The effects of fixation method of anterior cruciate ligament repair surgery on knee kinematics under anteroposterior and tibial rotatory loads

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Abstract

The anterior cruciate ligament (ACL) plays the primary role in resisting anterior tibial translation. ACL rupture inevitably causes alterations in knee kinematics and long-term functional impairment. The purpose of this study was to evaluate a new surgical technique, subosseous screw-suture anchor surgery (SSSAS), for ACL repair of the knee from a biomechanical point of view. Twelve porcine knees were tested with the ACL intact, cut, and repaired (using traditional Pull-Out method or the SSSAS method) on a mechanical testing apparatus. Tibial translation at four knee flexion angles (0°, 30°, 60°, 90°) under three tibial rotation loads (5 N-m, 0, -5 N-m) was measured to determine knee stability. A laxity recovery ratio was defined to account for individual variations and estimate the repair level. Our findings indicate both Pull-Out and SSSAS techniques significantly decreased AP laxity of the knee joint. In addition, the differences between the intact and repaired knees in the Pull-Out group were significant in all three tibial rotation positions. In the SSSAS group, they were significant at 0° and 90° knee flexion for both neutral and internal rotation positions and at 0°, 30°, and 90° knee flexion in the external rotation position. Concerning the laxity recovery ratio, the SSSAS group had higher laxity recovery ratio than the Pull-Out group. In other words, the fixation by directly fixating the ACL on the femoral interchodylar area instead of the fixation through femoral tunnel could give better outcome in terms of knee stability.

Key words: Anterior cruciate ligament, Surgical technique, Laxity, Mechanical properties, Knee stability, Laxity recovery ratio, Fixation methods

1. Introduction

Knee injuries occur frequently in sports because the nearly flat tibial surface has no socket to secure the femoral condyle. There are many cases of knee ligament injuries and complete ruptures of the ACL lead to knee instability and may cause associated tears and degeneration of the menisci. (Woo, et al., 1999) Surgical ligament fixation repairs or ligament reconstruction techniques are used to treat injured ACLs. Unfortunately, repair of the ruptured ACL is not always successful as about 20% of patients do not have good results, especially those receiving ligament fixation surgical repair. (Woo, et al., 2006, Woo, et al., 1999) This condition may progressively damage other knee structures if the knee does not stay stable.

With ACL injuries, bone-tendon ruptures are most frequently seen in the rotator cuff tendon, cruciate ligaments, and medial and collateral knee ligaments. Symptoms include pain, decreased range of motion, weakness and instability.
which result in considerable restriction of normal activity. Surgical repair is usually required.

Concerning ACL repair, previous studies demonstrated three failure modes including suture pullouts from the tendon, thread breakage, and suture-to-bone fixation failure. (Brand, et al., 2000, Steiner, et al., 1994, Weiler, et al., 1998) The location of the anterior tibial load was demonstrated to strongly influence anterior tibial translation. The clinical point of application of anterior tibial load achieves appropriate anterior tibial translation, compared to geometric, medial and lateral points. (Randy, et al., 2000) Some investigations focused on improving the tendon-grasping technique and suture material to prevent the fixation failure. (Kessler, 1973, Mortenson and Urbaniak, 1972) However, few studies investigated surgical repair techniques for tendon-bone fixation. The most common methods of fixation of the tendon to bone include transosseous Pull-Out suture (double or single), suture anchor system (MitecII anchor), metallic brush, screw-post fixation, or utilization of bone graft, metallic plate, or re-absorbable membrane for augmentation of the suture on bone. Several studies reported that bungee cord effect and tunnel widening may occur while suturing the ligament through the tunnel and induce the knee instability. (Blythe, et al., 2006, Maak, et al., 2010) Therefore, a new technique was developed in this study named Subosseous Screw-Suture Anchor Surgery (SSSAS) by modifying the conventional surgical operation-pullout (screw-post fixation) technique. (Brand, et al., 2000, Weiler, et al., 1998)

Joint kinematics measurements can indicate the degree of joint fitness. (Yoo, et al., 2005) Many studies assessing ACL operation success examined joint knee kinematics measurements, such as the anterior-posterior (AP) displacement and rotation angles since the ACL medial and lateral structures provide both anterior-posterior and rotational stability. (Yoo, et al., 2005) Increased restoration of normal tibial translation under anterior loads indicates good surgical results.

Biomechanical measurements such as knee stability, is widely used as an evaluation method to gauge the outcome of ligament reconstruction techniques. (Ho, et al., 2002) In the previous decade, biomechanical in-vitro tests were well-established to accurately measure the kinematics of the knee at different flexion angles or pivot shifts without making physical contact with the ligaments. For example, Bergfeld et al. compared the knee stability of two ligament reconstruction techniques by measuring AP mean knee laxity at four knee flexion angles with three tibia rotational positions. (Bergfeld, et al., 2005) Their results indicated better reconstruction technique is marked by lower mean knee laxity. (Bergfeld, et al., 2001)

In addition to mean knee laxity, a new assessment item – laxity recovery ratio – is introduced in this study to compensate for individual variations. The main purpose of this study was to assess the biomechanical effect of different ACL repair surgical techniques through quantitative measurement of kinematics and the kinetics data. Six pairs of porcine knees were used with each pair tested under AP and PA loads for three knee conditions, ACL-intact, ACL-cut, and ACL repaired at four knee flexion angles (0°, 30°, 60°, and 90°) with the tibia in three rotational positions, neutral, internal, and external position. This study tests the hypothesis that a better fixation of the ruptured ligament into its anatomic position by the application of screw would improve the stability of the knee. Hence, a mechanical testing system was designed to compare the mechanical behavior of this new fixation technique to the conventional pullout technique.

2. Materials and Methods

2.1 Specimen Preparation

Twelve fresh porcine knees were used as the specimens in this study. All knees were inspected prior to ensure no evidence of abnormal knee laxity, torsion and deformation. The femur and tibia were cut approximately 15 cm from the joint line. To isolate the ACL, the skin and the muscles were removed, leaving only ligaments, meniscus, and the joint capsules. The specimens were kept moist with saline during the dissection and testing. Half of the proximal end of the femur and the distal end of the tibia were potted in polymethyl methacrylate (PMMA) within aluminum cylinders.

2.2 Mechanical Testing System

The mechanical testing system consists of a biaxial material testing machine, the Bionix 858 MTS with Teststar II software (MTS System Corporation, Eden Prairie, Minnesota, U.S.A) (Fig. 1), a six-degree-of-freedom testing apparatus, a force/torque sensor (MC3A series Advanced Mechanical Technology, Inc, MA, USA) and data acquisition
hardware (InstruNet A/D box-#iNet-100, a PCMIA-card controller, #iNet-230, InstruNet Corporation). The biaxial material testing machine was used for applying AP and PA (anterior-posterior/posterior-anterior) loads on the knee while simultaneously measuring the displacement. Displacement, rotation angle, force and torque could be measured in response to applied loads. The experimental protocols were performed using MTS—Test Star II and the Testware-SX software. All the experimental protocols were controlled in displacement mode, that is, the kinetic data, force and torque were measured through the control of the displacement loads. An experimental limit of ± 100 N (AP/PA direction) ensured loading would stop when force value reached ± 100 N.

The six-degree-of-freedom testing apparatus described by Fleming et al. was constructed to connect the specimen and the MTS (Fig. 1a and 1c). (Fleming, et al., 1992) For applying AP and PA (AP/PA) loads to the knee, the potted femoral end of the specimen was clamped into the yoke attached to the load ram of the MTS. The epicondyle axis of the knee joint was aligned with the pivot axis of the flexion-extension yoke. The flexion yoke could be adjusted and locked at the desired knee joint flexion angle. The tibial yoke was attached to an axially rotatable shaft with a secondary force/torque sensor allowing free translation of the tibia in the horizontal plane during AP/PA loads and free varus-valgus angulation. During the experimental trials, the yoke was locked once the required load was reached (Fig. 1b). This testing rig was fixed on an X-Y table then mounted on the MTS. With 100 N AP/PA loads applied to the femur, the MTS biaxial load cell measured amount of the femoral displacement, i.e. the translation between the tibia and the femur in the midsagittal plane.

Neutral tibial rotation was defined as the midway between tibial rotations produced by 5 N-m of internal and external tibial torque. (Markolf, et al., 1997) The 5 N-m of the tibial torque was produced with weight hung on a bar attached to the unlocked tibial clamp. The internal and the external rotation positions were defined as the relative results of the applied internal and the external tibial torque of 5 N-m. Tibial rotation was locked after adjusting to the desired position then the AP/PA loads were applied with the MTS machine.

2.3 Surgical Techniques

Trans-osseous Pull-Out suture anchor surgery is a conventional surgical technique in ACL reconstruction (Fig. 2a). First, a knotted suture (double) was performed on the transected ACL. A tunnel was drilled at the femoral insertion site of ACL. The suture was pulled through the tunnel and tied with a screw. To hold and secure the suture on the ACL and the stump of the ruptured ACL, the suture and screw with a washer were fixed tightly to the femoral condylar area.

The new subosseous screw-suture anchor surgery technique was modified from the conventional Pull-Out surgical operation technique. (Brand, et al., 2000, Weiler, et al., 1998) By placing a screw with washer in the anatomical direction of the ligament, the suture on the tendon and part ruptured ligament was secured at the femoral insertion site of the ACL (Fig. 2b).
2.4 Experimental Procedure

Mean knee laxity is defined as the amount of maximal anterior-posterior and posterior-anterior tibial translations during the AP/PA loads at each flexion angle and rotation position. The experimental procedure for testing was set as follows; intact ACL, cut ACL, and ACL repaired using Pull-Out or SSSAS techniques. The zero-load position of the MTS was maintained while changing the knee flexion angle and tibial rotation between testing cycles. Displacement and force data in AP direction were collected by the MTS. Furthermore, through the extra force/moment sensor on the proximal tibial side, kinetic data of the tibia could be measured. The whole loading process is shown in Fig. 3.

After dissection and potting, the intact knees would be flexed between the full-flexion and full-extension ten times for preconditioning before the testing. Each specimen was installed on the testing apparatus and mounted to the MTS, and the unloaded specimen was manually adjusted to the least resistance condition. Each specimen was tested at the angles of 0°, 30°, 60°, and 90° for knee joint flexion with the potted tibia end locked in the neutral, internal, and external rotation positions. 100 N AP/PA loads controlled by the MTS software were applied to the femoral yoke with the conditions stated above. Under each condition, the cyclic loads on the femur were repeated three times and only the last cyclic loading data was collected for analysis.

The varus-valgus angulation was unconstrained in the midsagittal plane while the potted tibia was locked. In addition, translation in the coronal plane was allowed during the anterior tibial loads. Neutral, internal, and external rotation positions were redefined at the new knee joint flexion angles. The MTS recorded the kinetic and kinematic data of the specimen under applied loads. The extra force/moment sensor was connected to the InstruNet external A/D box with a PCMCIA-card controller. With additional software, the applied loads on the specimen were recorded.

In order to simulate torn ACL ligament, the ACL at the insertion site was transected, i.e., the portion connected to the head of the femur on the medial side of the lateral condyle. In addition, to maintain the same loading conditions, the specimen was clamped into the same zero-load neutral position under the previous intact knee testing sequence, and the

![Fig. 2 Schematic drawing of the ACL repair surgery with (a) Pull-Out technique and (b) SSSAS technique.](image)

![Fig. 3 The diagram of the AP loading process](image)
AP/PA loads were repeated on the specimen under the same testing parameters as before.

ACL-repaired knees using two different surgical techniques would be flexed between full-flexion and full-extension ten times for preconditioning before mechanical testing to minimize residual forces and moments on the repaired knees. The repaired knee would be installed on the MTS and the same mechanical testing performed.

Comparison of the mean knee laxity between two different surgical operations is the key measurement in this study, with the femoral and tibial rotation angle also taken into consideration. In addition, to account for individual variance between the specimens (different donors or even different feet may have different laxity), a new parameter, laxity recovery ratio, was defined to estimate the recovery level of the surgical techniques.

\[
\text{Laxity Recovery Ratio} = \frac{\text{ACL-repaired Laxity} - \text{ACL-cut Laxity}}{\text{ACL-intact Laxity} - \text{ACL-cut Laxity}}
\]

### 2.5 Statistical Analysis

In this study, the data was analyzed using SPSS 17. This data included the amount of AP translation between the tibia and the femur from six pairs of porcine knees for three conditions (intact ACL, ACL-cut, and ACL-repaired) at different flexion angles (0°, 30°, 60°, and 90°) and rotation positions (neutral, internal, and external). The differences of AP laxities between different conditions were tested by the application of repeated measure ANOVA. Post-hoc Bonferroni test was used to detect significant differences between different ACL conditions at specific flexion angle and rotation position. The Difference in laxity recovery ratio between two surgical techniques was assessed using independent t-test. The significance level was \( p < 0.05 \).

### 3. Results

In this study, the kinematics of ACLs under different conditions was estimated in order to assess the outcomes of the conventional Pull-Out and new SSSAS ACL surgical techniques. In kinematics, mean AP laxity was the primary indicator for assessment. Moreover, laxity recovery ratio was the other important factor because of the difference between individual specimens.

#### 3.1 Knee Laxity at Neutral Position

As shown in Fig. 4, with the tibia at the neutral position, the AP laxity in the ACL-cut knee was around three times greater than that in the intact knee. After ACL repair surgery, the mean anterior knee laxity decreased. In the Pull-Out group, the mean knee laxity of repaired ACL was significantly greater than that of the intact knee and smaller than that of ACL-cut knee at each of the four flexion angles (Fig. 4a). In the SSSAS group, measurements of AP laxity showed that the repaired ACL condition had a significantly lower laxity than ACL-cut (Fig. 4b). Additionally, the mean knee laxity of repaired ACL was significantly greater than the intact knee at the 0° and 90° flexion angles (Fig. 4b).

![Fig. 4 AP laxity of the intact ACL, ACL-cut, and ACL-repaired conditions at the neutral position. (a) Laxity at different conditions (intact, cut, and Pull-Out) and knee flexion of 0°, 30°, 60°, and 90°. (b) Laxity at different conditions (intact, cut, and SSSAS) and knee flexion of 0°, 30°, 60°, and 90°.](image)
3.2 Knee Laxity at Internal Rotation Position

At the tibial internal rotation position, the mean AP laxity of ACL-cut knee was around two times greater than that of the intact knee (Fig. 5). Mean knee laxity at the internal rotation position decreased after ACL repair surgery, similar to that at the neutral position. In the Pull-Out group, the repaired knees showed significantly higher mean knee laxity than the intact knees at four flexion angles (Fig. 5a). However, the mean knee laxity of SSSAS-repaired knees presented a significantly higher value as compared with that of the intact knee at 0° and 90° of flexion angle (Fig. 5b).

![Fig. 5](image)

Fig. 5 AP laxity of the intact ACL, ACL-cut, and ACL-repaired at the internal position. (a) AP laxity at different conditions (intact, cut, and Pull-Out) and knee flexion of 0°, 30°, 60°, and 90°. (b) AP laxity at different conditions (intact, cut, and SSSAS) and knee flexion of 0°, 30°, 60°, and 90°.

3.3 Knee Laxity at External Rotation Position

Mean knee laxity with the tibia at the external rotation position at different knee flexion angles is shown in Fig.6. Similar to the neutral and internal rotation positions, knee laxity decreased after ACL repair surgery as compared to the ACL-cut condition. In the Pull-Out group, mean knee laxity was significantly greater than the intact knee at four flexion angles (Fig. 6a). In the SSAS group, the mean knee laxity was greater than the intact knee at four flexion angles. The significant differences were found at 0°, 60° and 90° of flexion angles (Fig. 6b).

![Fig. 6](image)

Fig. 6 AP laxity of the Pull-Out group (a) and the SSSAS group (b) of the intact ACL, ACL-cut, and ACL-repaired conditions at the external rotation position at knee flexion of 0°, 30°, 60°, and 90°.

3.4 Knee Laxity Recovery after ACL Repair Surgery

The laxity recovery ratio accounts for the individual variance between the specimens and is used to estimate the
recovery level of surgical techniques. Results of laxity recovery ratio at neutral position, internal rotation position, and external rotation position are shown in Fig. 7. At neutral position, laxity recovery ratio of repaired ACL using Pull-Out technique were significantly lower than that using SSSAS technique at knee flexion angle of 0°, 60°, and 90° (Fig. 7a). In particular, the pullout group shows the mean laxity recovery ratio of 24.17% to 45.23% at four flexion angles while the SSSAS group has the mean laxity recovery ratio of 53.99% to 80.41%. Comparison of the recovery ratios between two techniques at the internal rotation position showed that laxity recovery ratio of Pull-Out group was significantly lower than that of the SSSAS group at flexion angle of 90° (Fig. 7b). Figure 7c presents the recovery ratio at the external rotation position. The laxity recovery ratio of the SSSAS group at four flexion angles were higher than that of the Pull-Out group, however, the difference was not significant. For all three tibial rotation positions, the SSSAS technique showed a better performance than Pull-Out technique in restoring ACL function (Fig. 7d).

**Fig. 7** Recovery ratio of the ACL-repaired knee with Pull-Out and SSSAS techniques at the (a) neutral position; (b) internal rotation position; (c) external rotation position at knee flexion of 0°, 30°, 60°, and 90°. (d) In general. ACL repaired by SSSAS had a higher recovery ratio than Pull-Out technique for both pure AP tibial load or combined AP and rotatory loads.

**4. Discussion**

In this study, the mechanical properties of porcine ACL under different conditions were measured in order to assess the outcomes of the conventional pullout and SSSAS ACL surgical techniques. In kinematics, mean AP laxity is the primary factor for assessment. Previous studies indicate that the anterior tibial translation was lower at the 0° flexion angle while it would increase at higher flexion angles of 30° to 60°. However, the anterior tibial translation would decrease when the flexion angle was beyond 90°. (Yoo, et al., 2005, Zavatsky and Wright, 2001) Additionally, the motion of anterior tibial translation has been demonstrated to cause the tibia to internally rotate, indicating that the ACL restrains internal rotational moments during AP translation. (Fukubayashi, et al., 1982) In the current study, the AP laxity of intact and repaired ACL during internal rotatory loads was less than those at neutral or external rotation positions. The laxity of intact ACL during knee movement from extension to flexion showed agreement with previous studies.

Our findings also indicated that both Pull-Out and SSSAS techniques significantly decreased knee AP laxity during...
AP loads and/or rotation loads as compared to ACL-cut. In addition, the differences between the intact and repaired knees in Pull-Out group were significant in three tibial rotation positions. The SSSAS group was significant at 0° and 90° of knee flexion in neutral and internal rotation positions and at 0°, 30°, and 90° of knee flexion in external rotation position. Hence, the SSSAS technique might be able to provide a similar laxity to intact ACL.

The laxity recovery ratio reduces individual variations between test samples. Concerning laxity recovery ratio, the SSSAS group had higher laxity recovery ratio than the Pull-Out group. In other words, directly fixing the ACL on the femoral interchodylar area instead of through a femoral tunnel may provide better knee stability. In particular, previous studies have demonstrated that tunnel widening may occur immediately following ACL reconstruction. Moreover, distal suspensory fixation could induce the “bungee cord effect” or “windshield-wiper effect” and lead to tunnel enlargement during the transition from flexion to extension. (Hoher, et al., 1998, Schultz, et al., 2007) Previous studies indicated that increased length between ACL fixation points may decrease stiffness and increase displacement during cyclic loading (Scheffler, et al., 2002) which results in decreasing the knee (Ishibashi, et al., 1997). Therefore, the lower laxity of knees repaired using SSSAS compared to the Pull-Out technique in the present study may be the result of decreased length between the fixation point and the tibial insertion site. In particular, higher stiffness of repaired ACL using SSSAS was found in this study (data not shown) which is consistent with findings using a robotic testing system. (Ishibashi, et al., 1997)

From the viewpoint of ACL anatomy, the ACL is known to have two major components, the anteromedial (AM) and posterolateral (PL) bundles, which have different functions in constraining knee motion. With the knee in full extension, the AM and PL bundles run parallel and resist the AP translation. During knee flexion, the AM bundle was tightened and twisted around the slackened PL bundle, therefore, the AM bundle plays the primary role in resisting the anterior tibial load at 90° of knee flexion. A previous study has reported when the reconstructed ACL is placed at the femoral insertion of the AM bundle, the orientation of ACL is close to the central axis of the femur and tibia. (Sakane, et al., 1997) This reduces the capacity to resist externally applied rotational loads. Nevertheless, both Pull-Out and SSSAS techniques used with single bundle repair for the current study. Therefore, the result of no significant difference of AP laxity of repaired ACL (Pull-Out or SSSAS) among different flexion angles may stem from the single bundle repair method.

The result of the present study suggests the SSSAS technique could provide better restoration of ACL function. Nevertheless, there are some limitations to this study. As with most ex vivo studies, this study investigated the effects of fixation methods on the kinematics of knees shortly after surgery. The long-term effects are not able to be gauged in this type of experimental design. Also, further investigations of various methods, such as double-bundle SSSAS and different screw types, are needed to investigate the best approach for ACL surgery.

5. Conclusions

The kinematics of ACL repaired by surgery with two different femoral site fixation techniques was evaluated in this study. Our biomechanical assessment findings indicate that the SSSAS ACL surgical technique has superior performance compared to the conventional Pull-Out technique in restoring ACL function for all three tested tibial rotation positions and had a higher recovery ratio under both pure AP tibial load or combined AP and rotatory loads. Specifically, the experimental data shows smaller mean knee laxity and higher laxity recovery ratio for the SSSAS group which supports the notion that this technique provides better results for ACL repair.

References