Anatomic double-bundle anterior crucial ligament reconstruction with G-ST

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Abstract The anterior cruciate ligament (ACL) consists of two primal functional bundles, anteromedial bundle and posterolateral bundles. Those two bundles play different functional roles and contribute differently to knee stability throughout the range of motion. Recent advancement in studies of anatomy and biomechanics of ACL has led surgeons to perform double-bundle ACL reconstruction to obtain better stability and kinematics. Consequently, variable surgical techniques of double-bundle ACL reconstruction have been reported to replicate native ACL. In addition, various surgical key points and problems in double-bundle ACL reconstruction techniques have also been reported. There has been a trend to more anatomically replicate native ACL bundles, not simply creating two bundles. We summarize the basic knowledge and current concepts of anatomic double-bundle ACL reconstruction using hamstrings tendons.

Keywords Anterior cruciate ligament · Reconstruction · Double-bundle · Hamstrings tendons · Knee

Introduction

Anterior cruciate ligament (ACL) injury is one of the most common knee traumas. Single-bundle reconstruction of the ACL is the traditional surgical treatment. The outcomes of the single-bundle reconstruction were relatively good. However,

it has been reported that only 30% to 40% of patients were rated as normal in International Knee Documentation Committee scores after single-bundle reconstruction and more than 60% of patients may not make a full recovery to preinjury levels [1]. In addition, it has been suggested that the single-bundle reconstruction did not fully restore normal knee kinematics by biomechanical studies [2, 3].

Anatomic studies have shown that native ACL is composed of two functional bundles, anteromedial (AM) and posterolateral (PL) bundle [4–7]. Therefore, there has been an increased interest in double-bundle ACL reconstruction, which replicates the two functional bundles, to more closely restore normal knee stability and kinematics [8–10]. During the past few years, there has been a shift from single-bundle reconstruction to double-bundle reconstruction and various double-bundle surgical techniques have been reported with relatively satisfactory clinical outcomes. In association with the increased popularity of double-bundle reconstruction, the double-bundle surgical techniques have been refined over the years and surgical key points have been also addressed. Currently, there has been a trend to pursue a more anatomic restoration of native ACL anatomy and kinematics, not simply creating two bundles. This paper describes the current concepts of “anatomic” double-bundle ACL reconstruction surgical techniques with hamstrings tendons, the key to performing this procedure, its outcome, and the controversies of double-bundle ACL reconstruction.

History of double-bundle ACL reconstruction

In 1983, Mott first described the first double-bundle procedure that creates two tunnels in both the femur and the tibia without clinical results [11]. Later, Zaricznyj reported the clinical results of a double-bundle procedure in which two tibial

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tunnels and one femoral tunnel were created using doubled semitendinosus tendon in 1987 [12]. Fourteen patients were treated with the procedure and all of the patients showed a negative pivot shift test and 12 patients were rated as excellent at 2 years post-operatively. Since then, during the early 1990s, the double-bundle procedure was not reported most likely due to the improved clinical results of single-bundle ACL reconstructions. In 1994, Rosenberg and Graf described a proposed double-bundle procedure using two isometric femoral sockets and one tibial tunnel [13]. Muneta et al. modified the techniques by creating two tunnels in both the femur and the tibia and reported the clinical results of the double-bundle reconstruction in 1999. They created the femoral tunnel for anteromedial bundle at around 12:30 and for posterolateral bundle at around 1:30 o'clock of the intercondylar space in the case of a left knee and reported favorable clinical outcomes at 2 years post-operatively [14]. Thereafter, a number of surgical techniques of double-bundle ACL reconstruction and the clinical outcomes have been published [15–23]. Most of them have reported satisfactory clinical results and better control of anterior–posterior stability or pivot shift. However, its advantage in a patient's subjective evaluation over single-bundle reconstruction is still controversial.

Anatomy

It is essential to understand the anatomy of the native ACL to perform anatomic reconstruction. ACL attaches to the medial side of the lateral femoral condyle (Fig. 1a) and to the medial internotch region of the tibia (Fig. 1d). Several studies revealed that the ACL is functionally composed of two functional bundles, the AM and PL bundle (Fig. 1b, c). In 1938, Palmer first described the ACL as composed of AM and PL bundle [4]. Then, Girgis et al. also reported the presence of the two bundles later [5]. They are named after the position of their insertion sites of tibia and the functional roles of the two bundles were investigated by more researchers [6, 7]. On the femoral side, two bundles are horizontally aligned and the AM bundle insertion site is located at a deeper position than the PL bundle insertion site with the knee in a 90° flexion (operating position). At the full extension of the knee, both bundles align vertically. The detailed bundle arrangement was examined by Hara et al. recently. They divided AM bundle and PL bundle into ten small bundles of 2 mm in diameter each in 20 cadaveric knees and examined the relationship between the femoral and tibial attachments of each small bundle. They found that the small bundles aligned in the anterior–posterior direction in the tibia corresponded to the bundles aligned in a high–low direction (arthroscopic view at 90° flexed position) in the femur in flexion. [24]. Some anatomic and biomechanical

studies have also shown that ACL can be divided into three functional bundles, AM, intermediate, and PL bundle, although the importance of the functional roles of the intermediate bundles has not been well understood [7].

Although recently the presence of the two functional bundles, AM bundle and PL bundle, has been widely accepted, some differences among reports regarding the attachment site of the two bundles still exist. Edwards et al. examined 55 cadaveric specimens and examined the tibial attachment site of the AM and the PL bundle. They found a wide variation in the attachment shapes and area. The center of the tibial attachments of the PL and AM bundles were 10 and 17 mm anterior to the “over-the-back ridge” (transverse interspinous ridge in the apex of the posterior slope of the tibial plateau, just anterior to the posterior cruciate ligament). The center of the PL and AM bundles were 4 and 5 mm, respectively, lateral to the medial tibial spine border [25]. The same group also examined the femoral attachment site using 22 cadaveric knees and had shown a wide variation in size and area [26]. A review of the studies on the morphology of the femoral origin and tibial insertion of native ACL has clearly shown the great variations in the area of AM and PL bundle. [27].

Ziegler et al. examined the center of the attachment site with respect to the arthroscopically pertinent bony and soft tissue landmarks using 11 cadavers. They reported that the femoral AM and the PL attachment center was 4.8 mm proximal and 5.2 mm distal to the bifurcate ridge and 7.1 and 3.6 mm posterior to the lateral intercondylar ridge, respectively. The tibial AM attachment center was 8.3 mm medial to the lateral meniscus anterior horn and 17.8 mm anterior to the retro-eminence ridge. The tibial PL bundle attachment center was 6.6 mm medial to the lateral meniscus anterior horn and 8.4 mm anterior to the retro-eminence ridge [28]. Zantop et al. also examined the distances from the center of the AM and PL bundles to the articular cartilage using the 20 cadaveric knees. According to the study, the center of the AM bundle was at a point 5.3 mm from the roof of the notch and 5.7 mm from the intercondylar line. The center of the PL bundle was located at 6.5 mm from the shallow cartilage margin and 5.8 mm from the inferior cartilage margin. On the tibia, the center of the AM bundle is aligned with the anterior horn of the lateral meniscus, while the center of the PL bundle was located 11.2 mm posterior and 4.1 mm medial to the anterior insertion of the lateral meniscus [29].

Peterson and Zantop described that the origin of AM bundle is located at the transition of the intercondylar line to the border of the articular cartilage [30]. In accordance with this observation, a recent histological study has shown that the ACL fibers attach to the concave area between the lateral intercondylar ridge (resident's ridge) and the articular cartilage margin [31]. Another anatomic study has also provided an osseous landmark “lateral bifurcate ridge” that exists between

Fig. 1 ACL attaches to the medial side of the lateral femoral condyle. **a** Two bundles are horizontally aligned and the AM bundle insertion site (*white circle*) is located at a deeper position than the PL bundle insertion site (*black circle*) with the knee in a 90° flexion. **b** At the full extension of the knee, both bundles align vertically. **c** AM, *white circle*; PL, *black circle*. ACL fibers attach to the concave area between the resident's ridge (*black line*) and the articular cartilage margin. AM bundle and PL bundle are named after the position of their insertion sites of tibia. The tibial attachment of the ACL insertion was located on the medial internotch region of the tibia, anterior to the transverse interspinous ridge in the apex of the posterior slope of the tibial plateau. **d** AM, *white circle*; PL, *black circle*

the femoral attachment site of AM and PL bundle to identify the femoral attachment site of each bundle [32]. Those studies have shown the importance of the anatomic bony landmarks as a reference for tunnel positions in anatomic double-bundle ACL reconstruction. Some radiographical assessments of the insertion site of each bundle using multiple evaluation methods have also been reported [29, 33–35].

Biomechanics and kinematics

It has been well known that ACL is a primary restraint for anterior tibial translation of tibia. Biomechanical studies have further shown the different functional roles of each bundle comprising ACL. Sakane et al. examined the in situ force and the force distribution between the AM and PL bundles of the ligament in response to anterior tibial loads at knee flexion angles of 0–90°. 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°, while the magnitude of the in situ force in the AM bundle remained relatively constant. [36]. Similarly, Gabriel et al. showed that the in situ force of the PL bundle was largest at full extension and became smaller during flexion in response to the anterior tibial load. On the other hand, the in situ force of the AM bundle was smaller than that of the PL bundle but it became larger at more than 30° of flexion. In addition, in response to the combined rotatory load of the valgus and the internal torque, the in situ force of the PL bundle was high at 15°

of knee flexion [37]. These reports agree that the role of the PL bundle is more predominant during low flexion angle.

Yagi et al. preformed a cadaveric study and compared the kinematics and in situ force among the intact knees, ACL-deficient knees, single-bundle-reconstructed knees, and anatomically reconstructed knees with the anterior tibial load or combined rotatory load of the internal tibial torque and the valgus torque. Both anterior tibial translation under the anterior tibial load and coupled anterior tibial translation under the combined rotatory load for the anatomic reconstruction were significantly closer to those of the intact knee than the single-bundle reconstruction was. In addition, with a combined rotatory load, the normalized in situ force for the single-bundle and anatomic reconstructions at 30° of flexion was 66% and 91%, respectively. Therefore, they concluded that anatomic reconstruction can provide better kinematics biomechanically especially during rotator load [9]. Mae et al. also examined the anterior tibial displacement in response to anterior tibial load between 0° and 90° of knee flexion after the single-bundle reconstruction or double-bundle reconstruction with two femoral sockets and one tibial tunnel. They reported that the anterior tibial displacement of the double-bundle reconstruction was smaller compared with that of the single-bundle reconstruction [8]. Yamamoto et al. examined the anterior tibial translation and in situ force under anterior tibial load or combined rotator loads of the valgus and the internal tibial torque using a robotic sensor system and compared among intact, ACL-deficient, anatomical double-bundle reconstructed, and laterally placed single-

bundle reconstructed knees. They reported that, although there was no significant difference in anterior knee stability in near extension, at 90° of knee flexion anterior tibial translation was significantly higher in the laterally placed single-bundle reconstruction than in a double-bundle reconstruction [38]. Those studies have provided fundamental data that double-bundle reconstruction can restore more closely to intact knees. Currently, there is an increasing number of studies in which single-bundle ACL reconstruction and double-bundle ACL reconstruction were compared by examining tibial anterior translation, combined rotatory load, or simulated pivot shift test using multiple techniques [10, 39–43]. Most of them have reported that double-bundle reconstruction can provide better stability than single-bundle reconstruction or can restore those parameters more closely to normal knees.

Anatomic double-bundle reconstruction

Portals

The usefulness of the three portal techniques was reported in several studies [44, 45•], which provide a proper view of the ACL remnants and bony landmarks such as the lateral intercondylar ridge (resident's ridge) and the lateral bifurcate ridge, facilitating an anatomical positioning of the graft. An accessory medial portal is created under arthroscopic visualization by piercing a spinal needle from the medial side of the knee directed to the femoral attachment site of ACL. The location of the accessory medial portal is usually just above the medial meniscus and slightly anterior to the medial condyle, not to interfere with the articular cartilage of the medial condyle during femoral tunnel drilling. The accessory medial portal is often used for creating the femoral socket of the PL bundle. Recently, it has also been reported that the accessory medial portal is useful for creating the femoral tunnels for the AM bundle [46].

Several anteromedial portal techniques for femoral socket creation have also been proposed without creating the third portal [47, 48]. Lubowitz et al. recommended that the medial portal is to be created as inferior as possible and also as medial as possible for a more perpendicular reaming, which is essentially the same location to the accessory medial portal mentioned above [47].

Graft harvest and preparation

As autograft, the use of hamstrings tendons for ACL reconstruction has become more common in recent years [49]. Double-stranded gracilis for PL and double-stranded

semitendinosus for AM in a double-bundle reconstruction are commonly reported [17, 18, 21]. It has also been reported that only the double-stranded semitendinosus tendon was used for both AM and PL bundle in a double-bundle reconstruction [19, 20, 22, 50, 51].

Notchplasty

Notchplasty is still used in some of the reported procedures, especially in the procedures using two portal techniques to obtain better visualization from the antero-lateral portal [52] or to avoid graft impingement. However, notchplasty seems to be less popular [49] than it used to be for the reasons described below. The three-portal techniques can provide a better view since an anteromedial portal is used as a viewing portal while an accessory medial portal can be used as a working portal. In addition, notchplasty can cause a loss of anatomical orientation for tunnel placements. Furthermore, since native ACL does not impinge in the notch, the placement of the anatomic position should not cause graft impingement. We also believe that notchplasty is unnecessary in anatomic double-bundle ACL reconstruction.

O'clock position

The clock face (o'clock position) was still used when determining the location of femoral tunnels. However, the clock face determination is a two-dimensional and is neglectful of the depth of the notch, and its position varies with knee flexion angle [53]. Several authors claimed that the o'clock positioning is not useful to describe the insertion site since the insertion site of PL bundle is out of the plane [15, 54].

Tunnel placement

The most technical error in ACL reconstruction has been non-anatomic tunnel placement [55, 56]. Therefore, it needs great caution when determining the position of the tunnel to place the anatomic position of each bundle. The remnant of the native ACL and bony landmarks such as the lateral intercondylar ridge (resident's ridge) and lateral bifurcate ridge are essential in determining the femoral positions [32, 57]. The lateral bifurcate ridge runs perpendicular to the resident's ridge and is located between the AM and PL bundles of femoral insertion site. These osseous landmarks can be useful to determine the position of the femoral tunnels. However, it may not be easy to identify those bony ridges in some cases. Therefore, the "footprint" of the original ACL is also a useful reference to determine the attachment site of the whole ACL and each bundle [52]. If the femoral insertion site cannot be determined by these

osseous landmarks and footprint, van Eck et al. recommended for one to visualize the whole medial wall of the lateral intercondylar notch and to place the tunnels in the lower 30% to 35% of the medial wall of the notch [58].

Drilling tunnels

Conventionally, transtibial drilling has been used for creating a femoral tunnel. However, the anatomic insertion site of AM is more distal and posterior than the position of the isometric point conventionally used. Now, it appears to be harder to create an AM tunnel through the AM tibial tunnel due to an increased risk of the posterior wall blow-out. Several studies have shown that transtibial techniques tend to fail to accurately place the femoral tunnel in anatomic positions [46, 59]. In addition, when creating the PL femoral tunnel transtibially in a flat angle to the medial tibial plateau, it also has a risk to damage the medial tibial plateau [60].

The direction of the guide-pin is largely dependent on the direction of the tibial tunnel. Therefore, it needs great caution when one is creating the femoral tunnels. A wire navigator that aids to determine the direction of the guide wire has been reported by Yasuda et al. to create both the femoral PL and AM tunnels transtibially [61•]. Very recently, Kopf et al. examined the accessibility of the anatomic insertion site of the AM bundle from three different approaches, AM tibial tunnel, PL tibial tunnel, and accessory medial portal during anatomic double-bundle ACL reconstruction. They reported that the center of the femoral AM insertion site was reached in 4.4%, 60.2%, and 100% of cases through the AM tibial tunnel, PL tibial tunnel, and accessory medial portal, respectively [46]. Outside-in technique has also been reported to be useful to create femoral tunnels more accurately [62] and to avoid a short tunnel [63]. When drilling the femoral tunnels, it is very important for surgeons to be familiar with these different approaches to reach the anatomic insertion site of each bundle.

The reported knee flexion angles during femoral tunnel drilling varied between 90° to 135°. Some key points regarding the drilling and creating of tunnels have been addressed. Zantop et al. described that the drilling of the femoral PL bundle tunnel through a high medial portal at low knee flexion angles may damage the subchondral bone of the lateral compartment. Consequently, they recommend for one to drill the femoral PL bundle tunnel through a low medial portal in high knee flexion [64]. Cadaveric studies have shown that the risk of common peroneal nerve injury significantly increases when creating femoral tunnels through the low-accessory anteromedial portal at a low angle such as 70° of knee flexion. For that reason, a higher angle of more than 110° of knee flexion is recommended to avoid peroneal nerve injury when creating a femoral tunnel

through the low medial accessory portal [65, 66]. Surgeons should consider those risks during drilling.

Initial tensioning

Double-bundle ACL reconstruction, in which the two bundles thought to have different effects on knee kinematics are reconstructed separately, is widely believed to more favorably restore normal knee kinematics than the conventional single-bundle ACL reconstruction. However, rotational kinematics during physiological movement after double-bundle reconstruction has rarely been tested. Hoshino et al. compared two different tensioning conditions using cadaver knees: 50 N on the anteromedial bundle and 0 N on posterolateral bundle (AM-favored condition); 0 N on anteromedial bundle and 50 N on posterolateral bundle (PL-favored condition). They reported that the tibia overcorrected posteriorly in both conditions, the tibia was significantly externally rotated after ACL reconstruction at a low flexion angle, and the over-correction in the AM-favored condition was larger than in the PL-favored condition. Thus, they recommended that a moderate tensioning force is applied to the PL bundle and a minimal tensioning force to the AM bundle in double-bundle reconstruction to obtain better knee kinematics [67]. Murray et al. performed a cadaveric study and compared the differences between two conditions: one was that both AM and PL bundles were tensioned at 20° of knee flexion with 22 N and the other condition was that the PL bundle was tensioned at 15° and the AM bundle was tensioned at 45° with 22 N. They reported that the condition in which both bundles undergo tensioning at 20° of knee flexion more closely restores the native ACL tension pattern; the PL bundle tension was greater than the AM bundle tension in extension but the AM bundle was greater than the PL bundle tension from 25° to 120°. They concluded that equal tensioning of both bundles at 20° of knee flexion is necessary to restore the relatively normal tension curves in each bundle [68]. These and other biomechanical studies have also shown that the sequence of graft fixation, fixing PL first or AM first, significantly affects the force distribution and in situ forces of grafts [69, 70]. Mae et al. examined the laxity match pretension by applying a total of 10 to 50 N to the grafts with 134 N anterior tibial load at 20° of knee flexion during the anatomic double-bundle ACL reconstruction. They estimated that 7.3 N was the laxity match pretension compared with normal knee in the anatomic double-bundle ACL reconstruction [71]. Based on the results, they performed ACL reconstruction with 20 N as initial tension and reported good clinical outcomes at 2 years post-operatively [72]. Therefore, they recommended using such a relative low tension as an initial tension for anatomic double-bundle reconstruction. Mae et al. also

examined the graft tension during double-bundle ACL reconstruction when the patients extend their knee semi-consciously. Two grafts were fixed with 10 N of the initial tension on each graft at 20° and the tension to each graft was recorded while the patients were actively extending their knee semiconsciously. They found that the highest graft tension was 62.8 N at 0° of flexion with a 2-kg weight placed around the ankle, when 20 N of the initial tension was applied at 20° of flexion in anatomic double-bundle ACL reconstruction. Thus, they recommended that active knee extension exercise should be performed moderately in the early phase after ACL reconstruction to protect the grafts from excessive stress [73]. Although these studies provided fundamental information on the biomechanical behavior of each graft immediately after fixation, it is still unknown how the initial tension changes during the postoperative course and how these changes affect the knee conditions for a long term. In addition, a large variation in initial graft tension, fixation angle, and fixation method exists among reported clinical studies. Accordingly, the advantages or adverse effects of the proposed conditions have not yet been clarified. The optimal condition still needs to be determined.

Conclusions

Accumulative biomechanical and clinical evidences have shown the advantages of anatomic double-bundle ACL reconstruction in the restoration of normal knee kinematics over the conventional single-bundle ACL reconstruction. Various surgical techniques of anatomic double-bundle ACL reconstruction have been reported and the surgical key points which the surgeons should know have also been described in many reports. However, there has still been a great variability in surgical techniques among reports. More detailed information and improvement of surgical techniques are required to more closely restore the functions of native ACL.

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