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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.

1. Separate Title Page

Current Concepts

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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 are evaluated as “normal” under the International Knee Documentation Committee (IKDC) evaluation criteria. However, all the “normal” knees evaluated with the IKDC criteria, which have anterior tibial translation of less than 3 mm, do not indicate a completely normal knee without any ACL injury. Biomechanically, Woo et al.[15] reported that single-bundle reconstruction with either of the 2 grafts has no significant effects on rotatory instability due to ACL insufficiency. In addition, recent kinetic studies with patients who underwent single-bundle ACL reconstruction have found that single-bundle ACL reconstruction with either the bone-patellar tendon-bone or hamstring grafts cannot restore tibial rotation to normal levels, not only during high-stress activities but also during low-stress activities, such as walking.[16-21] Thus, we can say that abnormal knee stability remains a problem after single-bundle ACL reconstruction. The degree of the abnormality appears to be small but significant, because the abnormal laxity may induce meniscus injury, cartilage injury, and osteoarthritis in the late phase after surgery. Actually, it remains unknown whether single-bundle ACL reconstruction can successfully prohibit meniscus injury, cartilage injury, and osteoarthritis in the long-term clinical results. We should note that an essential aim of ACL reconstruction is to restore normal knee stability.

In 2003 and 2004, Yasuda et al.[1,2] reported the first anatomic reconstruction procedure of the AM and PL bundles with the 2-year follow-up results, in which the 2 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

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

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

Thus, the biomechanical studies have demonstrated that the anatomic double-bundle ACL reconstruction produces knee function (including stability) significantly closer to the normal knee than the conventional single-bundle procedures. Recently, however, a few biomechanical studies evaluated newly developed single-bundle ACL reconstruction procedures in comparison with anatomic double-bundle procedures. Yamamoto et al.[56] compared the laterally placed single-bundle reconstruction in which a femoral tunnel was 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 with either PL or AM bundle reconstruction throughout range of knee motion. Yasuda et al.[62] measured graft tension of the AM and PL grafts during their anatomic double-bundle ACL reconstruction using strain gauge–type tensiometers attached at the end of the suture. The tension-versus-flexion curve pattern of each graft was similar to the normal one (Fig 5). Namely, the curve of the AM suture graft indicated that the tension was highest at full extension and then relaxed with knee flexion between 0° and 30°. The curve then showed a plateau between 30° and 90°, and the tension gradually increased thereafter. On the other hand, the curve of the PL suture graft showed that the tension was highest at full extension and gradually relaxed with knee flexion between 0° and 90°. The tension increased thereafter. The initial tension significantly affected the absolute values of each graft tension at each knee flexion angle, but did not significantly affect the curve patterns. Thus, these studies suggested that the clinical anatomic double-bundle procedures can reconstruct the knee having biomechanical functions closer to the normal range than single-bundle reconstruction, if surgeons have sufficient surgical skills to precisely perform the appropriate anatomic double-bundle procedures.

In addition, the clinical results of ACL reconstruction are affected by the tunnel position not only in double-bundle procedures but also in single-bundle procedures. For example, Kanaya et al.[64] intra-operatively evaluated their “lower femoral tunnel–placed” 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 double-bundle group had graft failure, whereas 4 patients in the single-bundle group did. In 2008, Kondo et al.[43] reported a large prospective comparative study using 328 patients, in which their anatomic double-bundle group was significantly superior to the single-bundle group in the anterior laxity and the pivot-shift test (Table 3). There were no significant differences in the other clinical evaluations or the rate of complications. According to Jarvela et al.,[40] the patients in the single-bundle groups had more graft failures than those in the anatomic double-bundle group (Table 3). Rotational stability, as evaluated by the pivot-shift test, was significantly better in patients with the double-bundle technique than in those with the single-bundle techniques at the 1-year follow-up (P = .005). The P value decreased to P = .078 at the 2-year follow-up. The double-bundle group had significantly better result than the single-bundle group with metallic screw fixation ($P < 0.05$), although the difference to the single-bundle group with bioabsorbable screw fixation was not significant. However, if the 7 failures with revision ACL surgery (5 in the single-bundle group with bioabsorbable screw fixation group) were included in the statistical analysis of the study, the double-bundle group would have significantly better results than the single-bundle group with bioabsorbable screw fixation ($P < .05$). No significant differences were found between the groups in knee scores. Siebold et al.[41] described that the pivot-shift test result was significantly better in their double-bundle procedure than in their single-bundle procedure, and the objective IKDC score 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.

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Legends

Figure 1. Arthroscopically assisted double-bundle procedure using 2 femoral and 1 tibial tunnels. Note that the 2 femoral tunnels were created between the 11:00 and 12:00 o'clock points. (From Rosenberg and Graf,[5] reprinted with permission.)

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.)

Figure 4. Relative elongation patterns of 4 portions of the ACL measured with implanted elastic transducer.[46] 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°.

Figure 5. Tension of the AM and PL grafts measured during anatomic double-bundle ACL reconstruction. Note that the tension-versus-flexion curve pattern of each graft was similar to the normal one shown in Fig 4. (From Yasuda et al.,[61] reprinted with permission.)

Figure 6. The first prospective comparative study to compare their anatomic double-bundle procedure (C) with their single-bundle (A) and non-anatomic double-bundle (B) procedures using 72 patients. 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. The arthroscopic findings (left knees) show that 2 bundle positions of the anatomic double-bundle procedure (C) are different from those of non-anatomic double-bundle procedure (B). (From Yasuda et al.,[2] reprinted with permission.)

Figure 7. Morphologic evaluation of the grafted tendons using postoperative second-look

arthroscopy (right knees). Placement of the (A) AM and (B) PL grafts. (C) Arthroscopic obseration at 1 year after reconstruction. Arthroscopic classification of PL grafts based on synovium coverage: (D) completely covered, (E) partially covered, and (F) almost not covered. (From Kondo et al.,[65] reprinted with permission.)

Figure 8. Clear visualization of tunnel positions using transparent 3-dimensional computed 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

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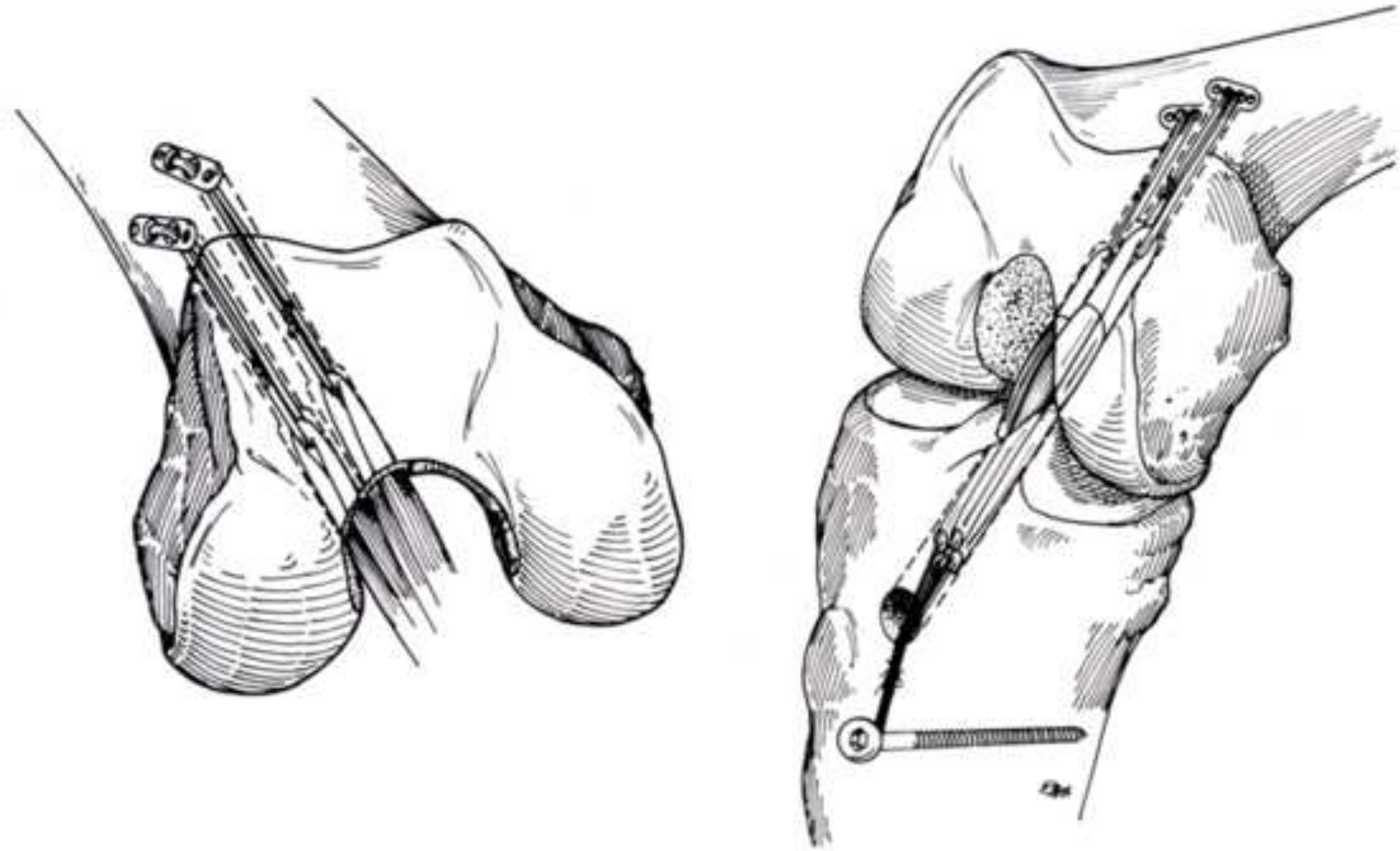

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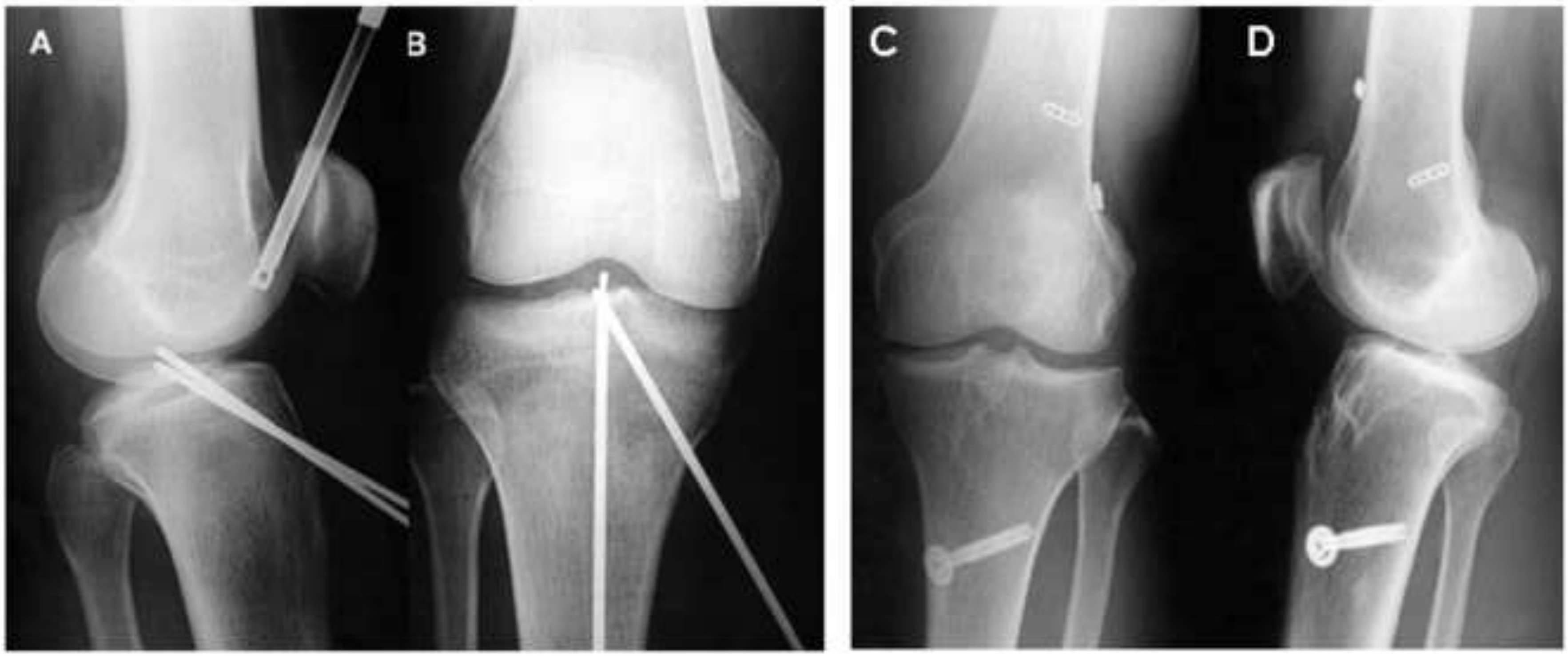

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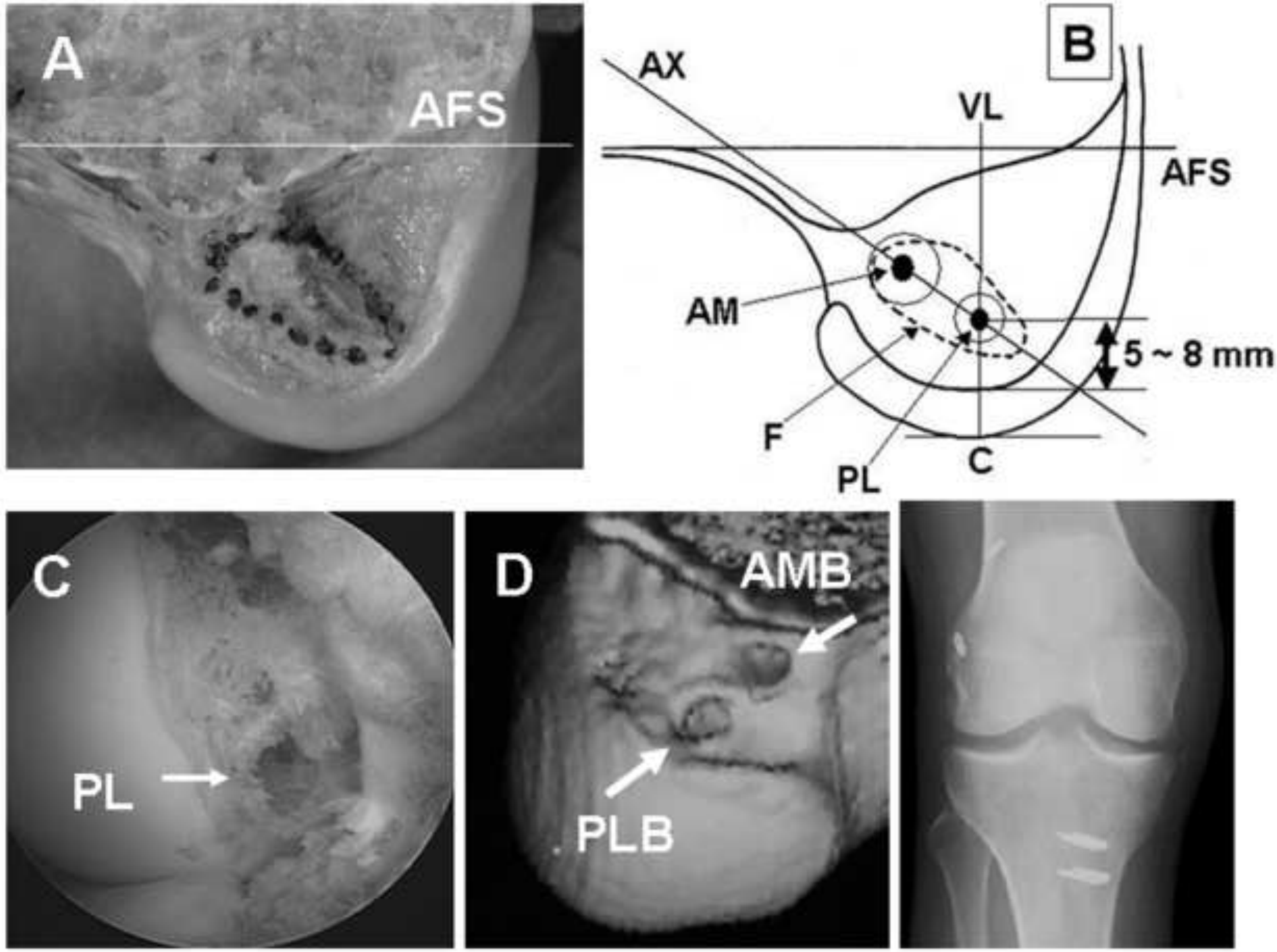

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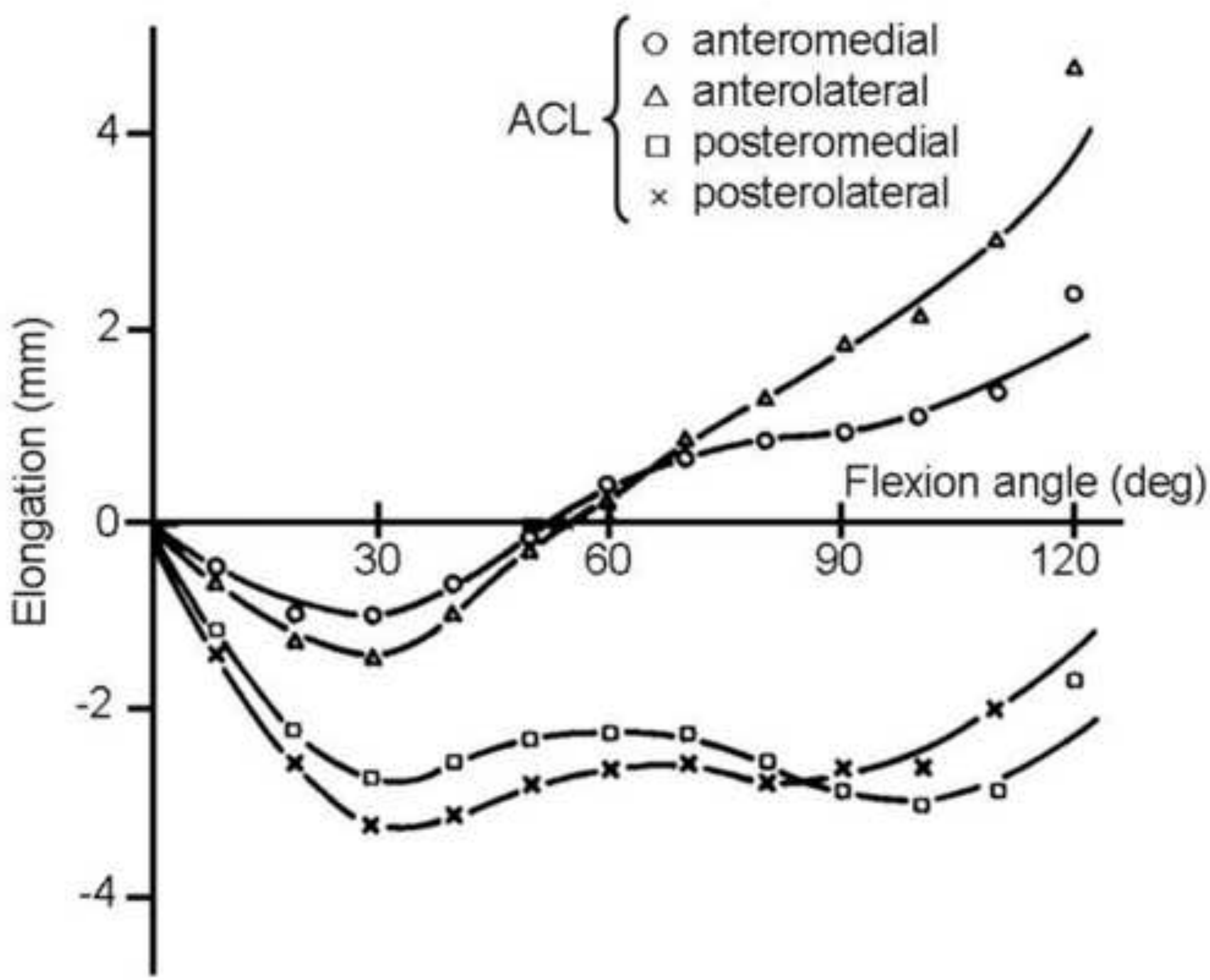

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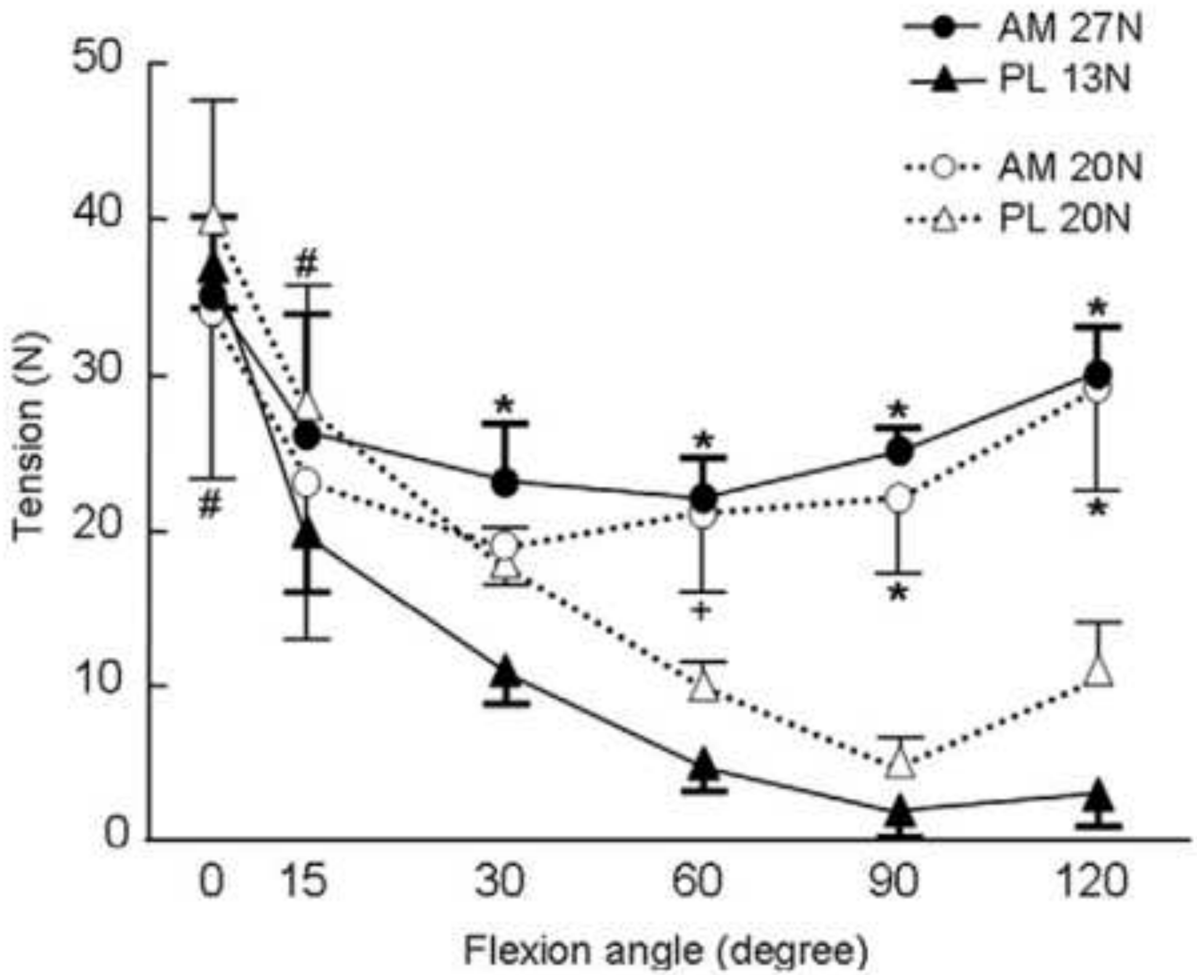

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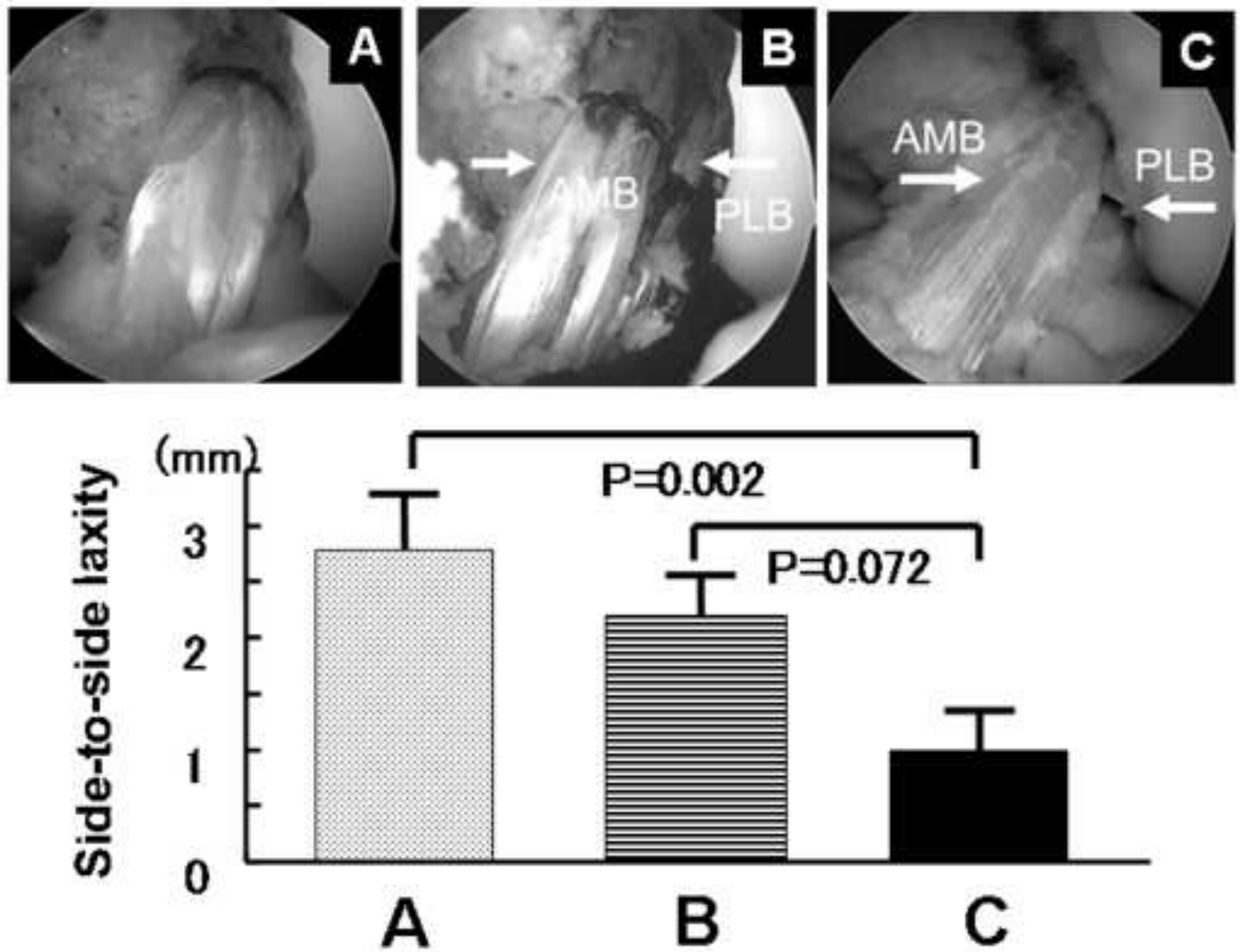

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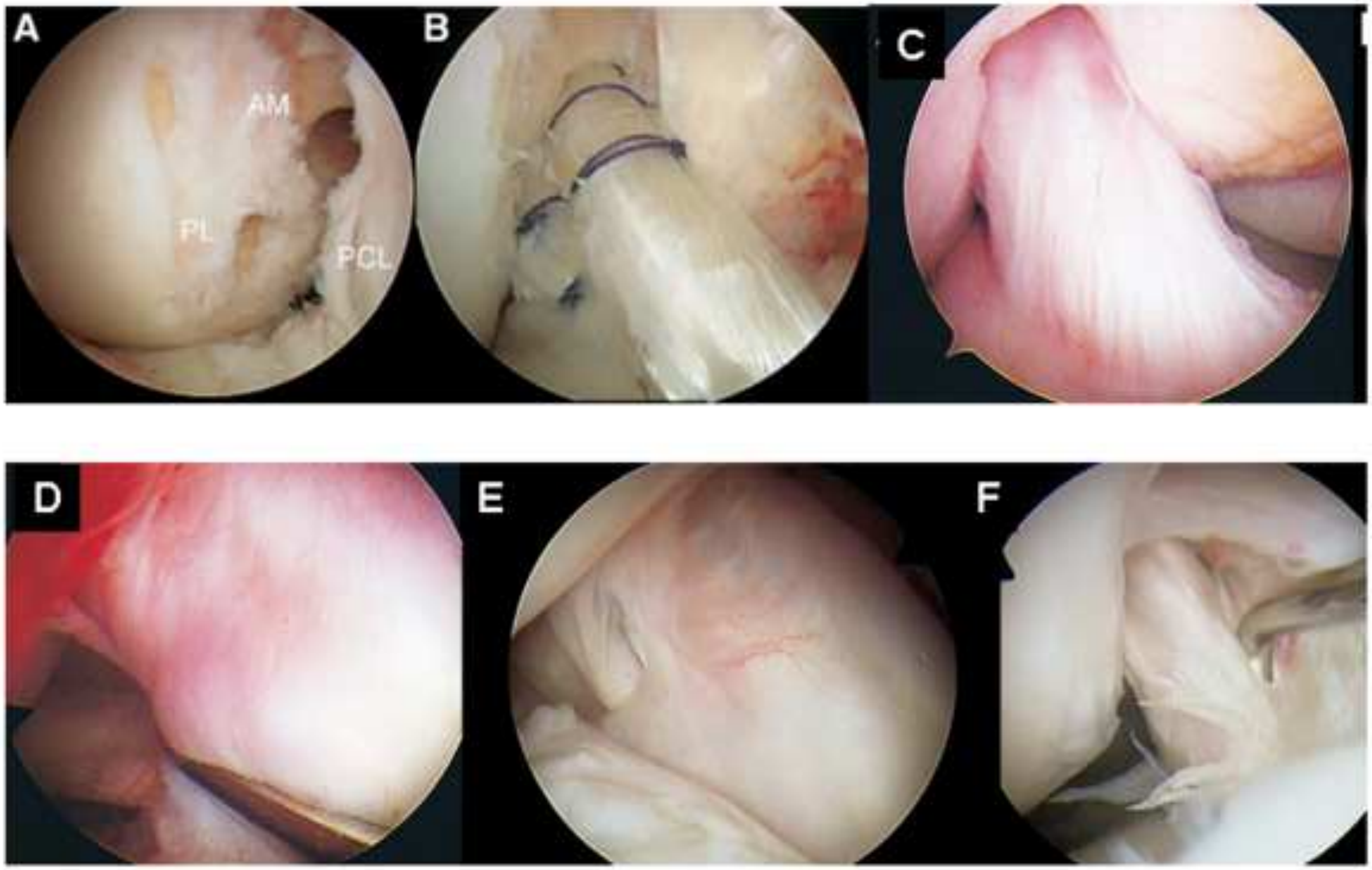

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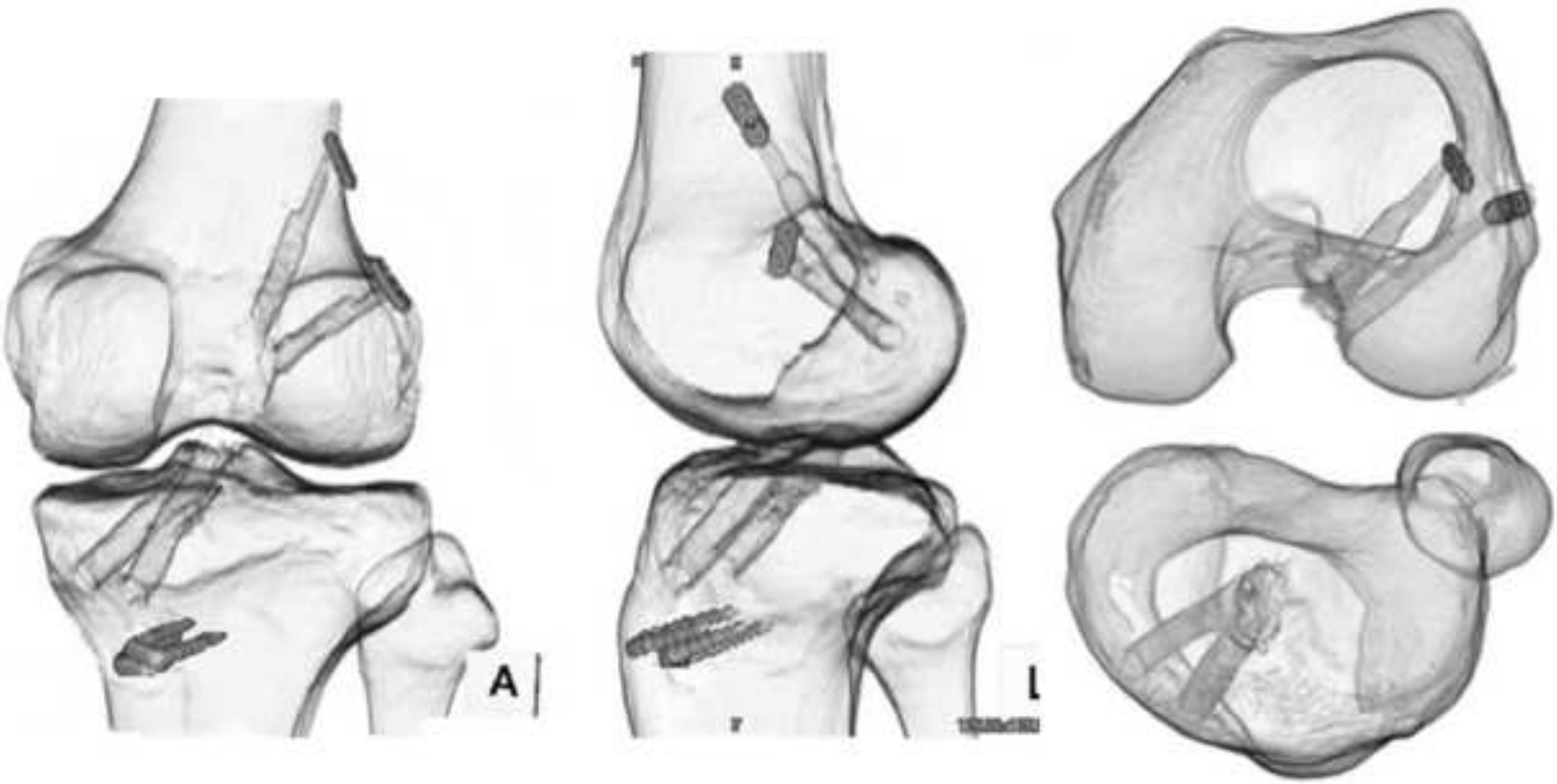

Fig. 8