal rotation (°)		Lateral tibial compartment anterior translation (mm)	
	30°	60°	30°	60°	30°	60°
ACL-intact	12.5 ± 6.0	14.1 ± 7.1	9.3 ± 3.2	22.4 ± 5.1	17.2 ± 10.6	25.5 ± 11.1
ACL-deficient	33.0 ± 5.3	33.5 ± 7.7	32.7 ± 8.2	41.3 ± 6.0	48.7 ± 9.7	53.0 ± 10.4
SB	22.5 ± 4.7	24.1 ± 4.2	18.9 ± 5.3	23.8 ± 4.9	31.9 ± 10.8	35.9 ± 8.1
OA	14.2 ± 6.3	18.9 ± 5.2	8.5 ± 2.3	15.3 ± 4.8	18.5 ± 11.9	26.6 ± 9.2

Mean ± SD, *SB* single-bundle ACL reconstruction, *OA* modified ACL reconstruction with over-the-top augmentation

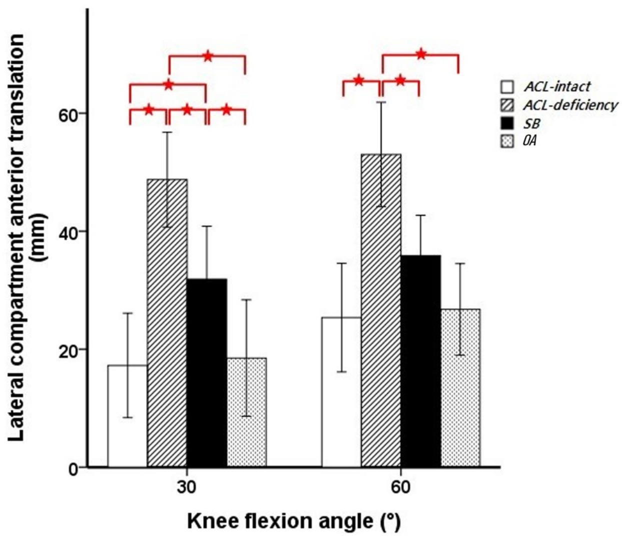


Fig. 7 Comparison of lateral tibial compartment anterior translation under combined rotatory load. The asterisk indicates statistically significant difference (*$P<0.05$) (*SB* single-bundle reconstruction, *OA* modified ACL reconstruction with over-the-top augmentation)

extra-articular tendon graft fixed at over-the-top. Assuming that tibia rotates with the center of the tibial plateau as its axis, the force of the combined vector of tension on the tendon graft at intra-articular and over-the-top is thought to impede internal rotation of the tibia.

Regarding internal rotation of the tibia, the tendon graft serves as a strong rotatory controller, especially at lower flexion angle. The tendon graft which passes through the intra-articular femoral tunnel would become tight at flexion and loose at extension, just like the anteromedial bundle in anatomical double-bundle ACL reconstruction. Meanwhile, the tendon graft fixated at over-the-top would become tight at extension and loose at flexion, just like the original posterolateral bundle [22]. Thus when the knee is flexed, the tendon graft passing over-the-top loosens, decreasing its role as a rotator controller to restrain internal rotation.

The rotational instability was evaluated subjectively with the Pivot shift test [24, 25]. Recently, efforts were made for the quantitative measurement of Pivot shifting and technological advancements made it possible to measure dynamic parameters such as change of velocity while performing Pivot shift test via accelerometry [19, 26–28]. Asai et al. [19] conducted an in vitro biomechanical study on the dynamic instability of single-bundle ACL reconstruction with over-the-top fixation using triaxial accelerometry. Zaffagnini et al. [29] used a photoelectronic and electromagnetic navigation measurement system to quantitatively evaluate knee laxity after ACL reconstruction with over-the-top fixation. However, the Pivot shift test is a manually conducted test making it vulnerable to intraobserver and interobserver error. In this study, to maintain consistent external load, we attached the specimen to the Instron testing machine and automatized the anterior and valgus loading procedure using a load cell connected to the pneumatic actuator. With this, we could apply a consistent anterior load, valgus load and internal torque creating similar conditions with Pivot shift stress and evaluate the degree of recovery of rotational instability by measuring the relative translation of tibia to the femur. Also based on the study by Bedi et al. [30] that the grade of pivot shifting can be assumed from the degree of translation of tibial lateral compartment, we calculated the value of anterior translation of tibial lateral compartment from tibial width, anterior translation of tibia, and relative tibial internal rotation angle.

We assumed the increase in the cross-sectional area of tendon graft by forming intra-articular triple strands could enhance stability, but our study revealed that the increase in the size of the graft has no direct effect on rotational stability. This was similar to the results by Bedi et al. [31] according to their biomechanical study that thick tendon graft does not enhance knee joint stability. However, the wider insertion area used on tibia and bone plug of Achilles tendon graft allows for a better press-fit of the tendons in the tibial tunnel, which then provides additional graft-bone fixation strength. This improvement could enable a more immediate and active rehabilitation program.

Limitations should be addressed regarding this study. First, our study is not a human cadaveric model, and it is impossible to evaluate knee kinetics on slightly flexed angles. Yet, porcine knee model has long been used as an important surrogate to study the effects of surgical intervention after ACL injury. It has been shown to be the closest to the humans based on the size and anatomy of the knee, functional dependence on the ACL, gait biomechanics, similarity of hematology and wound healing characteristics, and sex-related phenomena associated with ACL [32–37]. Secondly, this is an in vitro study, so we could not replicate functional loading and in vivo variables such as graft healing and graft relaxation. Lastly, only 10 porcine knees were used due to the limitation of resources, and we had to perform sequential reconstructions of two techniques per each knee using different grafts and this could have a potential effect on graft quality and graft-bone fixation. Yet, our efforts are worth it considering that this is a large animal study that is known to be the closest to the human knees.

Conclusion

Our study showed that the modified ACL reconstruction with over-the-top augmentation technique resulted in enhanced rotational stability compared to the conventional single-bundle ACL reconstruction, especially at lower flexion angle in a porcine model. Therefore, with several potential advantages as well as biomechanical superiority, our new technique could be clinically applicable in primary and revision ACL reconstruction. Further clinical studies are anticipated to evaluate the effectiveness of this technique in human trials.

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Declarations

Conflict of interest All authors declare no conflict of interest.

Ethical standard statement This article does not contain any studies with living human or animal subjects performed by the any of the authors.

Informed consent For this type of study informed consent is not required.

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