HOKKAIDO UNIVERSITY

Title	Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction
Author(s)	Yasuda, Kazunori; Tanabe, Yoshie; Kondo, Eiji; Kitamura, Nobuto; Tohyama, Harukazu
Citation	Arthroscopy : The Journal of Arthroscopic & Related Surgery, 26(9, Suppl. 1), S21-S34 https://doi.org/10.1016/j.arthro.2010.03.014
Issue Date	2010-09
Doc URL	http://hdl.handle.net/2115/43946
Type	article (author version)
File Information	Art26-9-S1_S21-S34.pdf

Instructions for use

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

Elsevier Editorial System(tm) for Arthroscopy: The Journal of Arthroscopic and Related Surgery

Manuscript Draft

Manuscript Number: ARTH-10-112R1

Title: Current Concepts in Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction

Article Type: Current Concepts

Corresponding Author: Dr. Kazunori Yasuda, M.D., Ph.D.

Corresponding Author's Institution: Hokkaido University School of Medicine

First Author: Kazunori Yasuda, M.D., Ph.D.

Order of Authors: Kazunori Yasuda, M.D., Ph.D.; Yoshie Tanabe, Ph.D., RPT; Eiji Kondo, M.D., Ph.D.; Nobuto Kitamura, M.D., Ph.D.; Harukazu Tohyama, M.D., Ph.D.

Abstract: Several double-bundle anterior cruciate ligament (ACL) reconstruction procedures were reported in the 1980s and 1990s. However, any significant differences were not found in the clinical results between these double-bundle procedures and single-bundle procedures, because these double-bundle procedures appeared to reconstruct only the anteromedial bundle with two bundles. In the early 2000s, the authors proposed a new concept of anatomical reconstruction of the anteromedial and posterolateral bundles, in which 4 independent tunnels were created through the center of each anatomical attachment of the 2 bundles, and they named "anatomic" double-bundle ACL reconstruction. Biomechanical studies have demonstrated that the anatomic double-bundle ACL reconstruction can restore knee stability significantly closer to the normal level than the conventional single-bundle reconstruction. Recent intra-operative measurement studies have showed that the clinically available anatomic double-bundle procedures can reconstruct knee stability significantly better and improve knee function close to the normal level at the time immediately after surgery than the conventional single-bundle procedures. However, the greatest criticism for the anatomic double-bundle reconstruction is whether the clinical results of anatomic double-bundle reconstruction are better than the results of single-bundle reconstruction. Currently, 10 prospective comparative clinical trials (Level I or II) and one meta-analysis have been reported to date (January, 2010) in order to compare single-bundle and anatomic double-bundle reconstructions using the hamstring tendons. In 8 out of the 10 papers, the anterior and/or rotatory stability of the knee was significantly better in the anatomic double-bundle ACL reconstruction than the conventional single-bundle reconstruction. However, one original trial and one meta-analysis indicated that there were no differences in the results between the two types of reconstructions. Thus, the utility of the anatomic double-bundle reconstruction has not been established as of yet. Our systematic review shows how much evidence exists as to the benefits of double-bundle ACL reconstruction at the present time.

Current Concepts

Current Concepts in Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction

Kazunori Yasuda, M.D., Ph.D., Yoshie Tanabe, Ph.D., R.P.T., Eiji Kondo, M.D., Ph.D., Nobuto Kitamura, M.D., Ph.D., and Harukazu Tohyama, M.D., Ph.D.

From the Department of Sports Medicine and Joint Surgery, Hokkaido University School of Medicine, Sapporo, Japan.

Address correspondence to: Kazunori Yasuda, M.D., Ph.D., Department of Sports Medicine and Joint Reconstruction Surgery, Hokkaido University School of Medicine, Kita-15 Nishi-7, Kita-ku, Sapporo, 060-8638, Japan. Tel: +81-11-706-7211, Fax: +81-11-706-7822, E-mail: yasukaz@med.hokudai.ac.jp

The authors declare that they have no potential conflicts of interests. The authors have received no financial support to write this review paper.

Current Concepts in Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction

Abstract: Several double-bundle anterior cruciate ligament (ACL) reconstruction procedures were reported in the 1980s and 1990s. However, no significant differences were found in the clinical results between these double-bundle procedures and single-bundle procedures because these double-bundle procedures appeared to reconstruct only the anteromedial bundle with two bundles. In the early 2000s, the authors proposed a new concept of anatomic reconstruction of the anteromedial and posterolateral bundles, in which 4 independent tunnels were created through the center of each anatomic attachment of the 2 bundles. They named it "anatomic" double-bundle ACL reconstruction. Biomechanical studies have shown that the anatomic double-bundle ACL reconstruction can restore knee stability significantly closer to the normal level than the conventional single-bundle reconstruction. Recent intraoperative measurement studies have showed that the clinically available anatomic double-bundle procedures can reconstruct knee stability significantly better and improve knee function close to the normal level at the time immediately after surgery than the conventional single-bundle procedures. However, the greatest criticism of the anatomic double-bundle reconstruction is whether the clinical results of anatomic double-bundle reconstruction are better than the results of single-bundle reconstruction. Currently, 10 prospective comparative clinical trials

(Level I or II) and 1 meta-analysis have been reported to date (January, 2010) that compare single-bundle and anatomic double-bundle reconstructions using hamstring tendons. In 8 of the 10 studies, the anterior and/or rotatory stability of the knee was significantly better in the anatomic double-bundle ACL reconstruction than the conventional single-bundle reconstruction. However, 1 original trial and the meta-analysis found that there were no differences in the results between the 2 types of reconstructions. Thus, the utility of the anatomic double-bundle reconstruction has not yet been established. Our systematic review shows how much evidence exists as to the benefits of double-bundle ACL reconstruction at the present time.

Introduction

Several double-bundle anterior cruciate ligament (ACL) reconstruction procedures were reported in the 1980s and 1990s. Concerning these procedures, however, no significant differences were found in the clinical results between single- and double-bundle procedures, as is described later in detail. In the early 2000s, since Yasuda et al.[1,2] reported a new concept of anatomic reconstruction of the anteromedial (AM) and posterolateral (PL) bundles of the ACL with the 2-year clinical results superior to conventional single-bundle ACL reconstruction, a number of anatomic, biomechanical, and clinical studies on the anatomic double-bundle reconstruction procedures have been conducted in the field of ACL

reconstruction, and several clinical trials have found that postoperative knee stability is superior in the anatomic double-bundle reconstruction compared with conventional single-bundle reconstruction. However, the utility of the anatomic double-bundle reconstruction has not yet been established. Our purpose in this article is to review how much evidence exists as to the benefits of double-bundle ACL reconstruction at the present time.

HISTORY OF ANATOMIC DOUBLE-BUNDLE ACL RECONSTRUCTION

In 1983, Mott[3] described the first double-bundle procedure, although he did not show where he created the intra-articular outlets of the 2 tunnels in the femur or the tibia. Zaricznyj[4] reported on a double-bundle procedure, in which 2 tibial tunnels and 1 femoral tunnel were created, in 1987. In the 1990s, the so-called “isometric” point was found for femoral tunnel creation in single-bundle ACL reconstruction, and results of single-bundle reconstruction improved greatly. In 1994, a technical manual produced under the advice of Rosenberg and Graf[5] displayed a few important drawings on an arthroscopically assisted double-bundle procedure using 2 femoral and 1 tibial tunnels, although the manual was not a scientific paper. According to these illustrations, the 2 femoral tunnels were created between the 11:00 and 12:00 o’clock positions (Fig 1). In 1999, Muneta et al.[6] improved on this procedure by creating 2 tunnels in the tibia (Fig 2). They described that the 2 femoral tunnels

were created at the 10:30 and 11:30 (or 12:30 and 1:30) o'clock orientations, respectively. Hereafter, several technical papers on double-bundle ACL reconstruction procedures were published.[7-12] However, concerning the clinical results of these double-bundle ACL reconstruction procedures, there were no clinical reports in the 1980s and 1990s. In the early 2000s, only a few clinical papers were published to evaluate the double-bundle procedures. Hamada et al.[13] and Adachi et al.[14] showed that there were no statistically significant differences in subjective results or measured knee stability between their single- and double-bundle procedures. In these studies, however, no surgeons described how to identify the center of the normal PL bundle attachment on the lateral femoral condyle in a surgical visual field, or how to anatomically reconstruct the PL bundle. Thus, the concept of double-bundle ACL reconstruction performed in the 1980s and 1990s did not include the concept of anatomic reconstruction of the PL bundle but rather meant to reconstruct the AM bundle with 2 bundles. Therefore, we should distinguish the double-bundle reconstruction performed in the 1980s and 1990s from the anatomic double-bundle reconstruction, in which the PL bundle is anatomically reconstructed (Fig 3).

On the other hand, clinical results of single-bundle ACL reconstruction greatly improved in the 1980s and 1990s. For example, almost of all patients returned to their previous sports after ACL reconstruction. The Lysholm score was restored to the normal level postoperatively; 70% to 85% of patients who underwent single-bundle ACL reconstruction

77 are evaluated as “normal” under the International Knee Documentation Committee (IKDC)
78 evaluation criteria. However, all the “normal” knees evaluated with the IKDC criteria, which
79 have anterior tibial translation of less than 3 mm, do not indicate a completely normal knee
80 without any ACL injury. Biomechanically, Woo et al.[15] reported that single-bundle
81 reconstruction with either of the 2 grafts has no significant effects on rotatory instability due
82 to ACL insufficiency. In addition, recent kinetic studies with patients who underwent
83 single-bundle ACL reconstruction have found that single-bundle ACL reconstruction with
84 either the bone-patellar tendon-bone or hamstring grafts cannot restore tibial rotation to
85 normal levels, not only during high-stress activities but also during low-stress activities, such
86 as walking.[16-21] Thus, we can say that abnormal knee stability remains a problem after
87 single-bundle ACL reconstruction. The degree of the abnormality appears to be small but
88 significant, because the abnormal laxity may induce meniscus injury, cartilage injury, and
89 osteoarthritis in the late phase after surgery. Actually, it remains unknown whether
90 single-bundle ACL reconstruction can successfully prohibit meniscus injury, cartilage injury,
91 and osteoarthritis in the long-term clinical results. We should note that an essential aim of
92 ACL reconstruction is to restore normal knee stability.
93 In 2003 and 2004, Yasuda et al.[1,2] reported the first anatomic reconstruction
94 procedure of the AM and PL bundles with the 2-year follow-up results, in which the 2
95 bundles were reconstructed with 4 independent tunnels created at the center of the 4 normal

attachments (Fig 3), and named it “anatomic” double-bundle ACL reconstruction.[1,22] Harner and Poehling[23] clearly pointed out the originality, importance, and concerns of this new surgical concept. Since then, a number of anatomical[24-27] and technical papers[28-34] on the anatomic double-bundle ACL reconstruction have been published. Concerning the clinical results of the anatomic double-bundle ACL reconstruction, a total of 11 prospective comparative clinical trials (Level I or II evidence) [35-45] that compared conventional single-bundle and anatomic double-bundle reconstruction procedures using hamstring tendons were available for review as of January, 2010. Nine of the 11 papers reported that their anatomic double-bundle ACL reconstruction showed better knee stability than their anatomic single-bundle ACL reconstruction without any adverse effects on the other clinical measures. However, 1 clinical trial and 1 meta-analysis indicated that there were no differences in any clinical evaluations. Thus, the utility of anatomic double-bundle reconstruction still remains controversial.

FUNCTIONS OF THE 2 BUNDLES OF THE NORMAL ACL

The ACL is functionally composed of the AM and PL bundles.[46] As fundamental knowledge for the anatomic double-bundle ACL reconstruction, it is important to understand functions of the 2 bundles of the normal ACL. Biomechanical studies have shown that the 2

bundles of the ACL have different functions during knee flexion-extension motion.[47-49] According to Kurosawa et al.,[47] the AM bundle is stretched in the full extension position, relaxed at 20° to 60° of knee flexion, and again stretched in a flexion position of more than 90°. The PL bundle is stretched more in the full extension position than the AM tunnel, while it is gradually relaxed during knee flexion and becomes slack in a flexion position of more than 90° (Fig 4). In response to an anterior tibial load, Sakane et al.[50] reported that the magnitude of the in situ force in the PL bundle was larger than that in the AM bundle at knee flexion angles between 0° and 45°, and Gabriel et al.[51] described that, under a combined rotatory load, the PL bundle is as important as the AM bundle, especially when the knee is in the near extension position. Recently, Zantop et al.[52] showed that isolated resection of the PL bundle significantly increases anterior tibial translation at 30° of knee flexion and combined rotation at 0° and 30°, compared with the intact knee and isolated resection of the AM bundle. That is, rupture of the ACL increases both anterior translation and internal rotation, resulting in a large movement of the mobile lateral tibial plateau.

BIOMECHANICAL COMPARISONS USING CADAVER KNEES BETWEEN SINGLE- AND DOUBLE-BUNDLE RECONSTRUCTIONS

Recently, a few biomechanical studies using a robotic manipulator have compared

the double-bundle reconstruction with the conventional single-bundle ACL reconstruction.[53-56] Yagi et al.[54] reported that anterior tibial translation after anatomic double-bundle reconstruction using 2 femoral tunnels and 1 tibial tunnel was significantly less than that after single-bundle reconstruction at full extension and 30° of knee flexion, although the translation values were significantly greater than those of the intact knee in both the reconstructions. They also showed that, under combined rotatory loads of internal tibial torque and valgus torque, the coupled anterior tibial translation after the anatomic reconstruction was significantly less than that of the single-bundle reconstruction at both 15° and 30° of flexion angles, although the translation values were significantly greater than those of the intact knee in both the reconstructions. Petersen et al.[55] showed that anatomic reconstruction with 2 tibial tunnels produced a better biomechanical outcome concerning both the anterior tibial translation and the in situ force at 0° and 30° of flexion, under both a 134-N anterior load and an internal rotatory and valgus torque applied to the tibia using a robotic manipulator. These studies concluded that the anatomic double-bundle reconstruction produces a better biomechanical outcome, especially during rotatory loads, compared with the conventional single-bundle reconstruction. Recently, Tsai et al.[57] compared knee motion between their single- and double-bundle procedures, and reported that the double-bundle procedure showed significantly greater improvement in restoring normal rotational knee motion against a coupled moment (5-Nm internal rotation and 10-Nm valgus) at 20°, 30°, and

153 60° of flexion, compared with the single-bundle procedure.

154 In addition, Belisle et al.[58] compared strain patterns of the bundles reconstructed
155 with single- and double-bundle procedures with the normal bundles of the ACL. They
156 showed that double-bundle reconstruction more closely replicated natural ACL strain patterns
157 than the single-bundle reconstruction, while the single-bundle reconstruction closely
158 simulated only normal AM bundle strain pattern. Morimoto et al.[59] compared the tibiofemoral
159 contact area and pressure under a 1,000-N axial load between single- and double-bundle ACL
160 reconstruction procedures. They concluded that, when compared with the intact knee,
161 double-bundle reconstruction showed no significant difference in the tibiofemoral contact
162 area and pressure, whereas single-bundle reconstruction had a significantly smaller contact
163 area on the lateral and medial tibiofemoral joints at 15° and 30° of flexion and significantly
164 higher pressures at 15° of flexion.

165 Thus, the biomechanical studies have demonstrated that the anatomic double-bundle
166 ACL reconstruction produces knee function (including stability) significantly closer to the
167 normal knee than the conventional single-bundle procedures. Recently, however, a few
168 biomechanical studies evaluated newly developed single-bundle ACL reconstruction
169 procedures in comparison with anatomic double-bundle procedures. Yamamoto et al.[56]
170 compared the laterally placed single-bundle reconstruction in which a femoral tunnel was
171 placed at the center of the anatomic attachment of the PL bundle with the anatomic

double-bundle reconstruction. The anterior tibial translation in the anatomic double-bundle reconstruction is significantly less than that in the laterally placed single-bundle reconstruction at 60° and 90° of knee flexion ($P < .05$), although there were no significant differences at full extension and 15° and 30° of knee flexion. However, it should be noted that the clinical results of the laterally placed single-bundle reconstruction has not yet been reported.

EVALUATIONS OF RELIABILITY OF CLINICAL PROCEDURES

In biomechanical studies with cadaver knee specimens, anatomic double-bundle ACL reconstruction can be precisely performed because an investigator can easily observe the anatomic attachment of the ACL. However, it is difficult for a surgeon to precisely perform it in arthroscopic-assisted surgery. Therefore, we should ask whether each clinical procedure for anatomic double-bundle ACL reconstruction can successfully reconstruct 2 bundles with nearly normal functions as shown in the biomechanical studies with cadavers. Recently, several intraoperative measurement studies using a navigation system or a specially designed system to measure graft tension have been reported.[60-63] For example, Ishibashi et al.[60] and Seon et al.[63] evaluated the intraoperative laxity of the knee using a navigation system, and described that double-bundle reconstruction significantly improved knee laxity compared

191 with either PL or AM bundle reconstruction throughout range of knee motion. Yasuda et al.[62]
192 measured graft tension of the AM and PL grafts during their anatomic double-bundle ACL
193 reconstruction using strain gauge–type tensiometers attached at the end of the suture. The
194 tension-versus-flexion curve pattern of each graft was similar to the normal one (Fig 5).
195 Namely, the curve of the AM suture graft indicated that the tension was highest at full
196 extension and then relaxed with knee flexion between 0° and 30°. The curve then showed a
197 plateau between 30° and 90°, and the tension gradually increased thereafter. On the other
198 hand, the curve of the PL suture graft showed that the tension was highest at full extension
199 and gradually relaxed with knee flexion between 0° and 90°. The tension increased thereafter.
200 The initial tension significantly affected the absolute values of each graft tension at each knee
201 flexion angle, but did not significantly affect the curve patterns. Thus, these studies suggested
202 that the clinical anatomic double-bundle procedures can reconstruct the knee having
203 biomechanical functions closer to the normal range than single-bundle reconstruction, if
204 surgeons have sufficient surgical skills to precisely perform the appropriate anatomic
205 double-bundle procedures.

206 In addition, the clinical results of ACL reconstruction are affected by the tunnel
207 position not only in double-bundle procedures but also in single-bundle procedures. For
208 example, Kanaya et al.[64] intra-operatively evaluated their “lower femoral tunnel–placed”
209 single-bundle procedure and double-bundle procedure using a navigation system, and

reported that no significant differences were found between the 2 groups in anteroposterior displacement and total range of tibial rotation at 30° and 60° of knee flexion. Thus, the intraoperative evaluation is useful for surgeons to clarify the initial effect of their surgery on the knee stability.

CLINICAL COMPARISONS BETWEEN ANATOMIC DOUBLE-BUNDLE RECONSTRUCTION AND SINGLE-BUNDLE RECONSTRUCTION

The greatest criticism of the anatomic double-bundle reconstruction is whether the clinical results of anatomic double-bundle reconstruction are better than the results of single-bundle reconstruction. Currently, 10 prospective comparative clinical trials with Level I or II evidence and 1 meta-analysis have been reported to date (January 2010) compare conventional single-bundle and various types of anatomic double-bundle reconstructions using the hamstring tendons (Tables 1-3).[35-45] In 2006, Yasuda et al.[35] reported the first prospective comparative study to compare their anatomic double-bundle procedure with their single-bundle and non-anatomic double-bundle procedures using 72 patients (Fig 6). The side-to-side anterior laxity was significantly less in the anatomic double-bundle group than in the single-bundle group, although there was no significant difference between the non-anatomic double-bundle and single-bundle groups (Fig 6). Concerning the pivot-shift test,

the anatomic double-bundle group was significantly superior to the single-bundle group. There were no significant differences in the IKDC evaluation, the range of knee motion, and the muscle torque. Between 2007 and 2009, the following 10 papers reported that knee stability measured with the KT arthrometer and/or pivot-shift testing was significantly better in their anatomic double-bundle reconstruction procedures with the hamstring tendon graft than their single-bundle reconstruction procedures (Table 3).

In 2007, Aglietti et al.[36] reported that their 2-incision anatomic double-bundle reconstruction was significantly superior to their single-bundle reconstruction not only in both the anterior laxity and the pivot-shift test but also in the IKDC evaluation (Table 3). There were no significant differences in the other clinical evaluations. Muneta et al.[39] also reported that their anatomic double-bundle group was significantly superior to their single-bundle group in both the side-to-side anterior laxity and the pivot-shift test results. There were no significant differences between the 2 groups in the other clinical measures (Table 3). Yagi et al.[37] found that their double-bundle reconstruction was significantly better in the pivot-shift test than 2 types of their single-bundle procedures, using the electromagnetic measurement system (Table 3). There were no differences in the other clinical evaluations. Jarvela[38] described that the double-bundle group was significantly better in the pivot-shift test than the single-bundle group, while there were no differences in the other clinical evaluations (Table 3). It was noted that none of their patients in the

248 double-bundle group had graft failure, whereas 4 patients in the single-bundle group did. In
249 2008, Kondo et al.[43] reported a large prospective comparative study using 328 patients, in
250 which their anatomic double-bundle group was significantly superior to the single-bundle
251 group in the anterior laxity and the pivot-shift test (Table 3). There were no significant
252 differences in the other clinical evaluations or the rate of complications. According to Jarvela
253 et al.,[40] the patients in the single-bundle groups had more graft failures than those in the
254 anatomic double-bundle group (Table 3). Rotational stability, as evaluated by the pivot-shift
255 test, was significantly better in patients with the double-bundle technique than in those with
256 the single-bundle techniques at the 1-year follow-up ($P = .005$). The P value decreased to P
257 = .078 at the 2-year follow-up. The double-bundle group had significantly better result than
258 the single-bundle group with metallic screw fixation ($P < 0.05$), although the difference to the
259 single-bundle group with bioabsorbable screw fixation was not significant. However, if the 7
260 failures with revision ACL surgery (5 in the single-bundle group with bioabsorbable screw
261 fixation group) were included in the statistical analysis of the study, the double-bundle group
262 would have significantly better results than the single-bundle group with bioabsorbable screw
263 fixation ($P < .05$). No significant differences were found between the groups in knee scores.
264 Siebold et al.[41] described that the pivot-shift test result was significantly better in their
265 double-bundle procedure than in their single-bundle procedure, and the objective IKDC score
266 was significantly higher for the former procedure than for the latter (Table 3). In addition,

graft failure occurred in 4 patients in the single-bundle group, while there were no patients with graft failure in the double-bundle group. However, the *P* value of the anterior knee laxity (*P* = .054) was slightly lower than a significance level. There were no differences in the other clinical evaluations. Most recently, Aglietti et al.[45] reported that their double-bundle reconstruction showed significantly better results in measurement with the KT-2000 arthrometer and evaluation with the visual analogue scale and the objective IKDC score compared with their single-bundle reconstruction, whereas no differences between the 2 groups were observed in the pivot-shift test (Table 3).

On the other hand, Streich et al.[42] reported that no statistical differences were found in all the clinical evaluations, including the anterior laxity or the pivot-shift test, between single- and anatomic double-bundle reconstructions (Table 3).[42] Recently, Meredick et al.[44] performed a meta-analysis using 4 randomized clinical trials[14,38-40] to compare single- and double-bundle reconstruction procedures. On average, KT-1000 arthrometer side-to-side difference was 0.52 mm closer to the normal level in patients treated with double-bundle reconstruction. There was no statistical difference in the odds of having a normal or nearly normal pivot-shift result in patients treated with double-bundle versus single-bundle reconstruction. However, it is noted that this study appeared to include both the anatomic and non-anatomic double-bundle reconstructions.

DISCUSSION

Biomechanical studies have found that the anatomic double-bundle ACL reconstruction can restore knee stability significantly closer to the normal level than the conventional single-bundle reconstruction. Intraoperative measurement studies showed that the clinically available anatomic double-bundle procedures can reconstruct knee stability significantly better and improve knee function close to the normal level at the time immediately after surgery than the conventional single-bundle procedures. However, we should note that the grafted tendon tissues are necrotized at first in any type of ACL reconstruction and then revascularized with mechanical deterioration. Therefore, short- and long-term follow-up studies are essential to evaluate the clinical utility of the anatomic double-bundle reconstruction. In 9 of the 10 previously published original trials using the hamstring tendons, the anterior and/or rotatory stability of the knee was significantly better in the anatomic double-bundle ACL reconstruction than the conventional single-bundle reconstruction (Table 1). In addition, Kondo et al.[65] morphologically evaluated the grafted tendons in 136 patients using postoperative second-look arthroscopy (Fig 7). At 1 year after their anatomic double-bundle ACL reconstruction, the AM bundle was evaluated as excellent in 79.5% of the knees, fair in 16.7%, and poor in 3.8% and the PL bundle was evaluated as excellent in 75.8%, fair in 21.2%, and poor in 3.0%. However, 1 original trial and 1 meta-analysis study

reported that there were no differences in the results between the 2 types of reconstructions. Thus, we have to say that there still remain many controversies on this issue.

In the actual clinical field, one of the most significant factors affecting the clinical outcome is the surgical skill of the surgeon who performs anatomic double-bundle ACL reconstruction. It is most essential in anatomic double-bundle ACL reconstruction to create 4 independent tunnels at the center of the 4 anatomic attachments of the AM and PL bundles, respectively.[1] Therefore, orthopaedic surgeons who intend to perform the anatomic double-bundle ACL reconstruction should sufficiently train their surgical skill to perform the essence. In previous reports, tunnel creation techniques for the anatomic PL bundle reconstruction are classified into a few different types: the transtibial tunnel technique, the transportal technique, and the double-incision outside-in technique. In each technique, it is possible for surgeons to create 4 independent tunnels at the center of the 4 anatomic attachments of the AM and PL bundles, respectively. However, the above-described 3 techniques have both advantages and disadvantages. Therefore, orthopaedic surgeons are required to master these techniques and understand both the advantages and the disadvantages.

In the previously published reports, the magnitude of the improvement of knee stability by the anatomic double-bundle reconstruction using the hamstring tendons, compared with the single-bundle reconstruction, is 1 to 2 mm on average (Table 3). A

criticism of this fact is that an average of only 1- to 2-mm of improvement may provide no clinical benefit to the patient. Our answer to the criticism is as follows: All patients with ACL insufficiency hope to have complete restoration of normal knee stability and function. Therefore, a final goal of ACL reconstruction should be the complete restoration of normal knee stability in all patients. Causes of the 1- to 2-mm improvement in average are that, in anatomic double-bundle ACL reconstruction, the IKDC knee stability grade improved from "Nearly normal (3-5 mm)" to "Normal (<3 mm)" in more patients, and that the complete normal stability with 0- to 1-mm side-to-side difference was reconstructed by surgery in more patients, as compared with the single-bundle reconstruction. In addition, anatomic double-bundle reconstruction significantly improved the rotatory stability in comparison with the single-bundle reconstruction. Thus, the anatomic double-bundle reconstruction can provide patients with a higher quality and quantity of knee stability without any loss of the other clinical measures. We believe that that this is a great benefit for patients.

Currently, when we attempt to compare the clinical results among the previously reported studies, we realize that there are some problems: First, many studies did not clearly show the 3-dimensional tunnel positions of the 4 tunnels created in their surgery, although the authors described that they performed an "anatomic" reconstruction. Therefore, readers of each paper cannot correctly evaluate whether the authors performed anatomic double-bundle reconstruction or non-anatomic double-bundle reconstruction. Second, there are so many

technical variations among the reported studies concerning graft fashioning, graft tensioning (angle of knee flexion, magnitude of initial tension, etc.), graft fixing (artificial devices, surgical techniques, and etc), and postoperative management (Tables 1 and 2). These problems have been great obstacles to conducting meta-analytic studies. To solve these problems in the near future, we should urgently establish a new and precise descriptive system, such as transparent 3-demensional computed tomography (Fig 8),[66] to objectively document the above-described critical points performed in each surgical study.[67] In addition, we should establish an advanced system to more precisely measure the anterior and rotatory laxity after ACL reconstruction in the near future. For example, it is needed to develop quantitative measurement tools for the pivot-shift test,[37] clinically available devices to measure in vivo kinematics during athletic activities, and clinical evaluation criteria concerning the secondary injuries of the meniscus and the cartilage that occur in the long-term follow-up examination after ACL reconstruction. Efforts to establish a better evaluation system will advance ACL reconstruction surgery in the near future.

To date, there have been few studies conducted to compare the anatomic double-bundle ACL reconstruction with the single-bundle ACL reconstruction with the bone–patellar tendon–bone graft. In addition, recently, anatomic single-bundle ACL reconstruction procedures have been evaluated.[68] Therefore, we should realize that there remain many controversies in the field of anatomic double-bundle ACL reconstruction. At the

present time, we should not discard any method of single- and anatomic double-bundle reconstructions. Further clinical studies are needed to establish the utility of each procedure. However, we believe that the anatomic double-bundle reconstruction will provide patients with ACL insufficiency, at least an option when considering ACL reconstruction procedures, particularly when the hamstring tendons are used as a graft tissue.

REFERENCES

1. Yasuda K, Kondo E, Ichiyama H, Kitamura N, Tanabe Y, Tohyama H, Minami A. Anatomical reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. *Arthroscopy* 2004;20:1015-1025.

2. Yasuda, K, Kondo E, Ichiyama H, et al. Anatomic reconstruction procedure for the anteromedial and posterolateral bundles of the anterior cruciate ligament. *Kansetsukyo (J Jpn Arthrosc Assoc)* 2003; 28: 17-23.

3. Mott HW. Semitendinosus anatomic reconstruction for cruciate ligament insufficiency. *Clin Orthop Relat Res* 1983;172:90-92.

4. Zaricznyj B. Reconstruction of the anterior cruciate ligament of the knee using a doubled tendon graft. *Clin Orthop Relat Res* 1987;220:162-175.

5. Rosenberg TD, Graf B. Techniques for ACL reconstruction with Multi-Trac drill guide.

381 Mansfield, MA: Acufex Microsurgical Inc, 1994.

382 6. Muneta T, Sekiya I, Yagishita K, Ogiuchi T, Yamamoto H, Shinomiya K. Two-bundle

383 reconstruction of the anterior cruciate ligament using semitendinosus tendon with

384 EndoButtons: Operative technique and preliminary results. *Arthroscopy* 1999;15:618-624.

385 7. Bellier G, Christel P, Colombet P, Djian P, Franceschi JP, Sbihi A. Double-stranded

386 hamstring graft for anterior cruciate ligament reconstruction. *Arthroscopy* 2004;20:890-894.

387 8. Caborn DN, Chang HC. Single femoral socket double-bundle anterior cruciate ligament

388 reconstruction using tibialis anterior tendon: Description of a new technique. *Arthroscopy*

389 2005;21:1273e1-1273e8.

390 9. Franceschi J-P, Sbihi A, Champsaur P. Dual arthroscopic reconstruction of the anterior

391 cruciate ligament using anteromedial and posterolateral bundles. *Rev Chir Orthop*

392 *Reparatrice App Mot* 2002;88:691-697.

393 10. Hara K, Kubo T, Suginoshita T, Shimizu C, Hirasawa Y. Reconstruction of the anterior

394 cruciate ligament using a double bundle. *Arthroscopy* 2000;16:860-864.

395 11. Marcacci M, Molgora AP, Zaffagnini S, Vascellari A, Iacono F, Presti ML. Anatomic

396 doble-bundle anterior cruciate ligament reconstruction with hamstrings. *Arthroscopy*

397 2003;19:540-546.

398 12. Takeuchi R, Saito T, Mituhashi S, Suzuki E, Yamada I, Koshino T. Double-bundle

399 anatomic anterior cruciate ligament reconstruction using bone-hamstring-bone composite

graft. *Arthroscopy* 2002;18:550-555.

13. Hamada M, Shino K, Horibe S, Mitsuoka T, Miyama T, Shiozaki Y, Mae T. Single- versus bi-socket anterior cruciate ligament reconstruction using autogenous multiple-stranded hamstring tendons with EndoButton femoral fixation: A prospective study. *Arthroscopy* 2001;17:801-807.

14. Adachi N, Ochi M, Uchio Y, Iwasa J, Kuriwaka M, Ito Y. Reconstruction of the anterior cruciate ligament. Single- versus double-bundle multistranded hamstring tendons. *J Bone Joint Surg Br* 2004;86:515-520.

15. Woo SL-Y, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH. The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon. *J Bone Joint Surg Am* 2002;84:907-914.

16. Georgoulis AD, Papadonikolakis A, Papageorgiou CD, Mitsou A, Stergiou N. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. *Am J Sports Med* 2003;31:75-79.

17. Ristanis S, Giakas G, Papageorgiou CD, Moraiti T, Stergiou N, Georgoulis AD. The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs. *Knee Surg Sports Traumatol Arthosc* 2003;11:360-365.

18. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament

419 reconstruction. *Arthroscopy* 2005;21:1323-1329.

420 19. Georgoulis, AD, Ristanis S, Chouliaras V, Moraiti C, Stergiou N. Tibial rotation is not

421 restored after ACL reconstruction with a hamstring graft. *Clin Orthop Relat Res*

422 2007;454:89-94.

423 20. Chouliaras V, Ristanis S, Moraiti C, Stergiou N, Georgoulis AD. Effectiveness of

424 reconstruction of the anterior cruciate ligament with quadrupled hamstrings and bone-patellar

425 tendon-bone autografts: An in vivo study comparing tibial internal-external rotation. *Am J*

426 *Sports Med* 2007;35:189-196.

427 21. Tashman S, Kolowich P, Collon D, Anderson K, Anderst W. Dynamic function of the

428 ACL-reconstructed knee during running. *Clin Orthop Relat Res* 2007;454:66-73.

429 22. Yasuda K, Kondo E, Ichiyama H, Ikema Y, Kitamura N, Yoshikawa T, Shu N, Tohyama

430 H. Anatomical reconstruction procedure for the anteromedial and posterolateral bundles of

431 the anterior cruciate ligament. *Kansetsukyo (J Jpn Arthrosc Assoc)* 2003;28:17-23.

432 23. Harner CD, Poehling GG. Double bundle or double trouble? *Arthroscopy*

433 2004;20:1013-1014.

434 24. Dodds JA, Arnoczky SP. Anatomy of the anterior cruciate ligament: A blueprint for

435 repair and reconstruction. *Arthroscopy* 1994;10:132-139.

436 25. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL. Quantitative

437 analysis of human cruciate ligament insertions. *Arthroscopy* 1999;15:741-749.

438 26. Mochizuki T, Muneta T, Nagase T, Shirasawa S, Akita KI, Sekiya I. Cadaveric knee
439 obervation study for describing anatomic femoral tunnel placement for two-bundle anterior
440 cruciate ligament reconstruction. *Arthroscopy* 2006;22:356-361.
441 27. Takahashi M, Doi M, Abe M, Suzuki D, Nagano A. Anatomical study of the femoral and
442 tibial insertions of the anteromedial nd posterolateral bundles of human anterior cruciate
443 ligament. *Am J Sports Med* 2006;34:787-792.
444 28. Aglietti P, Cuomo P, Giron F, Boerger TO. Double-bundle anterior cruciate ligament
445 reconstruction: Surgical technique. *Oper Tech Orthop* 2005;15:111-115.
446 29. Brucker PU, Lorenz S, Imhoff AB. Aperture fixation in arthroscopic anterior cruciate
447 ligament double-bundle reconstruction. *Arthroscopy* 2006;22:1250e1-1250e6.
448 30. Cha PS, Brucker PU, West RV, Zelle BA, Yagi M, Kurosaka M, Fu FH. Arthroscopic
449 double-bundle anterior cruciate ligament recosntruction: An anatomic approach. *Arthroscopy*
450 2005;21:1275e1-1275e8.
451 31. Christel P, Franceschi JP, Sbihi A, Colombet P, Djian P, Bellier G. Anatomic anterior
452 cruciate ligament reconstruction: The French experience. *Oper Tech Orthop*
453 2005;15:103-110.
454 32. Colombet P, Robinson J, Jambou S, Allard M, Bousquet V, de Lavigne C. Two-bundle,
455 four-tunnel anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*
456 2006;14:629-636.

457 33. Kim S-J, Jung K-A, Song D-H. Arthroscopic double-bundle anterior cruciate ligament
458 reconstruction using autogenous quadriceps tendon. *Arthroscopy* 2006;22:797e1-797e5.
459 34. Vidal AF, Brucker PU, Fu FH. Anatomic double-bundle anterior cruciate gament
460 reconstruction using tibialis anterior tendon allografts. *Oper Tech Orthop* 2005;15:140-145.
461 35. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H. Clinical evaluation of anatomic
462 double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon
463 grafts: Comparisons among 3 different procedures. *Arthroscopy* 2006;22:240-251.
464 36. Aglietti P, Giron F, Cuomo P, Losco M, Mondanelli N. Single-and Double-incision
465 Double-bundle ACL Reconstruction. *Clin Orthop Relat Res* 2007;454:108-113.
466 37. Yagi M, Kuroda R, Nagamune K, Yoshiya S, Kurosaka M. Double-bundle ACL
467 reconstruction can improve rotational stability. *Clin Orthop Relat Res* 2007;454:100-107.
468 38. Jarvela T. Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a
469 prospective, randomize clinical study. *Knee Surg Sports Traumatol Arthrosc*
470 2007;15:500-507.
471 39. Muneta T, Koga H, Mochizuki T, Ju YJ, Hara K, Nimura A, Yagishita K, Sekiya I. A
472 prospective randomized study of 4-strand semitendinosus tendon anterior cruciate ligament
473 reconstruction comparing single-bundle and double-bundle techniques. *Arthroscopy*
474 2007;23:618-628.
475 40. Jarvela T, Moisala AS, Sihvonen R, Jarvela S, Kannus P, Jarvinen M. Double-bundle

476 anterior cruciate ligament reconstruction using hamstring autografts and bioabsorbable
477 interference screw fixation: prospective, randomized clinical study with two-year results. *Am*
478 *J Sports Med* 2008;36:290-297.
479 41. Siebold R, Dehler C, Ellert T. Prospective randomized comparison of double-bundle
480 versus single-bundle anterior cruciate ligament reconstruction. *Arthroscopy* 2008;24:137-145.
481 42. Streich NA, Friedrich K, Gotterbarm T, Schmitt H. Reconstruction of the ACL with a
482 semitendinosus tendon graft: a prospective randomized single blinded comparison of
483 double-bundle versus single-bundle technique in male athletes. *Knee Surg Sports Traumatol*
484 *Arthrosc* 2008;16:232-238.
485 43. Kondo E, Yasuda K, Azuma H, Tanabe Y, Yagi T. Prospective clinical comparisons of
486 anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction
487 procedures in 328 consecutive patients. *Am J Sports Med* 2008;36:1675-1687.
488 44. Meredick RB, Vance KJ, Appleby D, Lubowitz JH. Outcome of single-bundle versus
489 double-bundle reconstruction of the anterior cruciate ligament: A meta-analysis. *Am J Sports*
490 *Med* 2008;36:1414-1421.
491 45. Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N. Comparison between
492 single- and double-bundle anterior cruciate ligament reconstruction: A prospective,
493 randomized, single-blinded clinical trial. *Am J Sports Med* 2009;38:25-34
494 46. Girgis FG, Marshall JL, Monajem ARS. The cruciate ligaments of the knee joint.

Anatomical, functional and experimental analysis. *Clin Orthop Relat Res* 1975;106:216-231.

47. Kurosawa H, Yamakoshi K, Yasuda K, Sasaki T. Simultaneous measurement of changes in length of the cruciate ligaments during knee motion. *Clin Orthop Relat Res* 1991;265:233-240.

48. Amis AA, Dawkins GPC. Functional anatomy of the anterior cruciate ligament. Fiber bundle actions and related to ligament replacement and injuries. *J Bone Joint Surg Br* 1991;73:260-267.

49. Back JM, Hull ML, Patterson HA. Direct measurement of strain in the posterolateral bundle of the anterior cruciate ligament. *J Biomechanics* 1997;30:281-283.

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

51. Gabriel MT, Wong EK, Woo SL-Y, Yagi M, Debski RE. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. *J Orthop Res* 2004;22:85-89.

52. Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W. The role of the anteromaedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. *Am J Sports Med* 2007;35:223-227.

53. Mae T, Shino K, Miyama T, Shinjo H, Ochi T, Yoshikawa H, Fujie H. Single- versus two-femoral socket anterior cruciate ligament reconstruction technique: Biomechanical

514 analysis using a robotic simulator. *Arthroscopy* 2001;17:708-716.

515 54. Yagi M, Wong EK, kanamori A, Debski RE, Fu FH, Woo SL. Biomechanical analysis of

516 an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med* 2002;30:660-666.

517 55. Petersen W, Tretow H, Weimann A, Herbort M, Fu FH, Raschke M, Zantop T.

518 Biomechanical evaluation of two techniques for double-bundle anterior cruciate ligament

519 reconstruction: One tibial tunnel versus two tibial tunnels. *Am J Sports Med*

520 2007;35:228-234.

521 56. Yamamoto Y, Hsu WH, Woo SL, Van Scyoc AH, Takakura Y, Debski RE. Knee stability

522 and graft function after anterior cruciate ligament reconstruction. A comparison of a lateral

523 and an anatomical femoral tunnel placement. *Am J Sports Med* 2004;32:1825-1832.

524 57. Tsai AG, Wijdicks CA, Walsh MP, Laprade RF. Comparative kinematic evaluation of

525 all-inside single-bundle and double-bundle anterior cruciate ligament reconstruction: A

526 biomechanical study. *Am J Sports Med* 2009 Dec 4. [Epub ahead of print]

527 58. Belisle AL, Bicos J, Geaney L, Andersen MH, Obopilwe E, Rincon L, Nyland J, Morgan

528 C, Caborn DN, Arciero RA. Strain pattern comparison of double- and single-bundle anterior

529 cruciate ligament reconstruction techniques with the native anterior cruciate ligament.

530 *Arthroscopy* 2007;23:1210-1217.

531 59. Morimoto Y, Ferretti M, Ekdahl M, Smolinski P, Fu FH. Tibiofemoral joint contact area

532 and pressure after single- and double-bundle anterior cruciate ligament reconstruction.

533 *Arthroscopy* 2009;25:62-69.

534 60. Ishibashi Y, Tsuda E, Tazawa K, Sato H, Toh S. Intraoperative evaluation of the

535 anatomical double-bundle anterior cruciate ligament reconstruction with the orthopilot

536 navigation system. *Orthopedics* 2005;28:s1277-s1282.

537 61. Mae T, Shino K, Matsumoto N, Nakata K, Nakamura N, Iwahashi T. Force sharing

538 between two grafts in the anatomical two-bundle anterior cruciate ligament reconstruction.

539 *Knee Surg Sports Traumatol Arthrosc* 2006;14:505-509.

540 62. Yasuda K, Ichiyama H, Kondo E, Miyatake S, Inoue M, Tanabe Y. An in vivo

541 biomechanical study on the tension-versus-knee flexion angle curves of 2 grafts in anatomic

542 double-bundle anterior cruciate ligament reconstruction: Effects of initial tension and internal

543 tibial rotation. *Arthroscopy* 2008;24:276-284.

544 63. Seon JK, Park SJ, Lee KB, Yoon TR, Seo HY, Song EK. Stability comparison of anterior

545 cruciate ligament between double- and single-bundle reconstructions. *Int Orthop*

546 2009;33:425-429.

547 64. Kanaya A, Ochi M, Deie M, Adachi N, Nishimori M, Nakamae A. Intraoperative

548 evaluation of anteroposterior and rotational stabilities in anterior cruciate ligament

549 reconstruction: lower femoral tunnel placed single-bundle versus double-bundle

550 reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2009;17:907-913.

551 65. Kondo E, Yasuda K. Second-look arthroscopic evaluations of anatomic double-bundle

552 anterior cruciate ligament reconstruction: Relationship with the postoperative knee stability.
553 *Arthorscopy* 2007;23:1198-1209.
554 66. Inoue M, Tokuyasu S, Kuwahara S, Yasojima N, Kasahara Y, Kondo E, Onodere S,
555 Yasuda K. Tunnel location in transparent 3-dimentional CT in anatomic double-bundle
556 anterior cruciate ligament reconstructionwith the trans-tibial tunnel technique. *Knee Surg*
557 *Sports Traumatol Arthrosc* 2009 Dec 10. [Epub ahead of print]
558 67. Kondo E, Yasuda K, Ichiyama H, Azuma C, Tohyama H: Radiologic evaluation of
559 femoral and tibial tunnels created with the transtibial tunnel technique for anatomic
560 double-bundle anterior cruciate ligament reconstruction. *Arthroscopy* 23: 869-876, 2007
561 68. Tsuda E, Ishibashi Y, Fukuda A, Tsukada H, Toh S. Comparable results between
562 lateralized single- and double-bundle ACL reconstructions. *Clin Orthop Relat Res*
563 2009;467:1042-1055.
564
565
566 **Legends**
567 Figure 1. Arthroscopically assisted double-bundle procedure using 2 femoral and 1 tibial
568 tunnels. Note that the 2 femoral tunnels were created between the 11:00 and 12:00 o'clock
569 points. (From Rosenberg and Graf,[5] reprinted with permission.)
570

Figure 2. Muneta et al.[6] created 2 tunnels in the tibia. They described that the 2 femoral tunnels were created at the 10:30 and 11:30 (or 12:30 and 1:30) o'clock orientations, respectively. (From Muneta et al.,[6] reprinted with permission.)

Figure 3. The first anatomic reconstruction procedure of the AM and PL bundles, in which the 2 bundles were reconstructed with 4 independent tunnels created at the center of the 4 normal attachments. (A) The attachment of the main fibers of the ACL (dotted line) was in the form of an egg. (AFS, a parallel line of the axis of the femoral shaft). (B) Geometric identification method for PL bundle reconstruction. When we drew a vertical line (VL) through the contact point (C) between the femoral condyle and the tibial plateau at 90° of flexion, the center of the attachment of the PL bundle was located approximately at this crossing point of the VL and the long axis of the ACL attachment (AX: inclined 30° to the AFS). (C) A tunnel for the PL bundle observed from the medial infrapatellar portal in the right knee. (D) Postoperative 3-dimensional computed tomograms of the right knee show that the 2 tunnels were created at the expected positions. (E) Postoperative radiograph after anatomic double-bundle reconstruction. Note that 2 EndoButton positions are different from those of non-anatomic double-bundle reconstruction shown in Fig 2. (From Yasuda et al.,[1] reprinted with permission.)

590 Figure 4. Relative elongation patterns of 4 portions of the ACL measured with implanted
591 elastic transducer.[46] The PL bundle is stretched more in the full extension position than the
592 AM tunnel, while it is gradually relaxed during knee flexion and becomes slack in a flexion
593 position of more than 90°.
594
595 Figure 5. Tension of the AM and PL grafts measured during anatomic double-bundle ACL
596 reconstruction. Note that the tension-versus-flexion curve pattern of each graft was similar to
597 the normal one shown in Fig 4. (From Yasuda et al.,[61] reprinted with permission.)
598
599 Figure 6. The first prospective comparative study to compare their anatomic double-bundle
600 procedure (C) with their single-bundle (A) and non-anatomic double-bundle (B) procedures
601 using 72 patients. The side-to-side anterior laxity was significantly less in the anatomic
602 double-bundle group than in the single-bundle group, although there was no significant
603 difference between the non-anatomic double-bundle and single-bundle groups. The
604 arthroscopic findings (left knees) show that 2 bundle positions of the anatomic double-bundle
605 procedure (C) are different from those of non-anatomic double-bundle procedure (B). (From
606 Yasuda et al.,[2] reprinted with permission.)
607
608 Figure 7. Morphologic evaluation of the grafted tendons using postoperative second-look

609 arthroscopy (right knees). Placement of the (A) AM and (B) PL grafts. (C) Arthroscopic
610 obseration at 1 year after reconstruction. Arthroscopic classification of PL grafts based on
611 synovium coverage: (D) completely covered, (E) partially covered, and (F) almost not
612 covered. (From Kondo et al.,[65] reprinted with permission.)
613
614 Figure 8. Clear visualization of tunnel positions using transparent 3-dimensional computed
615 tomography. (From Inoue et al.,[66] reprinted with permission.)

Tables

Table 1. Differences in procedures for creating anatomic tunnels among Level-I or II clinical trials (Ref. 35-43, 45). The steps shown in the table mean the order to create 4 tunnels.

Authors	Step 1	Step 2	Step 3	Step 4
Yasuda 2006 (Ref. 35) Kondo 2008 (Ref. 43)	Tibial PL tunnel - Special tibial guide developed for transtibial technique	Tibial AM tunnel - Special tibial guide developed for transtibial technique	Femoral AM tunnel - Transtibial technique - 1:30 O'clock position with an offset guide	Femoral PL tunnel - Transtibial technique - Geometric identification method reported in Ref. 1
Aglietti 2007 (Ref. 36)	Tibial AM tunnel - Howell tibial guide	Tibial PL tunnel - Special attacment to the tibial guide	Femoral AM tunnel - 2-incision outside-in technique - @ the lateral wall close to the over the top position with a rear entry guide	Femoral PL tunnel - 2-incision outside-in technique - Drilled 9 mm more shallow and inferior to the AM wire and 5 mm from the inferior cartilage border
Yagi 2007 (Ref. 37)	Femoral PL tunnel - Medial accessory portal technique - Geometric identification method reported in Ref. 1	Tibial AM tunnel - 20 degrees to the tibial axis	Tibial PL tunnel - 45 degrees to the tibial axis	Femoral AM tunnel - Transtibial technique - 1:30 orientation
Jarvela 2007 (Ref. 38) and 2008 (Ref.	Femoral AM tunnel: - Through the AM portal without a guide. - Placed as posterior as possible on the lateral wall, without breaking	Femoral PL tunnel - Through the AM portal without a guide. - Placed anteriorly and inferiorly from the AM tunnel	Tibial AM tunnel - 55-degree tibial guide - The starting point is the same as in standard single bundle technique.	Tibial PL tunnel - 55-degree tibial guide - A more medial starting point with an osseous bridge of ~1–2 cm between these two tunnels

40)	the posterior wall (2:00 O'clock)	- Placed as closed as possible to the AM femoral tunnel, without breaking the wall between these tunnels		
Muneta 2007 (Ref. 39)	Tibial AM tunnel - 65 degrees to the joint line	Tibial PL tunnel - 45 degrees to the joint line	Femoral AM tunnel - Transtibial technique - 1:30 orientation	Femoral PL tunnel - Transtibial technique - 3:30 orientation - 6 mm anteriorly from the posterior edge of the lateral wall.
Siebold 2008 (Ref. 41)	Tibial AM tunnel - 50 degrees to the tibial plateau in the horizontal plane - 1.5 cm medial to the tibial tuberosity in the sagittal plane	Tibial PL tunnel - 45° angle to the tibial plateau in the horizontal plane - 3.5 cm medial to the tibial tuberosity in the sagittal plane	Femoral AM tunnel - Transtibial technique - 4 to 5 mm inferior to the "over-the-top" position	Femoral PL tunnel - Accessorial anteromedial portal technique - 6 to 7 mm arthroscopically posterior to the anterior cartilage
Streich 2008 (Ref. 42)	Tibial PL tunnel - 55-degree angle guide - The tibial starting point: just anterior to the MCL fibers	Tibial AM tunnel - 55-degree angle guide - The starting point: more anterior and central than the PL one	Femoral AM tunnel - Transtibial technique - @ 1:00 o'clock position	Femoral PL tunnel - Transtibial technique - @ 2:30 o'clock position
Aglietti 2010 (Ref. 45)	Tibial AM tunnel - Howell 65° tibial guide	Tibial PL tunnel - Prototype rod guide (8-mm posterior to the center of the AM tunnel)	Femoral AM tunnel - 2-incision outside-in technique - Shino Guide - As deep as possible on the lateral wall below the over-the-top position	Femoral PL tunnel - 2-incision outside-in technique - Prototype rod guide - 9 mm apart and shallow, about 5 mm from the cartilage border

Table 2. Differences in procedures for graft preparation, tensioning, and fixation among Level-I or II clinical trials (Ref. 35-43, 45).

Authors	Graft preparation	Femoral fixation device	Tibial fixation device	Tensioning and fixation
Yasuda 2006 (Ref. 35)	Doubled 1/2 ST/GR	- EndoButton CL	- Tapes / 2 spiked staples	(1) A 40-N load to each tibial end (2) Simultaneous fixation of the 2 grafts at 30°
Aglietti 2007 (Ref. 36)	Single ST+GR	- 6-mm outside-in RCI screw - An additional staple	- Looped around the tibial bony bridge	(1) An unmeasured load to each femoral end (2) First, a PL graft at 10° (3) Then, an AM graft at 45°
Yagi 2007 (Ref. 37)	(1) Doubled ST for the AM (2) Doubled GR for the PL	- EndoButton CL	- Sutures / screw post	(1) An unmeasured load to each ftibial end (2) First, a PL graft at 15° (3) Then, an AM graft at 60°
Jarvela 2007 and 2008 (Ref. 38,40)	(1) Doubled ST for the AM (2) Doubled GR for the PL	- Bioabsorbable screws (inside-out)	- Biodegradable screws	(1) An unmeasured load to each ftibial end (2) First, a PL graft at 0° (3) Then, an AM graft at 30°
Muneta 2007 (Ref. 39)	Doubled 1/2 ST	- EndoButton CL	- Sutures / anchor staple	(1) A 40-N load to each tibial end (2) First, a PL graft at 30° (3) Then, an AM graft at 30°
Kondo 2008 (Ref. 43)	Doubled 1/2 ST	- EndoButton CL	- Tapes / 2 spiked staples	(1) A 30-N load to each tibial end (2) Simultaneous fixation of the 2 grafts at 10°
Siebold 2008 (Ref. 41)	(1) Doubled ST for the AM (2) Doubled GR for the PL	- EndoButton CL	- Biodegradable screws	(1) An unmeasured load to each ftibial end (2) An AM graft at 60° and a PL graft at 20° (The order in fixation was not clearly described)
Streich 2008 (Ref. 42)	Doubled 1/2 ST	- EndoButton CL	- Suture-Discs	(1) A 30-N load to each tibial end (2) First, a PL graft at 20° (3) Then, an AM graft at 50°
Aglietti	Single ST+GR	- 6-mm RCI screw (outside-in)	- Looped around	(1) An unmeasured load to each femoral end

2010 (Ref. 45)	- An additional staple	the tibial bony bridge	(2) First, a PL graft at 20° (3) Then, an AM graft at 40°

Table 3. Postoperative knee stability after ACL reconstruction using hamstring tendons in previously published original studies with the evidence level of I or II. (SB: single-bundle reconstruction, DB: double-bundle reconstruction)

Authors	Patients (pts)	Side-to-side anterior laxity (average)			Negative pivot-shift test		
		SB	DB	Statistics	SB	DB	Statistics
Yasuda et al (2006)	72	2.8 mm	1.1 mm	p=.002	54.2%	87.5%	p=.025
Aglietti et al (2007)	75	2.4	1.4	p<.05	58.3	84.0	p<.05
Muneta et al (2007)	68	2.4	1.4	p<.05	58.8	85.3	p<.05
Yagi et al (2007)	60	1.9	1.3	NS	923[1)]	2400[1)]	p<.05
Jarvela (2007)	55	1.5 [2)]	1.1[2)]	NS	64.0	96.7	p=.002
Kondo et al (2008)	328	2.5	1.2	p<.0001	60.0	81.3	p<.001
Jarvela et al (2008)	77	2.1[3)]	1.3	p<.05	50.0	81.8	p<.05
Siebold et al (2008)	70	1.6	1.0	p=.054	71.4	97.1	p=.01
Streich et al (2008)	49	0.94	1.10	NS	76.0	95.8	NS
Aglietti et al (2009)	70	2.1	1.2	p<.03	65.0	85.0	NS

1) Quantitative pivot-shift test was performed with magnetic sensors, and the acceleration values (unit: mm/s^2) were shown in the table. The values were calculated from the graph in the original paper.

2) The laxity values were calculated from the graph in the original paper.

3) This value did not include the laxity in the knees with graft failure

Figure 1

Click here to download high resolution image

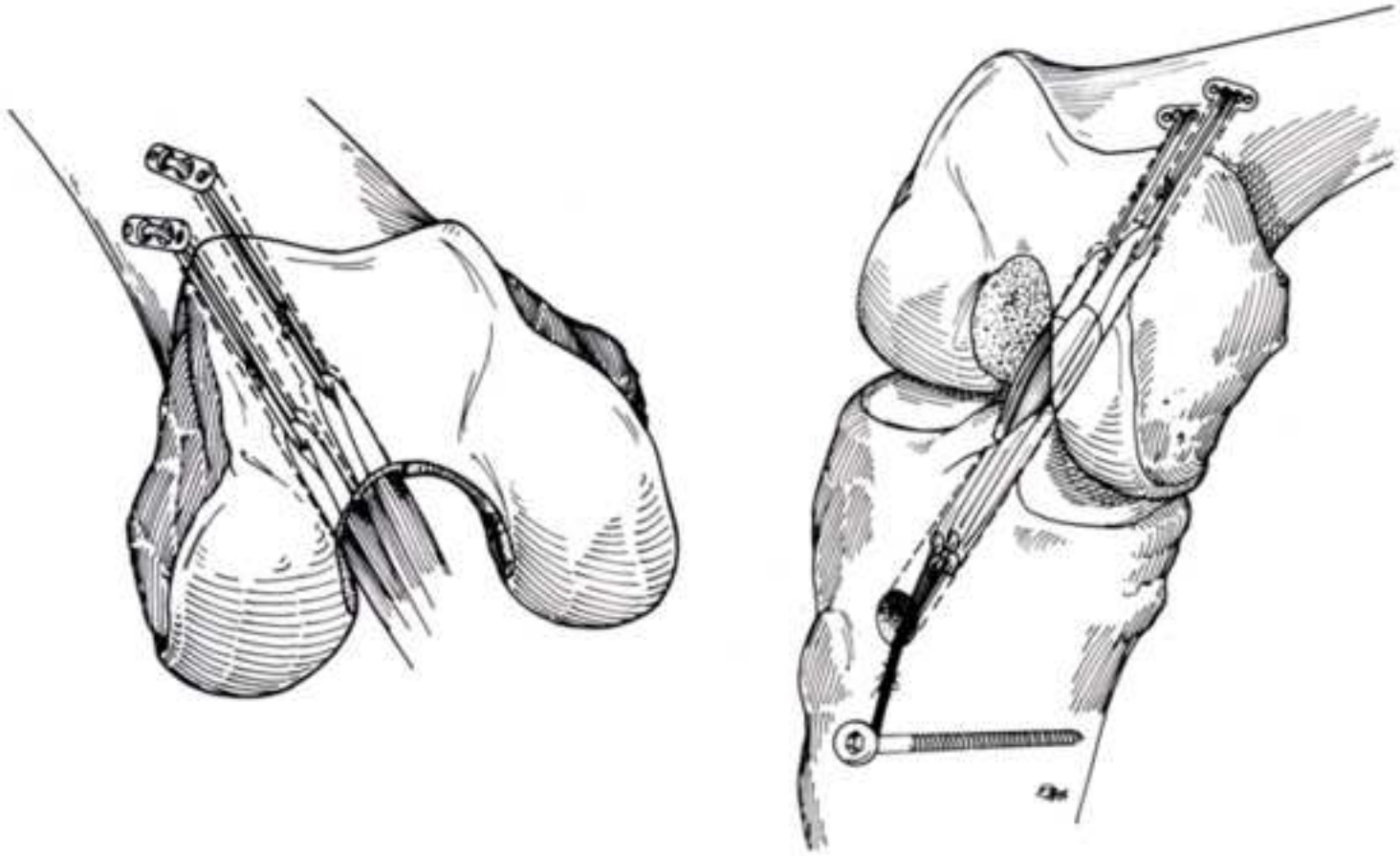

Figure 2

Click here to download high resolution image

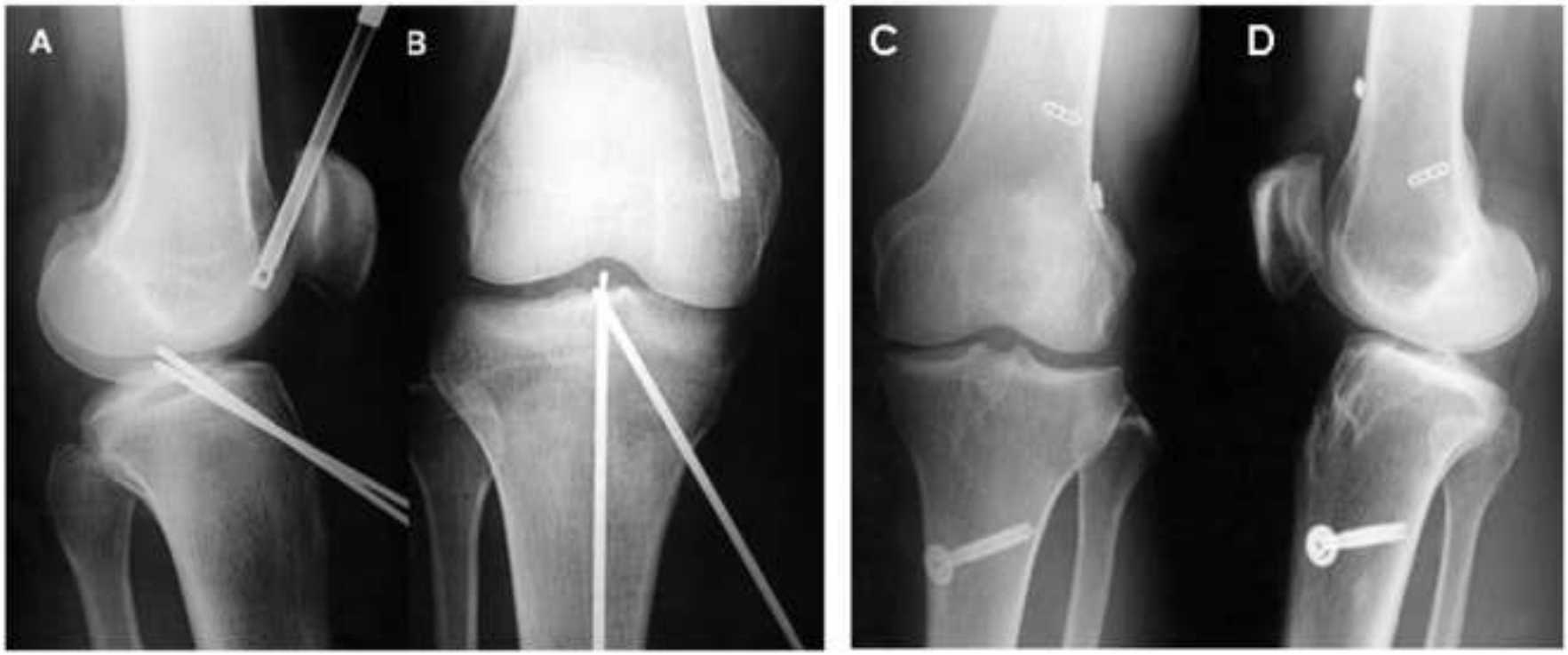

Figure 3

Click here to download high resolution image

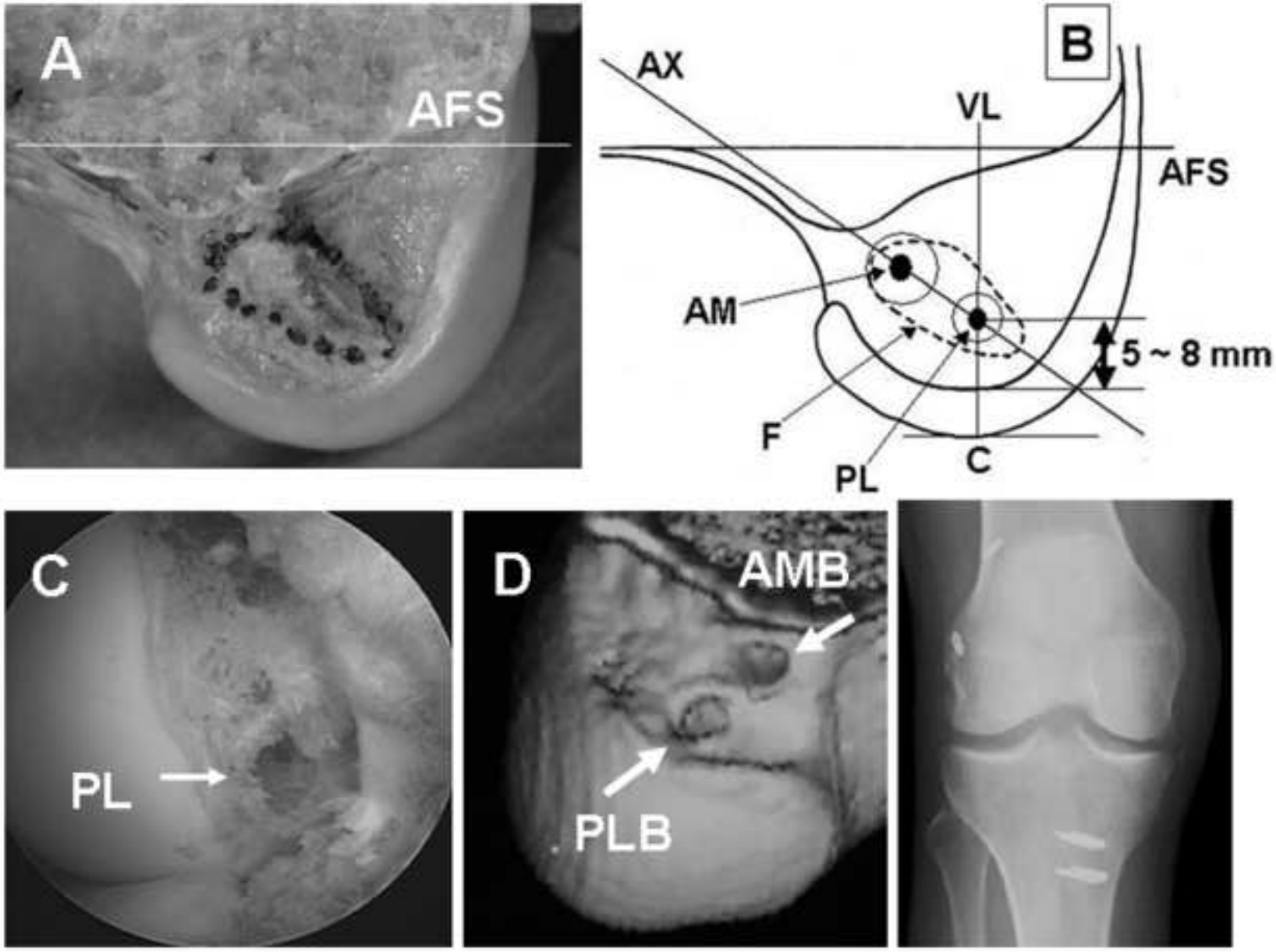

Figure 4

Click here to download high resolution image

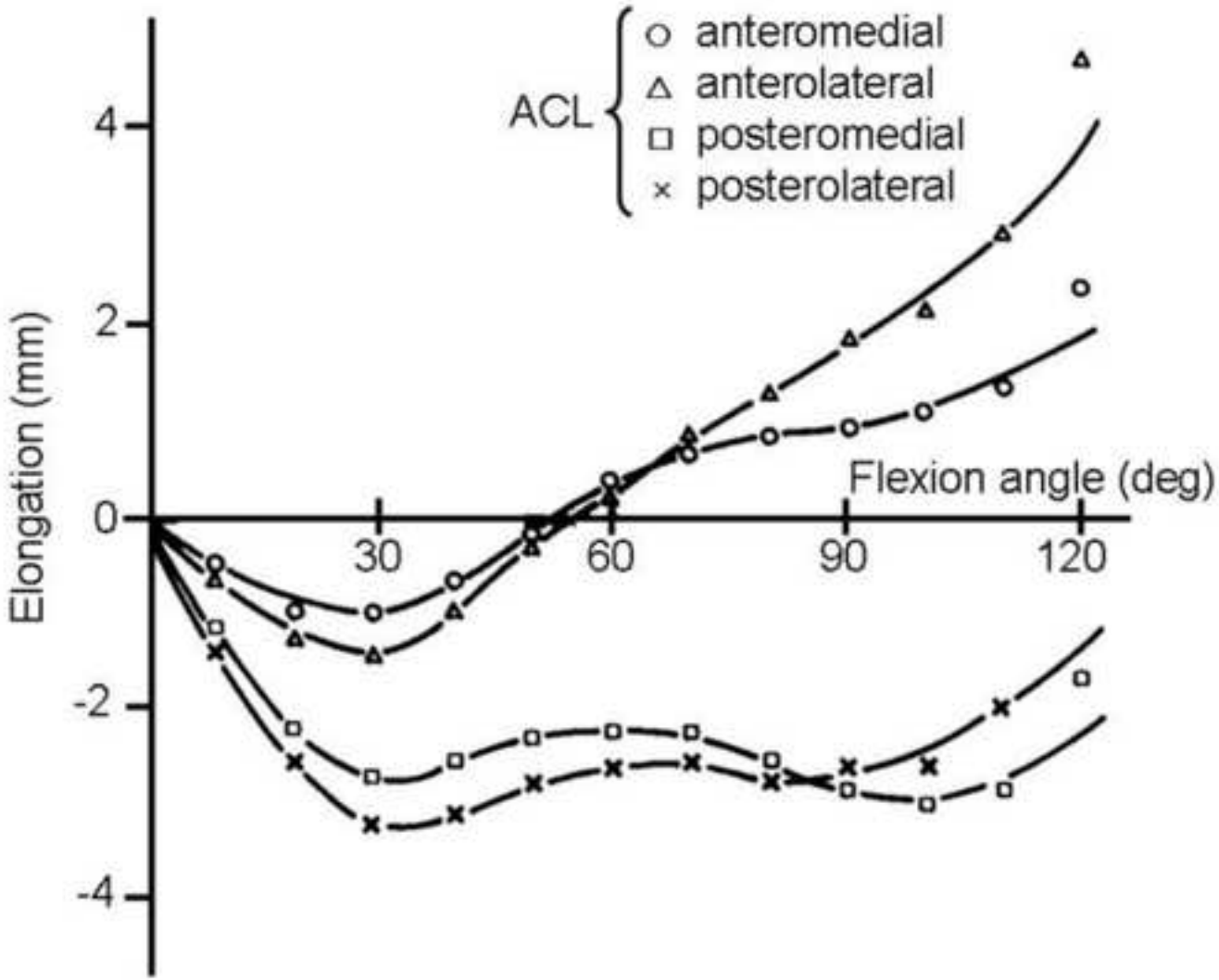

Figure 5

Click here to download high resolution image

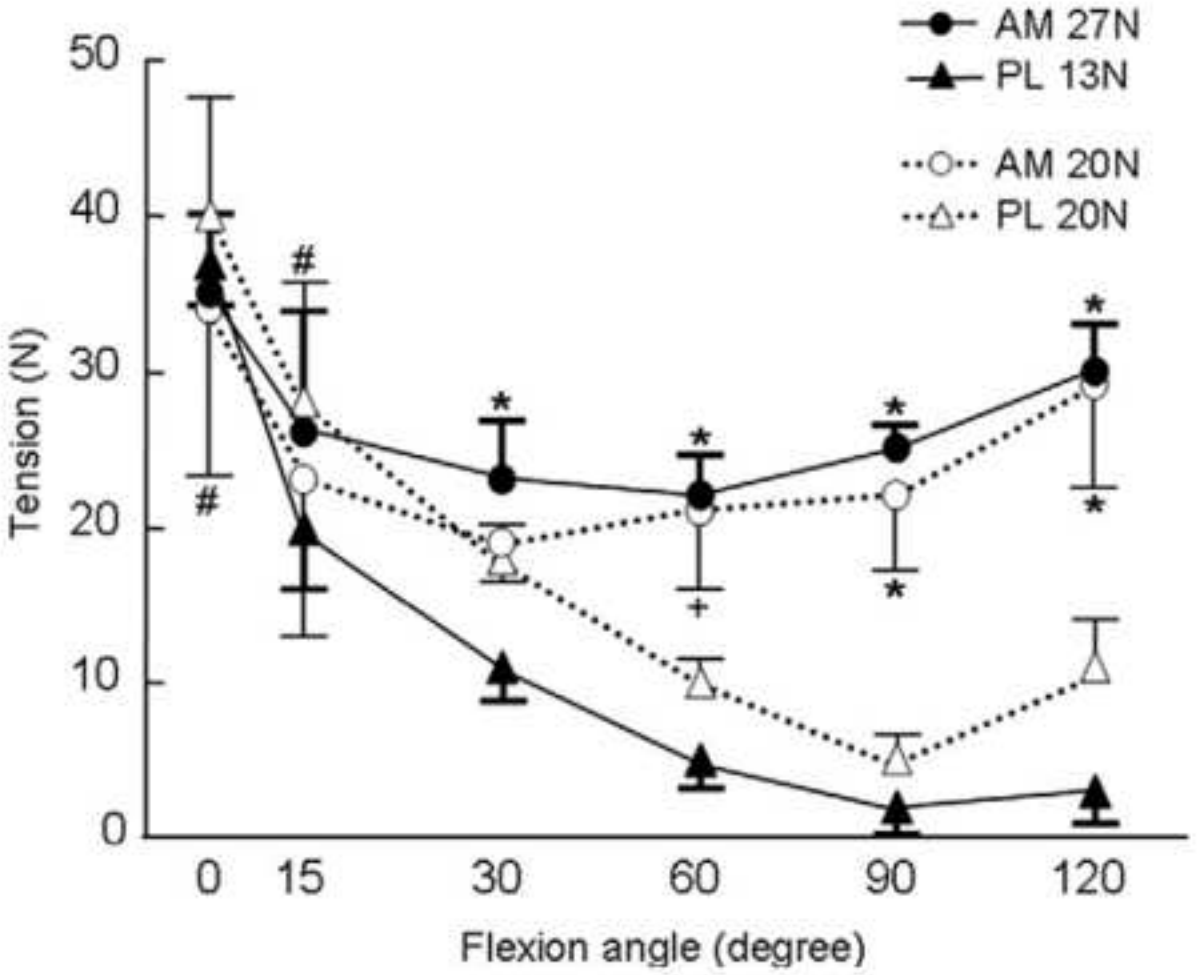

Figure 6

Click here to download high resolution image

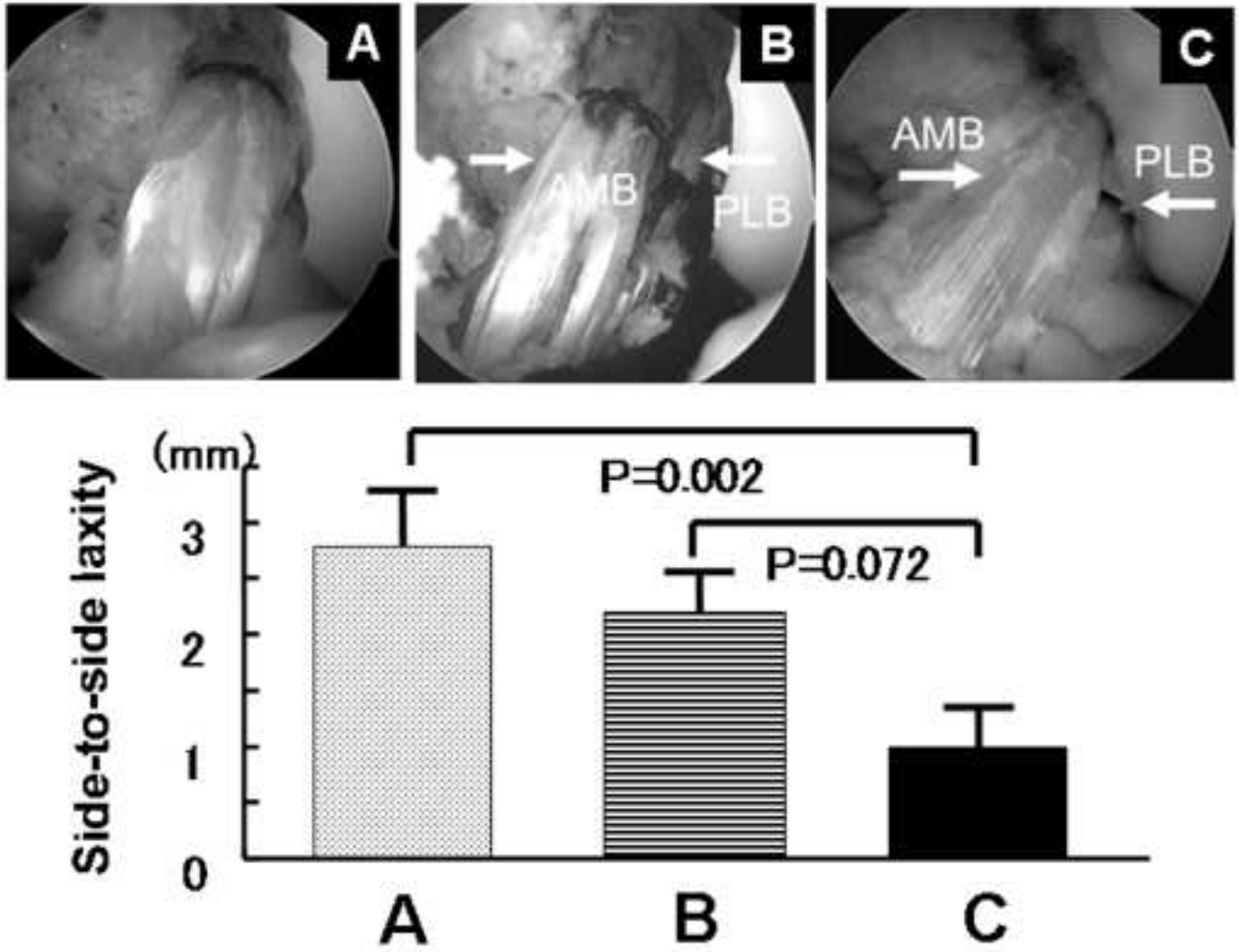

Figure 7

Click here to download high resolution image

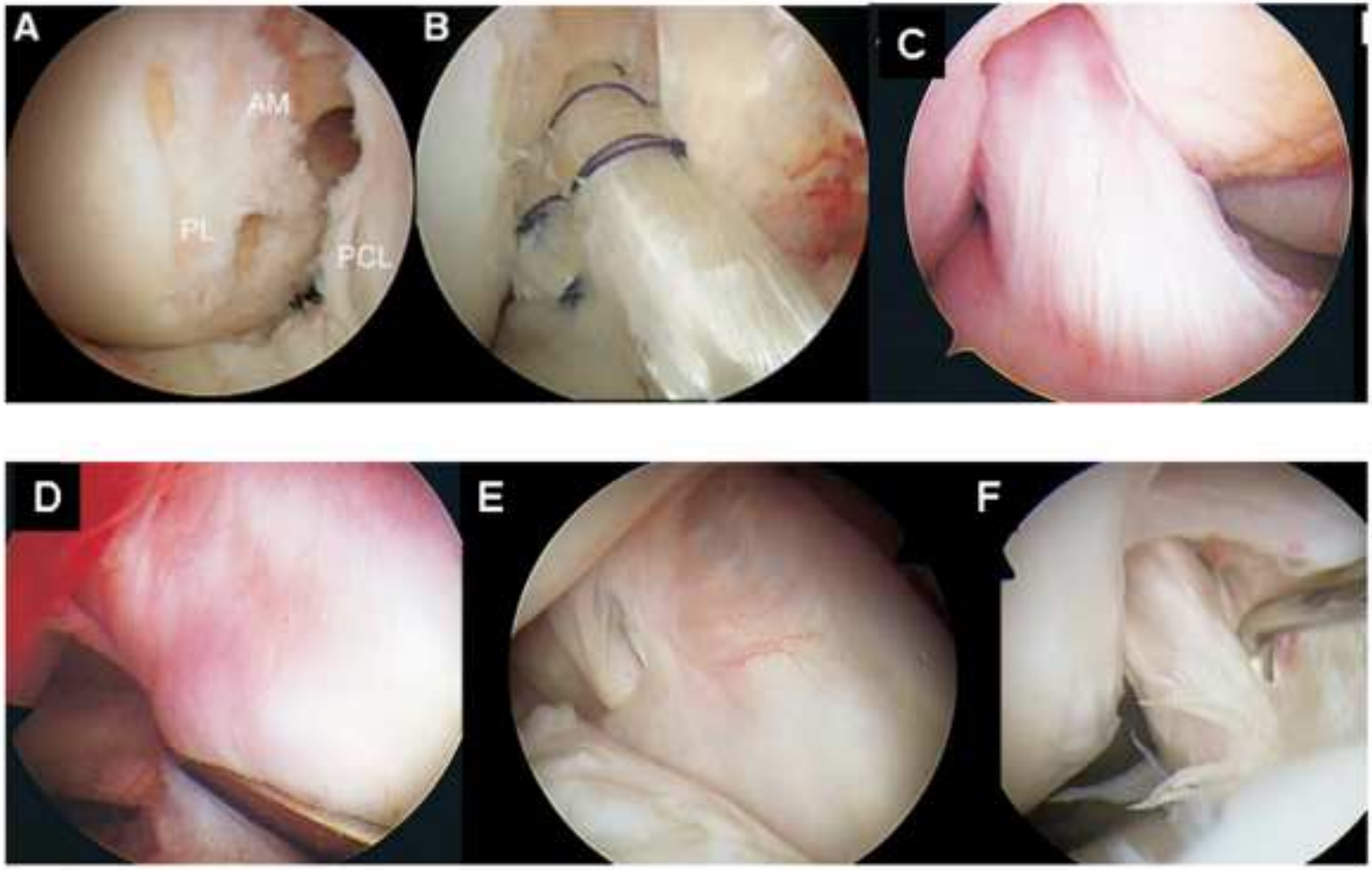

Figure 8

Click here to download high resolution image

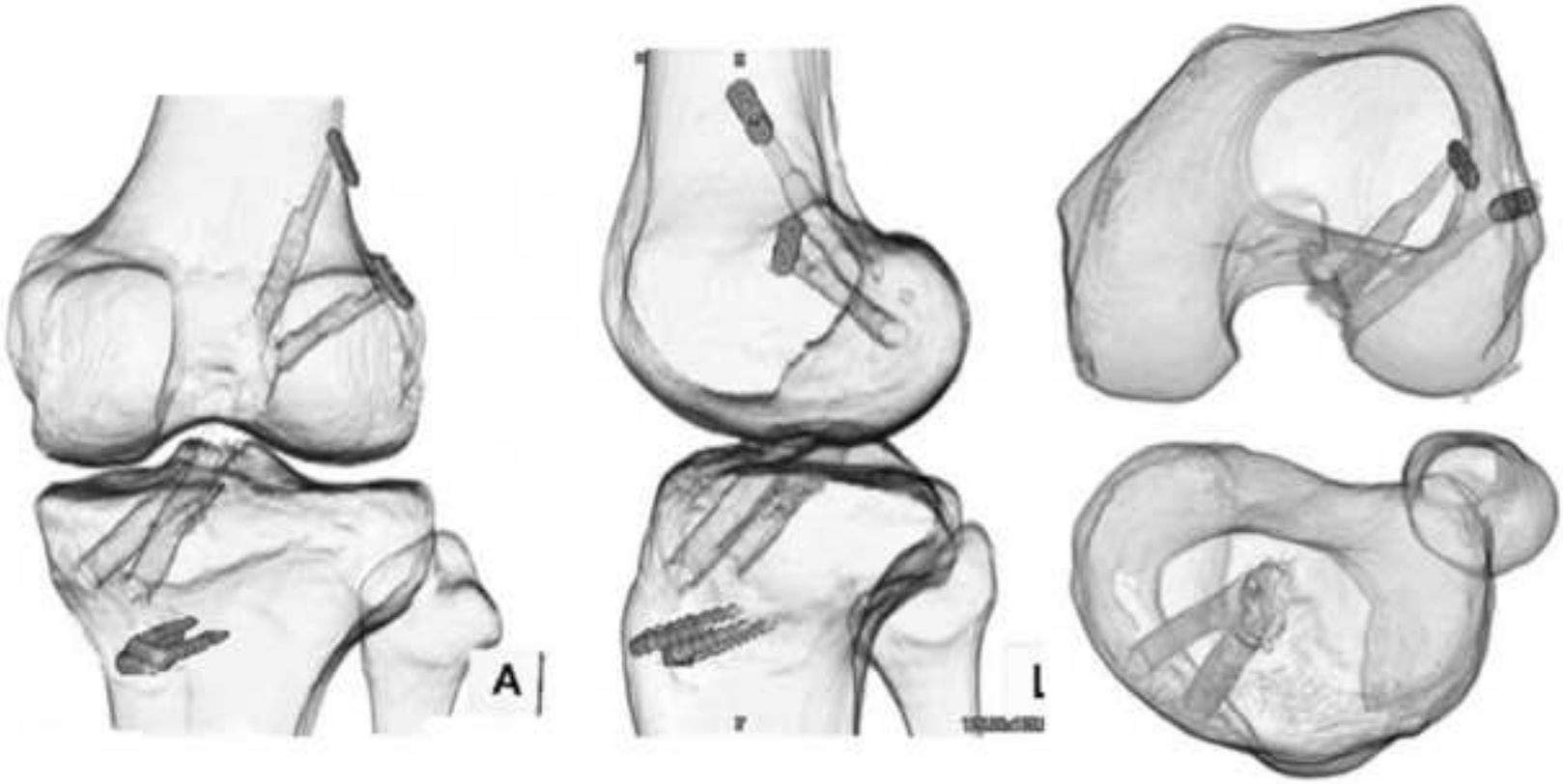

Fig. 8