学位論文

Effect of fixation angle and graft tension in double-bundle anterior cruciate ligament reconstruction on knee biomechanics
（膝前十字靱帯再建術における靱帯の脛骨固定手技が膝安定性に与える影響について、人屍体膝を用いたバイオメカニクスに関する研究）

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Effect of Fixation Angle and Graft Tension in Double-Bundle Anterior Cruciate Ligament Reconstruction on Knee Biomechanics

Abstract

Purpose To compare the effect of graft fixation angle and tension in double-bundle ACL reconstruction on knee biomechanics.

Methods Fourteen cadaver knees were tested using a robotic system under two loadings: (1) an 89-N anterior tibial load (ATL) at full extension (FE), 15°, 30°, 45°, 60°, and 90°, and (2) combined 7 N·m valgus and 5 N·m internal tibial torques (simulated pivot-shift test) at FE, 15°, 30°. Four graft fixation angles and tensions were used for the anteromedial (AM) and posterolateral (PL) bundles, respectively: (Recon 1) 30°/20N and FE/20N, (Recon 2) 30°/30N and FE/10N, (Recon 3) 45°/20N and 15°/20N, (Recon 4) 45°/30N and 15°/10N.

Results All fixation protocols closely restored the intact knee kinematics under ATL and simulated pivot shift loading. For the AM bundle under ATL, the *in situ* force (ISF) with Recon 3 at the FE was significantly lower than that of the intact knee. For the PL bundle under ATL, the ISF with Recon 3 at the FE, 15° and 30° was significantly higher than that of the intact knee. In PL bundle under simulated pivot shift loading, the ISF with Recon 1 and Recon 2 at FE, was lower and the ISF of the PL bundle with Recon 3 at the 15° was higher than that of the intact knee.

Conclusion The AM-45°/30N and PL-15°/10N fixation most closely matched intact knee kinematics,

however, stabilizing the knee during anterior tibial translation may risk an imbalance of the AM and the PL bundle loading. The results indicate that ACL bundle forces many not be restored even if the clinical assessment shows good results with the Lachman test and pivot-shift test. This may alter the loading on other structures of the knee.

Keywords: Double-bundle, anterior cruciate ligament, graft tension, fixation

Introduction

Anatomical observation has shown that the anterior cruciate ligament (ACL) consists of two bundles, the anteromedial (AM) bundle and posterolateral (PL) bundle [6,11]. Many biomechanical studies have also found that double bundle (DB) ACL reconstruction was better able to restore knee kinematics to that of the native ACL than single-bundle (SB) reconstruction [8,24,27,30,32,33,38,43,46,49]. However, in these studies, the fixation protocol varied widely and there was no consensus on the amount of graft tension applied or the knee flexion angle when the grafts are fixed. Many studies have reported the importance of the tension on the graft during tibial fixation [2,4,5,19,21,25-27,32,35,41,42,47].

In biomechanical laboratory studies, some results showed an effect of graft fixation angle in DB ACL reconstruction on knee kinematics [20,30,33,43]. Miura et al. reported on the biomechanical comparison between two fixation protocols at different knee flexion angles [30]. Their protocol compared the fixation angles of 30° /30° and 60° /full extension (FE) for the AM/PL grafts. They concluded there was an excessive force on the PL bundle with the 30° /30° protocol and an excessive force on the AM bundle with the 60° /full extension (FE) protocol. Vercillo et al. also reported that when the PL graft is fixed at 15° of knee flexion, the AM graft should be fixed between 15° and 45° [43]. However, a three-tunnel procedure with two femoral tunnels and one tibial tunnel was used for DB ACL reconstruction in both studies and the use of the single tibial tunnel may have affected the graft fixation tension. Having the independent tibial tunnels in a four tunnel DB ACL with two femoral tunnels and two tibial tunnels may allow better control of the graft fixation tension [38]. To our knowledge, there are no biomechanical studies that have compared the combinations of fixation angle and tension in a four tunnel anatomical DB ACL reconstruction techniques. Graft fixation is an important factor in ACL reconstruction. The relationship between the effect of fixation angle and tension should be evaluated in the restoration of knee biomechanics.

Some investigators have warned that excessive initial graft tension might lead to abnormal joint stiffness, loss of extension, graft failure, and degeneration of articular cartilage [5,28,29,34,48] and it has been suggested that the PL graft is exposed to excessive force. Otsubo et al. reported that 11% of PL grafts were partially or completely damaged at the femoral tunnel aperture in a clinical study and they suggested that the initial graft tension at the time of graft fixation might be reconsidered to avoid excessive loading of the PL graft [37].

The purpose of this study is to evaluate the effect of different combinations of knee flexion angles and graft tensions for graft fixation in four tunnel anatomical DB ACL reconstruction on knee biomechanics. It is hypothesized that (1) 45°/15° flexion angles for AM and PL bundle fixation will most closely restore the intact ACL bundle force, and (2) 30N/10N graft tensions will be better than 20N/20N graft tensions.

Material and Methods

Fourteen fresh-frozen human cadaveric knees with no evidence of prior injury and a mean age of 56.7±6.8 years (range, 46-65 years) were used in this study. Computed tomography (CT) scans of the specimens were taken and examined to ensure there was no evidence of osteoarthritis or any bony abnormalities. Before testing, the knees were stored at -20°C and thawed overnight at room temperature [31,44]. The surrounding skin and muscles more than 10 cm away from the joint line were removed to allow for mounting and testing. The femur and tibia were cut approximately 20 cm from the joint line and secured within thick-walled custom aluminum cylinders with polyester resin (Bondo®, 3M, USA). The femur was rigidly mounted to a base and the tibia was fixed to a universal force/moment sensor (UFS), (Model 4015, JR3 Inc, Woodland, CA)[9] on the end-effector of the robotic manipulator (CASPAR Stäubli RX90 robot, Orto MAQUET, Germany), that has an accuracy of ±0.2 N and ±0.1 N·m for forces and moments according to the manufacturer.

Using the robotic testing system, the 6-degrees of freedom (dof) knee kinematics, the in-situ forces in the intact ACL, the ACL graft, the AM, and PL bundles and their respective replacement grafts, were measured [9,10,23,39]. Based on the manufacturer specifications, the robotic system is capable of recording and reproducing positions with an accuracy of ±0.02 mm at each joint. The passive path of the intact knee from full extension (FE) to 90° of knee flexion was first determined by the robotic/UFS testing system in 0.5° increments, by minimizing all other forces and moments at each step [40]. This path serves as the reference position from which external loads are applied and kinematics data are collected. Two external loading conditions were tested in all knee states: (1) 89 N anterior tibial load (ATL) at FE, 15°, 30°, 60°, and 90° of knee flexion, and (2) combined rotational loads of 7 N·m of valgus torque and 5 N·m of internal tibial rotation torque at FE, 15° and 30° of knee flexion for a simulated pivot-shift test [17,18,46]. The anterior tibial translation (ATT) was calculated by comparing the tibial antero-posterior positions before and after loading, and *in situ* force of the ACL or ACL graft was also determined by comparing the force of the ACL-intact or DB-reconstructed knee to that of the ACL-deficient knee using the principle of superposition [23,39,40]. The AM and PL bundles of the ACL were separated and transected using a previously described technique, which resulted in two knee states, namely, AM bundle deficient and PL deficient knee [12]. The testing was repeated in ACL-intact, AM bundle deficient (or PL bundle deficient, alternated), ACL-deficient, and four reconstruction knee states. A single surgeon (YS) performed all the ACL reconstructions arthroscopically, and the order was alternated. The semitendinosus and gracilis tendons were chosen as ACL replacement grafts, which were harvested using a tendon stripper from each knee. A double strand semitendinosus tendons and gracilis tendons were used for the AM and the PL grafts, respectively.

Each ACL reconstruction was performed in an anatomic fashion using a 3-portal technique [7]. The femoral and tibial bone tunnel locations of both the AM and PL bundles were determined by the arthroscopic inspection. First, the AM bundle was identified and dissected, then the bone tunnels were created at the center of the insertion site and the same procedure was applied to the PL bundle. These femoral tunnels were created by free pin placement and over-drilling through the accessory medial portal and a direct drill guide (ACUFEX, Smith & Nephew Endoscopy, Andover, MA) was used for tibial tunnels. (Fig. 1) For both grafts, the femoral side was fixed using an extra-cortical button (EndoButton CL, Smith & Nephew, USA) and the tibial side was fixed using two spiked washers and two screws (Arthrex, Naples, FL).

For the first and second fixation protocols, the flexion angles of 30°/FE were selected for AM/PL graft fixations. These angles were selected to simulate a clinical fixation procedure [16]. For the third and fourth fixation protocols, the angles of 45°/15° were selected for AM/PL graft fixation, respectively. These angles were selected to copy a previously reported protocol [43]. In addition, different graft fixation tensions for the AM and PL bundles, 20N/20N and 30N/10N, were used for 30°/FE and 45°/15° protocols in order to investigate the effect of reduced graft tension of the PL bundle [37]. Thus, four fixation protocols were used for the AM/ PL grafts: (Recon 1) 30°/20N and FE/20N, (Recon 2) 30°/30N and FE/10N, (Recon 3) 45°/20N and 15°/20N, (Recon 4) 45°/30N, and 15°/10N. Prior approval was obtained for this study from the University of Pittsburgh Committee for Oversight of Research and Clinical Training Involving Decedents (CORID) # 396.

Statistical Analysis

An a priori power analysis was performed (G*power 3.1.9.2 Dusseldorf, Germany) using significance level of 0.05, a power of 0.80 and based on being able to detect a difference in graft force of 10 N based on previous data [42] and resulted in N = 13.

Statistical analysis of the ATT and in-situ forces was performed using a 2-factor repeated measures analysis of variance (ANOVA) with knee state and knee angle as the factor, followed by Scheffé's post hoc test because all variables were measured on the same specimen and multiple contrasts were performed. The two factors evaluated were the condition of the knee and the knee flexion angle with statistical significance set at $P<0.05$. All tests were performed using SPSS version 18.0 (SPSS Inc, Chicago, Illinois).

Results

In response to the two loadings, the ATT and coupled ATT for all the fixation protocols was not significantly different from the intact knee at the all knee flexion angle (n.s.). (Fig.2)

The *in-situ* force of the AM bundle under ATL with Recon 3 was significantly lower than that of the intact bundle at all flexion angles. (Fig. 3, Fig. 4)

The *in-situ* force of the AM bundle with every reconstruction was significantly lower than that of the intact bundle at every flexion angle other than full extension. Under anterior loading, the *in-situ* force of the PL bundle with Recon 3 at the 0°, 15° and 30° was significantly higher than that of the intact knee

(P=0.02, 0.00 and 0.00, respectively).For the AM bundle under simulated pivot shift loading, the *in-situ* force of each reconstruction at the all angles was significantly lower than the intact bundle (P<0.05). (Fig. 5) For the PL bundle under simulated pivot shift, the ISF of the PL bundle with Recon 1 and Recon 2 at FE was lower than that of the intact knee (P=0.02 and 0.01, respectively) and the *in-situ* force with Recon 3 at the 15° was greater than that of the intact knee (P=0.01).

Discussion

The most important finding of this study is that while different ACL reconstructions can restore knee kinematics and certain fixation protocols can restore the PL bundle *in situ* force, the AM bundle force is more difficult to restore. Vercillo et al. showed that three-tunnel DB reconstruction restored normal knee kinematics in a biomechanical study, [43] while Petersen et al. showed that four-tunnel DB reconstruction more closely restored the intact ACL kinematics than three-tunnel DB reconstruction [38]. This study assessed different combinations of knee flexion angles and graft tensions at fixation in anatomical four-tunnel DB ACL reconstruction.

The *in-situ* force analysis in this study found that the PL graft had a different pattern in each reconstruction. Both the 30°/FE fixation protocols, Recon 1 (30°/20N and FE/20N) and Recon 2 (30°/30N and FE/10N), had a lower PL bundle *in-situ* force than the intact state, while Recon 3 (45°/20N and 15°/20N) gave a higher *in-situ* force than the intact state. Recon 4 (45°/30N and 15°/10N) was able to restore the PL bundle *in-situ* force better than the other reconstructions. Thus, graft fixation with 10N was enough to restore the *in-situ* force of the PL bundle. Mae et al. indicated that anatomic DB ACL reconstruction with a total of 20 N of initial tension yielded good clinical outcomes [26] if the PL graft fixation was tensioned at 10N or less. Thus, depending on the flexion angle, a PL bundle fixation tension of 10 N may be adequate.

For the AM bundle, neither of the reconstructions restored the *in situ* force of the bundle to the intact state under anterior tibial nor simulated pivot shift loading scenarios. The difference in *in situ* forces under simulated pivot shift may indicate that AM bundle should to be fixed at lower flexion angle, as described in some clinical studies, in order to restore the rotational function [15,22]. This result is different from previous studies using ACL reconstruction with three tunnels procedure that found 45°/15° protocol for AM/PL bundle was able to restore the native kinematics of the knee. Therefore, anatomical DB reconstruction may require a different fixation protocol than the three-tunnel procedure. Hoher et al. found that the tibial position at the time of graft fixation was an important factor for ATT and *in-situ* force results during ACL reconstruction and stated that a 67 N posterior tibial load should be applied during graft fixation for normal knee kinematics, which was not done in this study [13]. In this study, the reduced *in situ* force of AM bundle might be caused by the tibial position at the time of graft fixation.

This study found that the *in-situ* force of AM bundle and PL bundle varied by reconstruction, however, all of the fixation protocols reproduced the knee kinematics within 3 mm of those of the intact knee during in response to the two applied loads. With arthrometer testing, ACL deficiency is defined as a side-to-side difference of greater than 3 mm [3]. This discrepancy between restoration of the knee kinematics and *in situ* forces of the ACL was similar to that seen in other studies. Vercillo et al. showed that although statistically significant differences in the *in situ* force were found between their fixation protocols and the intact knee, while the maximum difference in anterior translation of 2.2 mm was still within the clinically acceptable range [43]. A study by Murry et al. showed that normal knee kinematics were restored with both tensioning protocols even though the loading of the individual bundles differed significantly [33]. Yasuda et al. also showed that differences in initial tension applied to the two grafts significantly affected the absolute value of each graft force at each knee flexion angle but did not significantly affect the force versus flexion curve pattern [47].

Some clinical studies have reported that anatomical double-bundle reconstruction resulted in better restoration of knee kinematics than the anatomical single-bundle reconstruction [1,14,16] however; factors other than knee kinematics may affect clinical results. It has been found that re-injury of the reconstructed ACL occurred in 11% of the PL grafts after DB ACL reconstruction, and the authors reasoned that high tension in the PL graft caused this partial rupture in DB ACL reconstruction [37]. The results of the current study suggest that patients who have DB ACL reconstruction may have different AM and PL bundle *in situ* force patterns, even if the clinical evaluation of knee stability is classified as excellent or good. Finally, these findings are an indication of the goals to restore both the anatomy and function of ACL including stability, *in-situ* force pattern and graft tension.

The main limitation of this study is that it is a time zero study and graft healing and graft remodeling under in vivo conditions were not considered. In addition, graft tension can decrease due to repeat loading during testing. Numazaki et al. showed that the peak load of the ACL graft dramatically decreased five thousand cyclic loadings, even though a bone patella bone graft was fixed with interference screws [36]. This effect may need to be considered with the graft tensioning. Furthermore, the cadaver specimens were older than the typical age of ACL injury and differences of in bone quality and ligament properties may affect the results.

This study found that all the tibial fixation protocols reproduced the kinematics of the intact knee during ATT in response to anterior tibial and combined rotatory loads. However, the *in-situ* force of the AM graft was low in all reconstructions and the *in-situ* force of the PL graft had a different pattern in each reconstruction. These results indicate that bundle forces may not be restored after ACL reconstruction, even if the clinical assessment show good result with the Lachman test and pivot-shift test.

Conclusion

In anatomic double bundle ACL reconstruction, using hamstring tendons, fixing the AM graft with 30 N at a knee flexion angle of 45° and the PL graft with 10 N at 15° best restored the intact in situ forces of the bundles under two different loadings among four different fixation protocols.

Conflict of Interest

The authors have no conflict of interest to report.

References:[1-5,7,9-20,22-40,42-48]

1. Araki D, Kuroda R, Kubo S, Fujita N, Tei K, Nishimoto K, Hoshino Y, Matsushita T, Matsumoto T, Nagamune K, Kurosaka M (2011) A prospective randomised study of anatomical single-bundle versus double-bundle anterior cruciate ligament reconstruction: quantitative evaluation using an electromagnetic measurement system. Int Orthop 35 (3):439-446.

2. Arnold MP (2005) The Normal Anterior Cruciate Ligament as a Model for Tensioning Strategies in Anterior Cruciate Ligament Grafts. Am J Sports Med 33 (2):277-283.

3. Bach BR, Jr., Warren RF, Flynn WM, Kroll M, Wickiewiecz TL (1990) Arthrometric evaluation of knees that have a torn anterior cruciate ligament. J Bone Joint Surg Am 72 (9):1299-1306

4. Boylan D, Greis PE, West JR, Bachus KN, Burks RT (2003) Effects of initial graft tension on knee stability after anterior cruciate ligament reconstruction using hamstring tendons: a cadaver study. Arthroscopy 19 (7):700-705.

5. Brady MF, Bradley MP, Fleming BC, Fadale PD, Hulstyn MJ, Banerjee R (2007) Effects of initial graft tension on the tibiofemoral compressive forces and joint position after anterior cruciate ligament reconstruction. Am J Sports Med 35 (3):395-403. doi:10.1177/0363546506294363

6. Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH (2006) Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. J Bone Joint Surg Am 88 Suppl 4:2-10. doi:10.2106/JBJS.F.00616

7. Cohen SB, Fu FH (2007) Three-portal technique for anterior cruciate ligament reconstruction: use of a central medial portal. Arthroscopy 23 (3):325 e321-325. doi:10.1016/j.arthro.2006.07.030

8. Desai N, Bjornsson H, Musahl V, Bhandari M, Petzold M, Fu FH, Samuelsson K (2014) Anatomic single- versus double-bundle ACL reconstruction: a meta-analysis. Knee Surg Sports Traumatol Arthrosc 22 (5):1009-1023.

9. Fujie H, Livesay GA, Woo SL, Kashiwaguchi S, Blomstrom G (1995) The use of a universal force-moment sensor to determine in-situ forces in ligaments: a new methodology. J Biomech Eng 117 (1):1-7

10. Fujie H, Mabuchi K, Woo SL, Livesay GA, Arai S, Tsukamoto Y (1993) The use of robotics technology to study human joint kinematics: a new methodology. J Biomech Eng 115 (3):211-217

11. Girgis FG, Marshall JL, Monajem A (1975) The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res (106):216-231

12. Harner CD, Giffin JR, Dunteman RC, Annunziata CC, Friedman MJ (2001) Evaluation and treatment of recurrent instability after anterior cruciate ligament reconstruction. Instr Course Lect

50:463-474

13. Hoher J, Kanamori A, Zeminski J, Fu FH, Woo SL (2001) The position of the tibia during graft fixation affects knee kinematics and graft forces for anterior cruciate ligament reconstruction. Am J Sports Med 29 (6):771-776
14. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH (2012) Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. Am J Sports Med 40 (3):512-520.
15. Ishibashi Y, Tsuda E, Fukuda A, Tsukada H, Toh S (2008) Intraoperative biomechanical evaluation of anatomic anterior cruciate ligament reconstruction using a navigation system: comparison of hamstring tendon and bone-patellar tendon-bone graft. Am J Sports Med 36 (10):1903-1912.
16. Jarvela T (2007) Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective, randomize clinical study. Knee Surg Sports Traumatol Arthrosc 15 (5):500-507.
17. Kanamori A, Woo SL, Ma CB, Zeminski J, Rudy TW, Li G, Livesay GA (2000) The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test: A human cadaveric study using robotic technology. Arthroscopy 16 (6):633-639.
18. Kanamori A, Zeminski J, Rudy TW, Li G, Fu FH, Woo SL (2002) The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. Arthroscopy 18 (4):394-398
19. Kim SG, Kurosawa H, Sakuraba K, Ikeda H, Takazawa S (2006) The effect of initial graft tension on postoperative clinical outcome in anterior cruciate ligament reconstruction with semitendinosus tendon. Arch Orthop Trauma Surg 126 (4):260-264.
20. Koga H, Muneta T, Yagishita K, Ju YJ, Sekiya I (2012) The effect of graft fixation angles on anteroposterior and rotational knee laxity in double-bundle anterior cruciate ligament reconstruction: evaluation using computerized navigation. Am J Sports Med 40 (3):615-623.
21. Koga H, Muneta T, Yagishita K, Watanabe T, Mochizuki T, Horie M, Nakamura T, Sekiya I (2014) Effect of femoral tunnel position on graft tension curves and knee stability in anatomic double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 22 (11):2811-2820.
22. Kondo E, Yasuda K, Miyatake S, Kitamura N, Tohyama H, Yagi T (2012) Clinical comparison of two suspensory fixation devices for anatomic double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 20 (7):1261-1267. doi:10.1007/s00167-011-1687-6
23. Livesay GA, Fujie H, Kashiwaguchi S, Morrow DA, Fu FH, Woo SL (1995) Determination of the in situ forces and force distribution within the human anterior cruciate ligament. Ann Biomed Eng 23 (4):467-474
24. Mae T, Shino K, Matsumoto N, Hamada M, Yoneda M, Nakata K (2007) Anatomical two-bundle

versus Rosenberg's isometric bi-socket ACL reconstruction: a biomechanical comparison in laxity match pretension. Knee Surg Sports Traumatol Arthrosc 15 (4):328-334.

25. Mae T, Shino K, Matsumoto N, Nakata K, Kinugasa K, Yoshikawa H, Yoneda M (2012) In vivo graft tension in anatomic double-bundle anterior cruciate ligament reconstruction during active leg-raising motion with the knee splinted. Arthroscopy 28 (4):532-538.

26. Mae T, Shino K, Matsumoto N, Natsu-Ume T, Yoneda K, Yoshikawa H, Yoneda M (2010) Anatomic double-bundle anterior cruciate ligament reconstruction using hamstring tendons with minimally required initial tension. Arthroscopy 26 (10):1289-1295.

27. Mae T, Shino K, Miyama T, Shinjo H, Ochi T, Yoshikawa H, Fujie H (2001) Single– versus two– femoral socket anterior cruciate ligament reconstruction technique. Arthroscopy 17 (7):708-716.

28. Mae T, Shino K, Nakata K, Toritsuka Y, Otsubo H, Fujie H (2008) Optimization of graft fixation at the time of anterior cruciate ligament reconstruction. Part I: effect of initial tension. Am J Sports Med 36 (6):1087-1093.

29. Melby A, 3rd, Noble JS, Askew MJ, Boom AA, Hurst FW (1991) The effects of graft tensioning on the laxity and kinematics of the anterior cruciate ligament reconstructed knee. Arthroscopy 7 (3):257-266

30. Miura K, Woo SL, Brinkley R, Fu YC, Noorani S (2006) Effects of knee flexion angles for graft fixation on force distribution in double-bundle anterior cruciate ligament grafts. Am J Sports Med 34 (4):577-585.

31. Moon DK, Woo SL, Takakura Y, Gabriel MT, Abramowitch SD (2006) The effects of refreezing on the viscoelastic and tensile properties of ligaments. J Biomech 39 (6):1153-1157.

32. Muneta T, Koga H, Ju YJ, Yagishita K, Sekiya I (2011) Effects of different initial bundle tensioning strategies on the outcome of double-bundle ACL reconstruction: a cohort study. Sports Med Arthrosc Rehabil Ther Technol 3:15.

33. Murray PJ, Alexander JW, Gold JE, Icenogle KD, Noble PC, Lowe WR (2010) Anatomic double-bundle anterior cruciate ligament reconstruction: kinematics and knee flexion angle-graft tension relation. Arthroscopy 26 (2):202-213.

34. Nabors ED, Richmond JC, Vannah WM, McConville OR (1995) Anterior cruciate ligament graft tensioning in full extension. Am J Sports Med 23 (4):488-492

35. Nicholas SJ (2004) A Prospectively Randomized Double-Blind Study on the Effect of Initial Graft Tension on Knee Stability After Anterior Cruciate Ligament Reconstruction. Am J Sports Med 32 (8):1881-1886.

36. Numazaki H, Tohyama H, Nakano H, Kikuchi S, Yasuda K (2002) The effect of initial graft tension in anterior cruciate ligament reconstruction on the mechanical behaviors of the femur-graft-tibia complex during cyclic loading. Am J Sports Med 30 (6):800-805

37. Otsubo H, Shino K, Nakamura N, Nakata K, Nakagawa S, Koyanagi M (2007) Arthroscopic

evaluation of ACL grafts reconstructed with the anatomical two-bundle technique using hamstring tendon autograft. Knee Surg Sports Traumatol Arthrosc 15 (6):720-728.

38. Petersen W, Tretow H, Weimann A, Herbort M, Fu FH, Raschke M, Zantop T (2007) Biomechanical evaluation of two techniques for double-bundle anterior cruciate ligament reconstruction: one tibial tunnel versus two tibial tunnels. Am J Sports Med 35 (2):228-234.

39. Rudy TW, Livesay GA, Woo SL, Fu FH (1996) A combined robotic/universal force sensor approach to determine in situ forces of knee ligaments. J Biomech 29 (10):1357-1360

40. Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res 15 (2):285-293.

41. Shi D, Zhou J, Yapici C, Linde-Rosen M, Smolinski P, Fu FH (2014) Effect of graft fixation sequence on knee joint biomechanics in double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3158-3

42. van Kampen A, Wymenga AB, van der Heide HJ, Bakens HJ (1998) The effect of different graft tensioning in anterior cruciate ligament reconstruction: a prospective randomized study. Arthroscopy 14 (8):845-850

43. Vercillo F, Woo SL, Noorani SY, Dede O (2007) Determination of a safe range of knee flexion angles for fixation of the grafts in double-bundle anterior cruciate ligament reconstruction: a human cadaveric study. Am J Sports Med 35 (9):1513-1520.

44. Woo SL, Orlando CA, Camp JF, Akeson WH (1986) Effects of postmortem storage by freezing on ligament tensile behavior. J Biomech 19 (5):399-404

45. Xu Y, Liu J, Kramer S, Martins C, Kato Y, Linde-Rosen M, Smolinski P, Fu FH (2011) Comparison of in situ forces and knee kinematics in anteromedial and high anteromedial bundle augmentation for partially ruptured anterior cruciate ligament. Am J Sports Med 39 (2):272-278.

46. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med 30 (5):660-666

47. Yasuda K, Ichiyama H, Kondo E, Miyatake S, Inoue M, Tanabe Y (2008) An in vivo biomechanical study on the tension-versus-knee flexion angle curves of 2 grafts in anatomic double-bundle anterior cruciate ligament reconstruction: effects of initial tension and internal tibial rotation. Arthroscopy 24 (3):276-284.

48. Yoshiya S, Andrish JT, Manley MT, Bauer TW (1987) Graft tension in anterior cruciate ligament reconstruction. An in vivo study in dogs. Am J Sports Med 15 (5):464-470

49. Zaffagnini S, Marcheggiani Muccioli GM, Signorelli C, Lopomo N, Grassi A, Bonanzinga T, Nitri M, Marcacci M (2014) Anatomic and nonanatomic double-bundle anterior cruciate ligament reconstruction: an in vivo kinematic analysis. Am J Sports Med 42 (3):708-715.

Figures

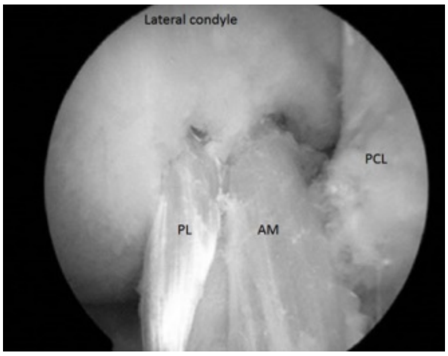

Fig.1 Completed DB-ACLR with knee at 90° of flexion as viewed from the central portal. (AM-anteromedial bundle, PL- posterolateral bundle, PCL- posterior cruciate ligament)

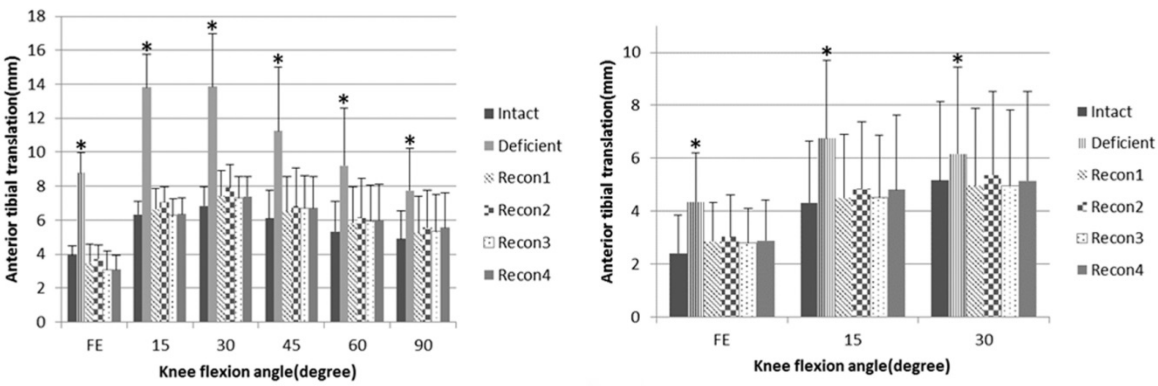

Fig. 2 Anterior tibial translation under an 89-N anterior tibial load (left) and coupled anterior tibial translation (right) under simulated pivot shift load with different knee conditions. (*P<0.05 compared to intact ACL and all reconstructions, FE-full extension, Recon 1: 20N/20N-30°/FE, Recon 2: 30N/10N - 30°/FE, Recon 3: 20N/20N - 45°/15° and Recon 4: 30N/10N - 45°/15°)

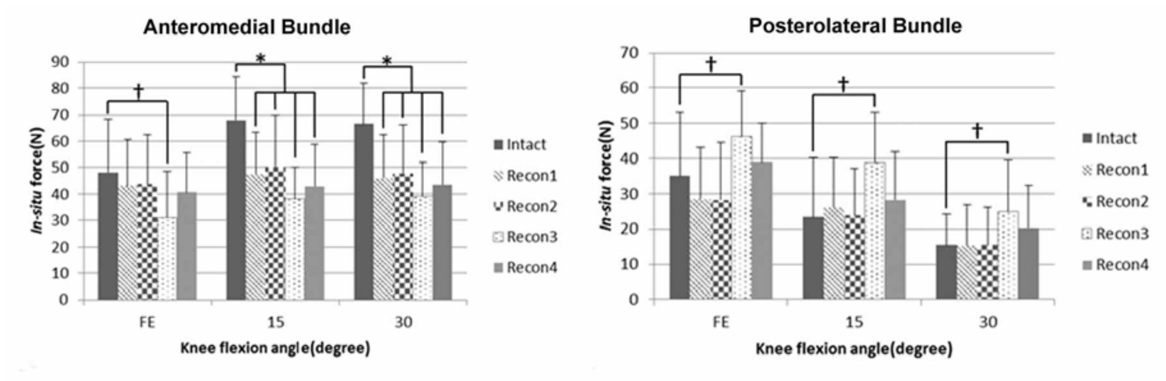

Fig. 3 *In situ* force in the AM (left) and PL (right) bundles in response to an 89 N anterior tibial load at different flexion angles. (*P<0.05 compared to ACL intact, †P<0.05 between ACL intact and Recon 3, FE-full extension, Recon 1: 20N/20N-30°/FE, Recon 2: 30N/10N-30°/FE, Recon 3: 20N/20N-45°/15° and Recon 4: 30N/10N-45°/15°)

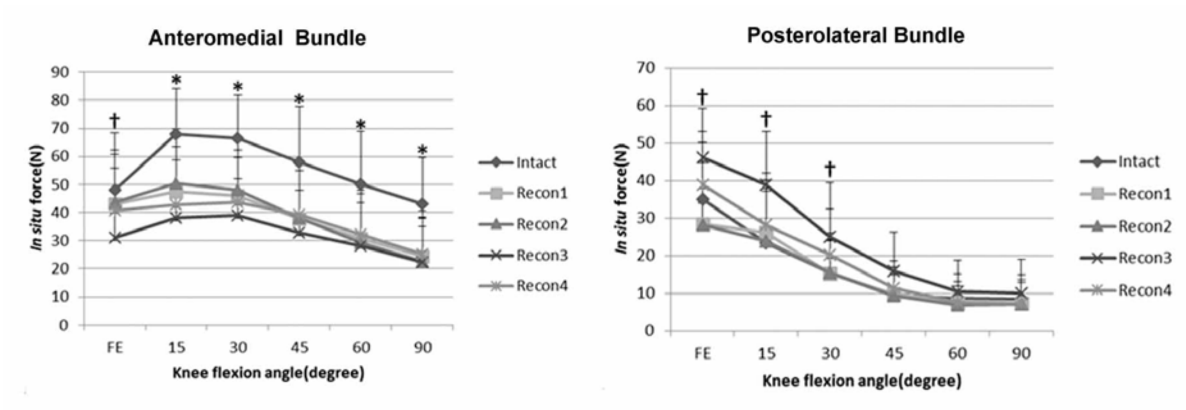

Fig. 4 *In situ* force in AM (left) and PL (right) bundles in response to an 89-N anterior tibial load at the all knee flexion angles (mean ± SD). (*P<0.05 between intact ACL and all reconstructions, †P<0.05 between intact ACL and Recon 3, FE-full extension, Recon 1: 20N/20N-30°/FE, Recon 2: 30N/10N-30°/FE, Recon3: 20N/20N-45°/15° and Recon4: 30N/10N-45°/15°)

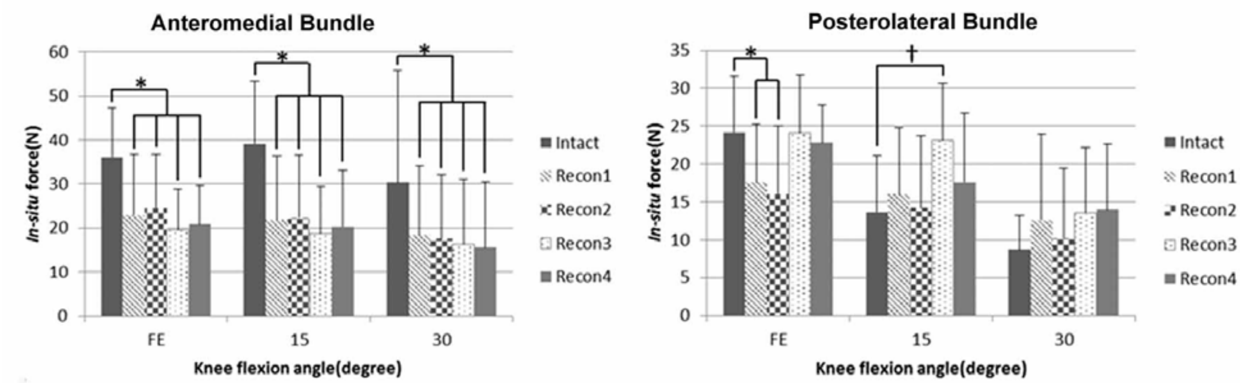

Fig. 5 *In situ* force in AM (left) and PL (right) bundles in response to simulated pivot shift load. (*P<0.05 compared to ACL intact, †P<0.05 between ACL intact and Recon 3, FE-full extension, Recon 1: 20N/20N-30°/FE, Recon 2: 30N/10N-30°/FE, Recon 3: 20N/20N-45°/15° and Recon 4: 30N/10N-45°/15°)