Anatomic Anterior Cruciate Ligament Reconstruction: Surgical Techniques

94

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Contents

Abstract

Rupture of the anterior cruciate ligament (ACL) is a common sports injury. In order to return to their pre-injury level, many patients elect to undergo an ACL reconstruction. Over the past decade, the concept of ACL reconstruction has evolved from a surgical technique that emphasized placement of the ACL femoral tunnel at a location that minimized the change in length of the ACL graft with flexion/extension of the knee (isometry) and placement of the tibial tunnel at a location that minimized the potential for roof impingement to a surgical technique in which the bone tunnels are placed within the native ACL attachment sites (anatomic ACL reconstruction). This chapter will review the anatomy and biomechanics of the ACL, define what an anatomic ACL reconstruction is and where to place the bone tunnels, and compare the location and ACL graft orientation achieved by the transtibial, anteromedial portal, and outside–in surgical techniques.

Introduction

Rupture of the anterior cruciate ligament (ACL) is common in sports involving cutting, pivoting, deceleration or sudden stops, and landing from a jump (Olsen et al. 2004; Hewett et al. 2005; Krosshaug et al. 2007; Silvers and Mandelbaum 2007; Zantop and Petersen 2008; Koga

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M.N. Doral, J. Karlsson (eds.), *Sports Injuries*,
DOI 10.1007/978-3-642-36569-0_260

et al. 2010). The incidence of ACL rupture has been reported to be 1 in 3,000 people in the general population in the United States (Miyasaka et al. 1991). In order to return to their pre-injury status, many patients elect to undergo ACL reconstruction. The incidence of ACL reconstruction has been reported to be 29.6–52 per 100,000 in the general population (Csintalan et al. 2008; Janssen et al. 2012). ACL reconstruction is the fourth most commonly performed procedure by the American Board of Orthopaedic Surgery applicants in their first 2 years of practice (Harner et al. 2003). In the United States alone, it is estimated that approximately 300,000 ACL reconstructions are performed annually (Chang et al. 2013). Most isolated ACL ruptures occur as a result of a noncontact, deceleration, valgus-external rotation injury (Olsen et al. 2004; Hewett et al. 2005; Krosshaug et al 2007; Silvers and Mandelbaum 2007; Zantop and Petersen 2008; Koga et al. 2010). Other mechanisms for noncontact ACL injuries include hyperextension and hyperflexion of the knee (Olsen et al. 2004; Krosshaug et al 2007; Silvers and Mandelbaum 2007; Zantop and Petersen 2008; Koga et al. 2010). A complete rupture of the ACL may result in chronic instability of the knee, which can lead to meniscal tears, secondary damage to the articular cartilage, and an early onset of osteoarthritis (Jonsson et al. 2004; Andriacchi et al. 2006; Stergiou et al. 2007; Andriacchi et al. 2009; Yasada et al. 2011). Restoring stability to the knee is therefore an important goal when treating patients with a torn ACL. This chapter will review the anatomy and biomechanics of the ACL, define what an anatomic ACL reconstruction is and where to place the bone tunnels, and compare the location and ACL graft orientation achieved by the transtibial, anteromedial portal, and outside–in surgical techniques.

Anatomy and Biomechanics of the ACL

Differing terms are often used to describe locations and directions in the knee. The use of differing terms is often a source of confusion when reading anatomical studies and surgical technique papers related to the ACL. Anatomical terms, such as proximal, distal, anterior, and posterior, are used to describe positions and directions in the extended knee. Arthroscopic terminology, high (superior), low (inferior), shallow, and deep, is used to describe the knee at 90° flexion, as viewed by the arthroscopic surgeon (Amis and Jakob 1998; Edward et al. 2008; Karlsson et al. 2011). To avoid confusion, in this chapter locations and directions in the knee will be described according to the above convention (Fig. 1).

The femoral attachment of the ACL has an oval- or elliptical-shaped attachment site on the lower third of the inner wall of the lateral femoral condyle (Girgis et al. 1975; Bach 1989; Bernard et al. 1997; Harner et al. 2003; Columbet et al. 2006; Heming et al. 2007; Edward et al. 2008; Purnell et al. 2008; Tsukada et al. 2008; Feretti et al. 2012; Fig. 2). There are no ACL fibers which attach directly to the roof of the intercondylar notch (Purnell et al. 2008; Fig. 3). There is a great deal of variation in the size of the ACL femoral attachment site (Harner et al. 2003; Edward et al. 2008; Kopf et al. 2009, 2011). The length of the ACL femoral attachment site has been reported to range from 14 to 23 mm, and the width from 7.8 to 11.2 mm (Columbet et al. 2006; Heming et al. 2007; Baer et al. 2008; Edward et al. 2008; Purnell et al. 2008; Kopf et al. 2009; Sasaki et al 2012). Arthroscopic measurements using a malleable ACL ruler in 137 patients undergoing primary ACL reconstruction found the length of the ACL femoral attachment site to vary from 12 to 20 mm, with a mean length of 16.5 mm (Kopf et al. 2012). In two-thirds of the patients, the ACL femoral attachment site length was between 16 and 18 mm; 25 % had an attachment site length less than 16 mm, and 11 % had an attachment site length greater than 18 mm (Kopf et al. 2012). The ACL femoral attachment site is defined by two bony ridges located on the lower third of the inner side of the lateral femoral condyle, the lateral intercondylar and the lateral bifurcate ridges (Fu and Jordan 2007; Baer et al. 2008; Purnell et al. 2008; Shino et al. 2010; van Eck et al. 2010; Ziegler et al. 2011; Feretti et al. 2012; Sasaki et al. 2012; Fig. 4). The lateral intercondylar

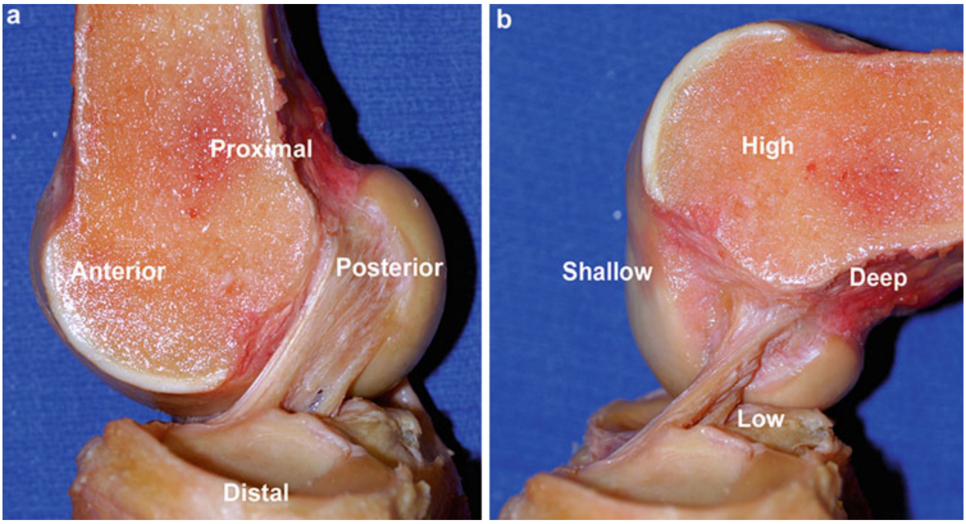


Fig. 1 This figure illustrates the anatomic terminology versus the arthroscopic terminology as demonstrated in a right knee cadaveric specimen. (**a**), the knee is in full extension and the anatomic nomenclature is shown. (**b**), the knee is in 90° of flexion and the arthroscopic terminology is shown

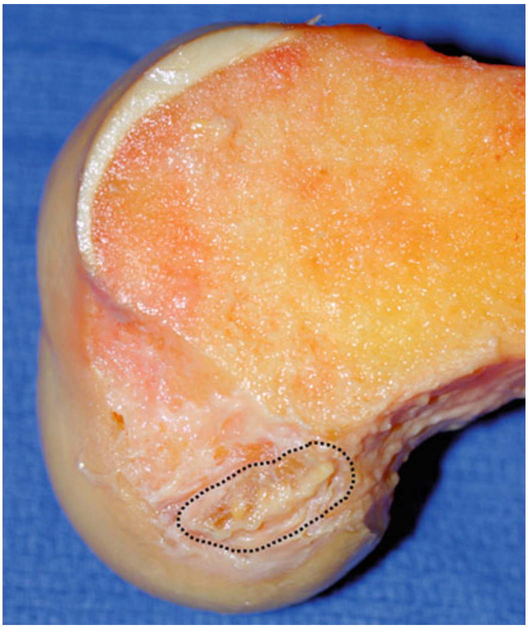


Fig. 2 Right knee. The fibers of the ACL attach to lower third of the medial wall of the lateral femoral condyle in the shape of an ellipse

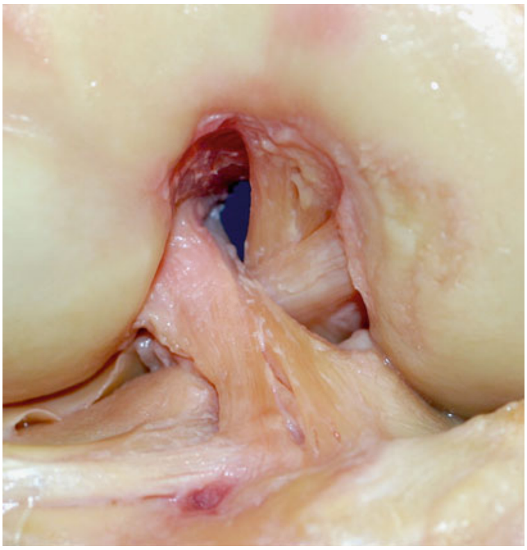


Fig. 3 Right knee. The femoral attachment of the ACL is entirely along the lateral wall of the intercondylar notch. There are no ACL fibers which directly insert onto the roof of the intercondylar notch

ridge, also called “the resident’s ridge,” was first described by Dr. William Clancy Jr. (Hutchinson and Ash 2003; Purnell et al. 2008). With the knee at 90° of flexion (arthroscopic position), the lateral intercondylar ridge runs from a deep to shallow position in the notch at a 35° angle with respect to the long axis of the femoral shaft (Purnell et al. 2008; Fig. 5). The lateral intercondylar ridge is an important bony landmark for the placement of the ACL femoral tunnel since it has been

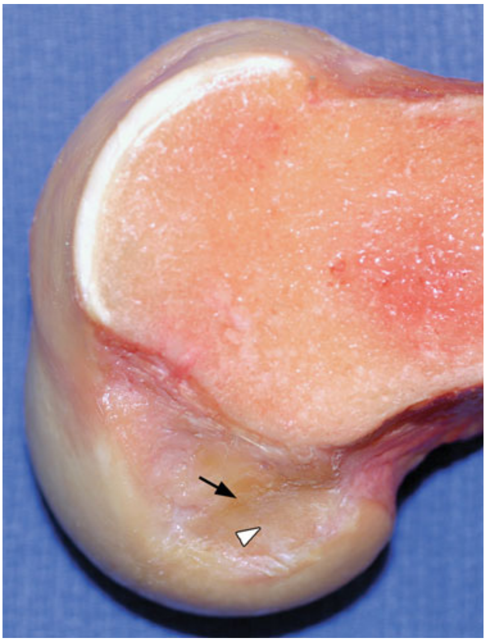


Fig. 4 Right knee. The ACL femoral attachment site is located on the lower third of the inner side of the lateral femoral condyle. The ACL femoral attachment site is defined by the lateral intercondylar ridge (*black arrow*) and the lateral bifurcate ridge (*white arrow head*)

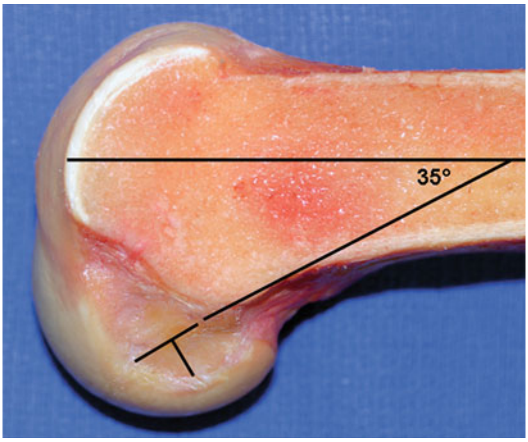


Fig. 5 The lateral intercondylar ridge runs from a deep to shallow position along the inner side of the lateral femoral condyle at a 35° angle with respect to the long axis of the femoral shaft

shown that the native ACL always attaches inferior (posterior) to this ridge (Baer et al. 2008; Purnell et al. 2008; Shino et al. 2010; Feretti et al. 2012; Sasaki et al. 2012). The lateral intercondylar ridge can be identified arthroscopically in 88 % of subacute and chronic ACL-deficient knees and is therefore a consistent anatomic landmark to assist the knee surgeon with anatomic placement of the ACL femoral tunnel (van Eck et al. 2010). The lateral bifurcate ridge runs perpendicular to the lateral intercondylar ridge and divides the ACL femoral attachment site into the attachment site areas for the anteromedial (AM) and posterolateral (PL) bundles (Feretti et al. 2012). The lateral bifurcate ridge was indentified arthroscopically in only 48 % of subacute and chronic knees (van Eck et al. 2010).

The ACL inserts onto the tibia in a depression or fovea in the anterior intercondylar area between the medial and lateral tibial plateaus (condyles) (Purnell et al. 2008; Ziegler et al. 2011). Confusion exists in the terminology used to describe bony landmarks in the anterior intercondylar area. Using anatomic terminology the bony landmarks are the intercondylar eminence (tibial spine), which lies between the medial and lateral tibial condyles; the medial and lateral intercondylar tubercles, which lie at the ends of the intercondylar eminence and are often incorrectly called the medial and lateral tibial spines; and the medial intercondylar ridge of the tibia, which is an anterior extension of the medial intercondylar tubercle (Purnell et al. 2008; Ziegler et al. 2011; Fig. 6). The posterior fibers of the ACL insert onto the tibia just anterior to a curved ridge (the ACL ridge) that runs between the medial and lateral intercondylar tubercles (Purnell et al. 2008). There are no ACL fibers which insert directly on the intercondylar eminence. Medially, the ACL inserts just lateral to and not onto the tip of the medial intercondylar tubercle (Edward et al. 2008; Purnell et al. 2008; Feretti et al. 2012). The medial border of the ACL tibial attachment site is defined by a distinct bony ridge, the medial intercondylar ridge of the tibia (Purnell et al. 2008). The medial intercondylar ridge of the tibia extends anteriorly from the medial intercondylar tubercle. Medially, the ACL fibers insert directly onto this ridge. There are no ACL fibers that insert medial to this ridge. There is no distinct lateral border of the ACL; the fibers blend

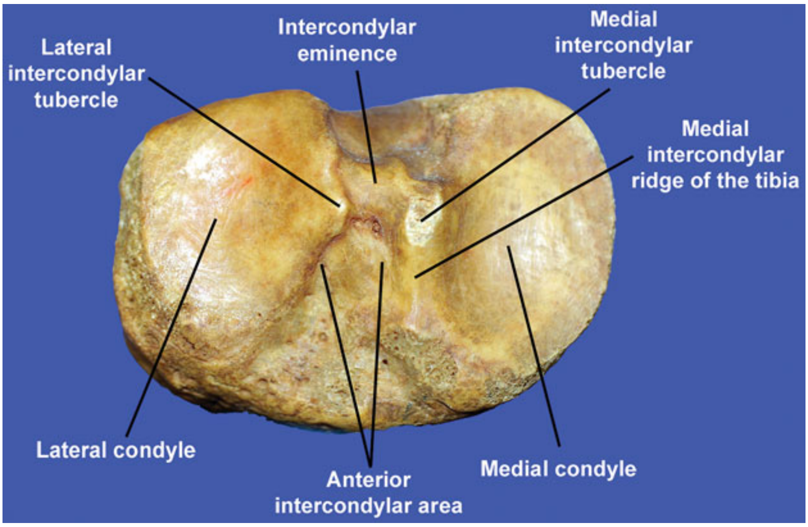


Fig. 6 Right knee. Bony topography of the proximal tibia

Fig. 7 Right knee. The majority of the ACL fibers insert onto the tibia anterior to posterior edge of the anterior horn of the lateral meniscus

into the anterior horn of the lateral meniscus. The majority of the ACL fibers insert onto the tibia anterior to the posterior edge of the anterior horn of the lateral meniscus (Fig. 7). The anterior border of the ACL tibial attachment site is marked by the intermeniscal or transverse ligament (Kongcharoensombat et al. 2011).

The ACL tibial attachment site has been reported to be wider and longer than the ACL femoral attachment site and the shape to vary from oval to triangular (Harner et al. 1999; Edwards et al. 2007; Kongcharoensombat et al. 2011). Similar to the ACL femoral attachment site, there is great variation in the length and width of the ACL tibial attachment site (Edwards et al. 2007; Heming et al. 2007; Purnell et al 2008; Kopf et al. 2009, 2011; Hwang et al 2012). In human cadaveric knees, the length of the ACL tibial attachment site has been reported to range from 14 to 29 mm, and the width from 9 to 12.7 mm (Edwards et al. 2007; Heming et al. 2007; Purnell et al 2008; Kopf et al. 2009, 2011; Hwang et al. 2012). Arthroscopic measurements with a malleable ACL ruler in 137 patients undergoing ACL reconstruction found the length of the ACL tibial attachment site to range from 12 to 22 mm with a mean value of 17 mm (Kopf et al. 2011). In two-thirds of the patients, the length of the ACL tibial attachment site was between 16 and 18 mm; in approximately half of the remaining patients, the tibial attachment site length was less than 16 mm, and in the other remaining half greater than 18 mm.

It is generally accepted that the ACL consists of two functional bundles, the anteromedial (AM) and the posterolateral (PL) bundles (Girgis et al. 1975; Harner et al. 1999; Columbet et al. 2006; Edwards et al. 2007; Petersen and Zantop 2007; Baer et al. 2008; Edwards et al. 2008; Tsukada et al. 2008; Yasada et al. 2011; Ziegler et al. 2011). The two bundles are named according to their insertion onto the tibia (Fig. 8). Although there is debate as to

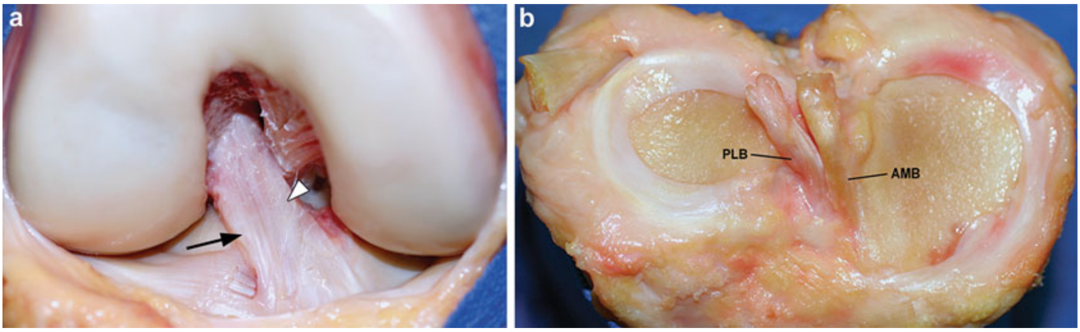


Fig. 8 Right knee. (**a**), the anteromedial (*AM*) bundle fibers are shown by the *white arrow head* and the posterolateral (*PL*) bundle fibers by the *black arrow*. (**b**), the bundles are named according to their insertion onto the tibia. The AM bundle fibers attach anterior and medial and the PL bundle fibers posterior and lateral

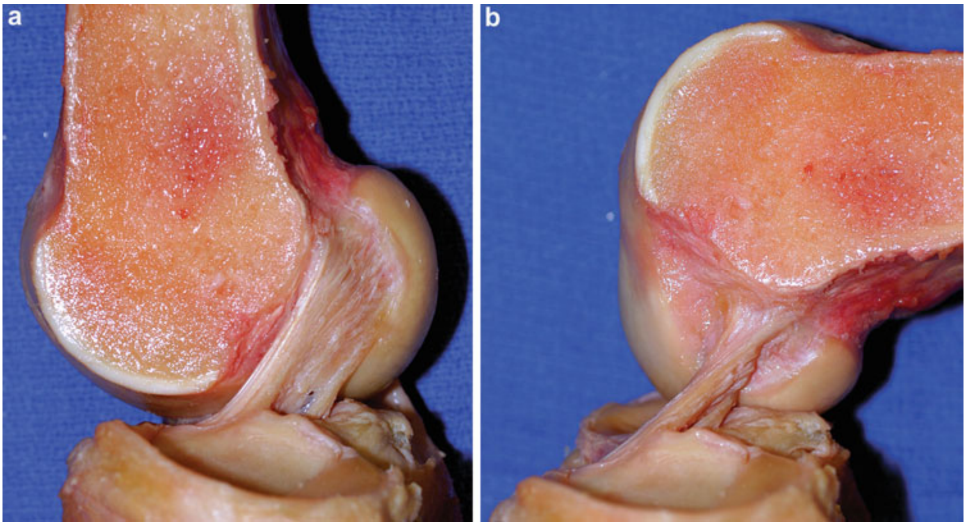


Fig. 9 Right knee. (**a**), in extension the PL bundle is tight and the AM bundle slightly relaxed. (**b**), in flexion the PL bundle is slack and the AM bundle is tight

whether there is a true anatomic division of the ACL into two bundles, it is generally agreed that two separate bundles can be distinguished by the tension that varies in the ligament fibers with flexion/extension of the knee (Girgis et al. 1975; Petersen and Zantop 2007; Baer et al. 2008; Noyes 2009; Yasada et al. 2011; Amis 2012). With the knee in extension, the ACL femoral attachment site is vertically oriented and the PL bundle is tight and the AM bundle is slightly relaxed (Amis and Dawkins 1991; Petersen and Zantop 2007; Baer et al. 2008; Yasada et al. 2011; Amis 2012) With flexion of the knee, the ACL femoral attachment site rotates and becomes more horizontal, the PL bundle fibers shorten and slacken, and the AM bundle fibers lengthen and tighten (Girgis et al. 1975; Amis and Dawkins 1991; Petersen and Zantop 2007; Baer et al. 2008; Yasada et al. 2011; Amis 2012; Fig. 9).

The ACL is the primary restraint against anterior tibial translation, providing 87 % of the total restraining force at 30° of flexion and 85 % at 90° of flexion (Butler et al. 1980). The ACL is a secondary restraint against valgus and varus rotation (Grood 1992). The ACL may act as restraint to internal tibial rotation, but there are conflicting data and opinions on this point (Zantop et al. 2007; Jones and Grimshaw 2011; Amis

2012). Some studies have shown that sectioning of the entire ACL leads to a small increase in internal tibial rotation (Zantop et al. 2007; Jones and Grimshaw 2011; Amis 2012). However, this small increase (2–4°) may be difficult to detect clinically and therefore may not be clinically relevant (Jones and Grimshaw 2011; Amis 2012). Other studies have shown that the ACL has no effect on resisting internal tibial rotation. Internal tibial rotation is resisted primarily by the lateral extra-articular structures (Nakamura et al. 2009). At the present time, the role of the ACL in resisting internal tibial rotation is unclear. One of the primary functions of the ACL is to resist the combined motions of anterior tibial translation and internal tibial rotation and the resulting anterior subluxation of the lateral and medial compartments that represent the pivot-shift phenomenon (Zantop et al. 2007; Nakamura et al. 2009; Jones and Grimshaw 2011; Amis 2012). As a result of their changing tensioning patterns during flexion/extension of the knee, the two ACL bundles play different roles in restoring the stability of the knee. The AM bundle is dominant in resisting anterior tibial translation in the flexed knee, whereas the PL bundle is more important in resisting anterior tibial translation in the extended knee (Amis 2012). It has been hypothesized that the two ACL bundles have different roles with respect to controlling rotational motion of the knee. It has been postulated that the AM bundle which is more vertically oriented in the coronal plane and more closely aligned with the axis of rotation plays a much smaller role in controlling tibial rotation compared to the PL bundle (Amis 2012). Due to the fact that the PL bundle is oriented more horizontally in the coronal plane and better aligned to mechanically resist tibial rotation, it has been postulated that the PL bundle plays a more important role in controlling tibial rotation compared to the AM bundle (Amis 2012). However, biomechanical studies have found conflicting results with respect to the role that the two ACL bundles play in controlling rotation. Most studies have shown only small increases in tibial rotation after sectioning the PL bundle alone (Zantop et al. 2007; Jones and Grimshaw 2011; Amis 2012).

Evolution of Intra-articular ACL Reconstruction

Over the last decade, the concept of ACL reconstruction has evolved from a surgical technique in which the objectives were placement of the ACL femoral tunnel at a location that minimized the change in length of the ACL graft with flexion/extension of the knee (isometry) and placement of the tibial tunnel at a location that minimized the potential for roof and PCL Posterior Cruciate Ligament impingement toward an “anatomic” surgical technique which attempts to reproduce the anatomy of the native ACL (Karlsson et al. 2011; van Eck et al. 2011; Schindler 2012; Brown et al. 2013; Chambat et al. 2013; Fig. 10). This change was prompted by the recognition that positioning the ACL femoral tunnel at the most isometric location on the lateral femoral condyle and positioning the ACL tibial tunnel in a location that avoided roof and PCL impingement of the ACL graft would often result in the bone tunnels of the ACL reconstruction lying outside of the native ACL attachment sites (Yaru et al. 1992; Arnold et al. 2001; Kopf et al. 2010; Marchant et al. 2010; Kopf et al. 2012; Chambat et al. 2013; Iriuchishima et al. 2013).

It was understood early on that in order to meet the simultaneous requirements of maintaining knee joint stability and allowing a full range of motion, an intra-articular ACL replacement graft could not be placed at liberty within the knee joint (Graf 1987; Sapega et al. 1990; Grood 1992; Bylski-Austrow et al. 1993). Placement of the ACL graft in a position where it would undergo excessive lengthening (tightening) would lead to graft failure or loss of motion, and placement of the graft in a location where it would undergo excessive slackening or loosening would cause pathologic laxity of the knee (Sapega et al. 1990; Grood 1992). The concept of “isometry” was developed as a solution to minimize excessive tightening and slackening of the ACL graft (Graf 1987; Schindler 2012). The goal of “isometric” ACL graft placement was to place the ACL graft in a location that would allow full range of motion of the knee while minimizing elongation of the

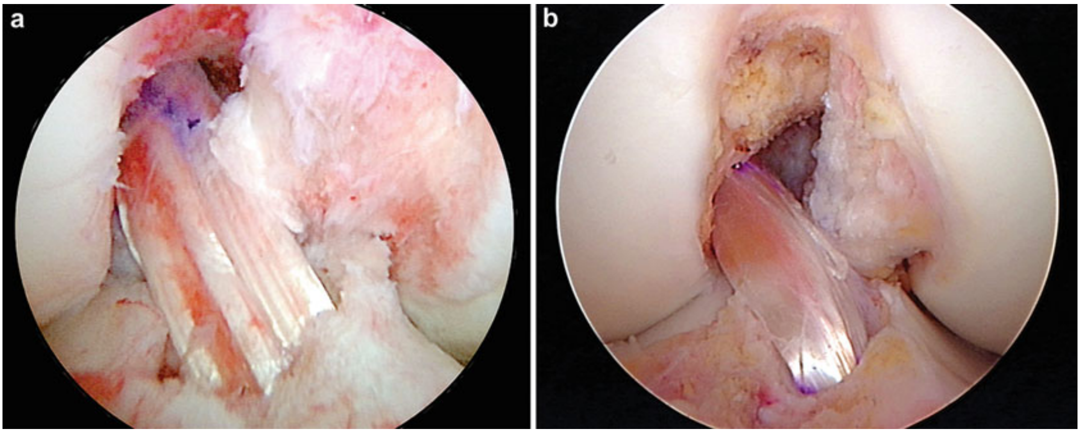


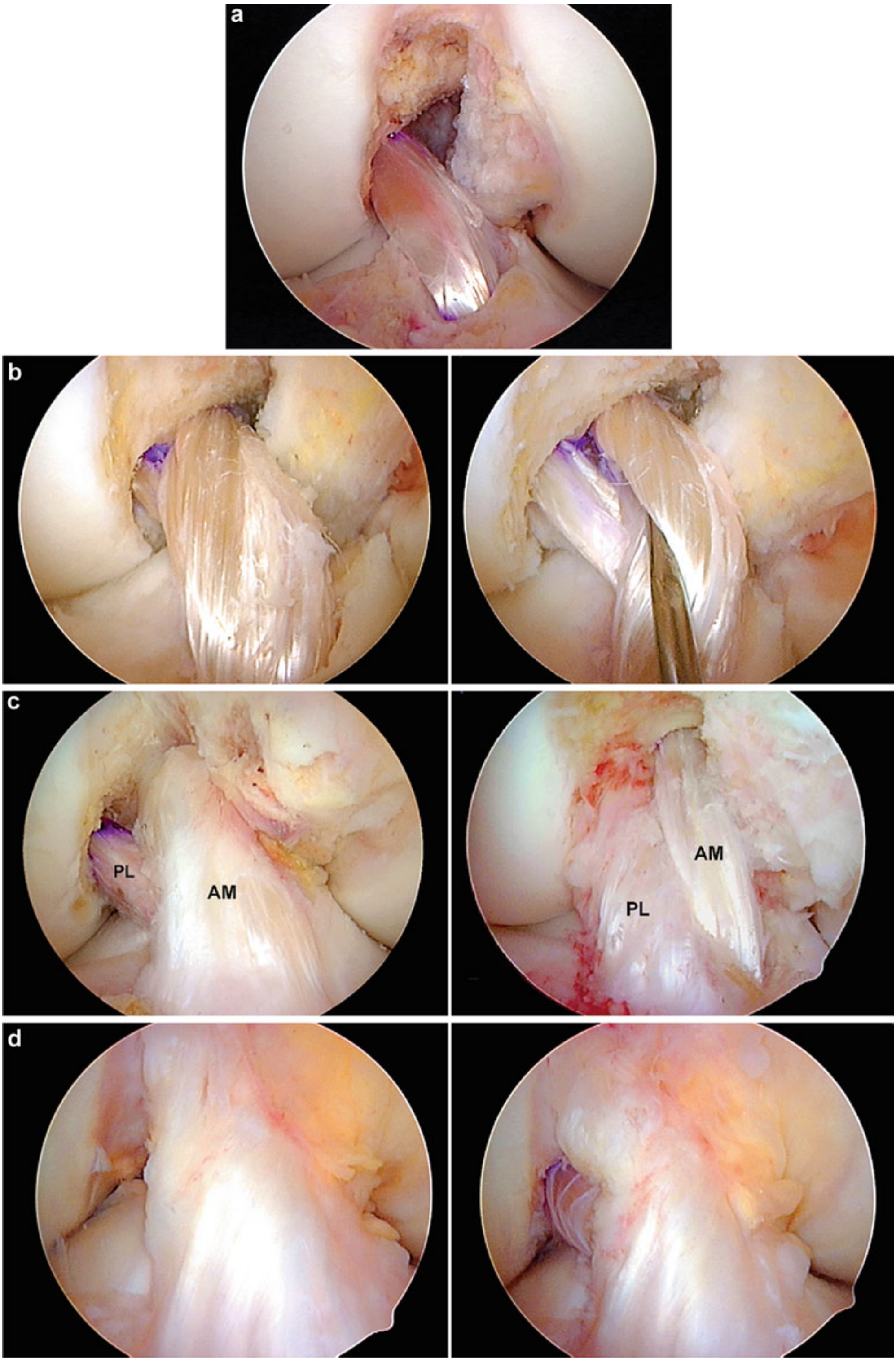
Fig. 10 (**a**), isometric-positioned ACL femoral tunnel. The tibial tunnel is positioned in the posterior half of the native ACL tibial attachment site. (**b**), anatomic ACL reconstruction. The tibial and femoral tunnels are positioned at the center of the native ACL attachment sites

graft (Graf 1987; Sapega et al. 1990; Schindler 2012). Experimental studies demonstrated that the most "isometric" location required the ACL femoral tunnel to be placed higher and deeper in the notch than the native ACL femoral attachment site (Graf 1987; Siddles et al. 1988; Hefzy et al. 1989; Sapega et al. 1990; Schindler 2012). In order to reach this "isometric" femoral tunnel position with a transtibial technique and to simultaneously avoid roof impingement of the ACL graft, it was necessary to position the ACL tibial tunnel in the posterior part of the native ACL tibial attachment site (Yaru et al. 1992; Noyes 2009; Kopf et al. 2010; Marchant et al. 2010; Kopf et al. 2012; Iriuchishima et al. 2013). The combination of a high-deep ACL femoral tunnel and a posterior ACL tibial tunnel produced a nonanatomic ACL graft which was vertically oriented in the sagittal and coronal planes (Heming et al. 2007; Hantes et al. 2009; Noyes 2009; Kopf et al. 2010; Marchant et al. 2010; Bowers et al. 2011; Kopf et al. 2012; Iriuchishima et al. 2013). Biomechanical and clinical studies have demonstrated that a vertical ACL graft may control anterior tibial translation but often fails to control the combined motions of anterior tibial translation and internal tibial rotation which occur during the pivot-shift phenomenon (Yagi et al. 2002; Loh et al. 2003; SCopp et al. 2004; Yamamoto et al. 2004; Musahl et al. 2005; Heming et al. 2007; Lee et al. 2007; Moisala et al. 2007; Noyes 2009; Ristanis et al. 2009; Steiner et al. 2009; Herbort et al. 2010; Kato et al. 2010; Marchant et al. 2010; Bedi et al. 2011; Kondo et al. 2011; Sadoghi et al. 2011; Driscoll et al. 2012; Park et al. 2012; Inderhaug et al. 2013; Kato et al. 2013). The inability of a vertical ACL graft to control the pivot-shift phenomenon may result in the patient continuing to complain of instability symptoms and experiencing giving-way episodes despite having an intact ACL graft and normal or near-normal anterior tibial translation (Lee et al. 2007; Marchant et al. 2010; Inderhaug et al. 2013). It has been proven biomechanically and clinically that placing the bone tunnels of the ACL graft within the native ACL attachment sites better restores anterior tibial translation, rotational stability, and normal knee kinematics compared to an "isometric," nonanatomic ACL reconstruction (Yagi et al. 2002; Scopp et al. 2004; Yamamoto et al. 2004; Musahl et al. 2005; Moisala et al. 2007; Steiner et al. 2009; Alentorn-Geli et al. 2010; Herbort et al. 2010; Kato et al. 2010; Bedi et al. 2011; Kondo et al. 2011; Sadoghi et al. 2011; Driscoll et al. 2012; Hussein et al. 2012a; Kato et al. 2013; Wang et al. 2013). In an attempt to improve knee kinematics and rotational stability after ACL reconstruction, the concept of anatomic ACL reconstruction has emerged.

What Is Anatomic ACL Reconstruction?

According to van Eck et al. (2011), "Anatomic ACL reconstruction is defined as the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites." Operationally, an "anatomic" ACL reconstruction refers to a single-bundle (SB) or double-bundle (DB) reconstruction, an ACL augmentation or remnant preservation procedure, or a revision ACL reconstruction in which the femoral and tibial bone tunnels are placed within the native ACL attachment sites. According to Karlsson et al. (2011), there are four principles of anatomic ACL reconstruction. The first principle of anatomic ACL reconstruction is to reproduce as closely as possible the size, shape, and location of the native ACL attachment sites (Karlsson et al. 2011; Siebold 2011; van Eck et al. 2011). The second principle is to restore the two functional bundles of the ACL (Karlsson et al. 2011; van Eck et al. 2011). In order to create an ACL graft that mimics the functional behavior of the two ACL bundles, it is necessary to reproduce the size, shape, and location of the native ACL attachment sites. The third principle is that the ACL graft should reproduce the tensioning pattern of the native ACL (Karlsson et al. 2011; van Eck et al. 2011). The AM bundle fibers of the native ACL are taut throughout the range of motion, while the PL bundle fibers tighten rapidly during the last 30° of extension (Amis and Dawkins 1991; Amis 2012). The reconstructed ACL graft should mimic this tensioning pattern. The final principle of anatomic ACL reconstruction is to individualize the surgical procedure for each patient. Every patient and every knee is different, so the same surgical procedure may not necessarily be performed in each case (Karlsson et al. 2011; van Eck et al. 2011; Hussein et al. 2012b). A commonly held misconception is that anatomic ACL reconstruction implies that the surgeon must perform a DB ACL reconstruction. It is important to recognize that anatomic ACL reconstruction is a concept and not a specific surgical procedure, and reproducing the two functional bundles of the ACL does not always require the surgeon to perform a DB ACL reconstruction. The concept of anatomic ACL reconstruction can be applied to a SB reconstruction, a DB reconstruction, an augmentation procedure for a partial ACL tear, an ACL remnant preservation procedure, and a revision ACL reconstruction with an intact ACL graft (Fig. 11). The specific surgical procedure should be based on the ACL injury pattern (complete ACL tear, partial ACL tear, ACL injury with intact ACL remnants), the size of the native ACL attachment sites, and the degree of rotational laxity (Hussein et al. 2012b; Hofbauer et al. 2013). Hussein et al. (2012b) have shown that when anatomic ACL reconstructions are individualized to the size, shape, and orientation of the patient's native ACL, SB and DB ACL reconstructions yield similar subjective and objective results.

One of the major objectives of anatomic ACL reconstruction is to reproduce as closely as possible the size, shape, and location of the native ACL attachment sites (Karlsson et al. 2011; Siebold 2011; van Eck et al. 2011). During surgery, a malleable ACL ruler can be used to measure the length and width of the ACL attachment sites (Kopf et al. 2011; Siebold 2011; Brown et al. 2013; Fig. 12). These measurements can be helpful to the surgeon when selecting the type of ACL replacement graft and the surgical procedure (Siebold 2011). Four-strand hamstring tendon grafts may adequately restore 12–14 mm-long ACL attachment sites, whereas attachment sites that are 16 mm or longer may be better restored with larger-diameter ACL grafts such as 5- and 6-strand hamstring tendon grafts, a bone–patellar tendon–bone graft, or a quadriceps tendon graft (Siebold 2011; van Eck et al. 2011). Restoring the maximum percentage of the ACL attachment sites requires performing a DB ACL reconstruction (Siebold 2011; van Eck et al. 2011). This concept is supported by recent clinical studies that have demonstrated a higher failure rate for hamstring



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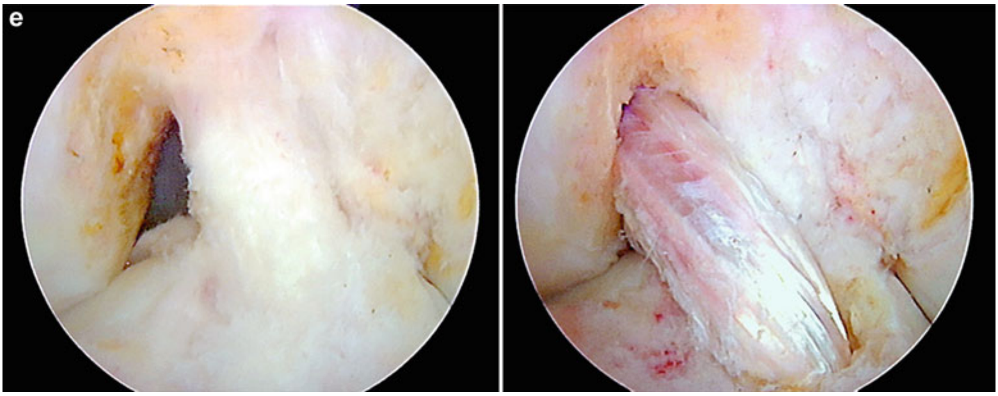

Fig. 11 (**a**), single-bundle ACL reconstruction. (**b**), double-bundle ACL reconstruction. (**c**), (*left*) PL bundle augmentation, (*right*) AM bundle augmentation. (**d**), ACL remnant preservation. (**e**), revision ACL reconstruction with intact ACL graft

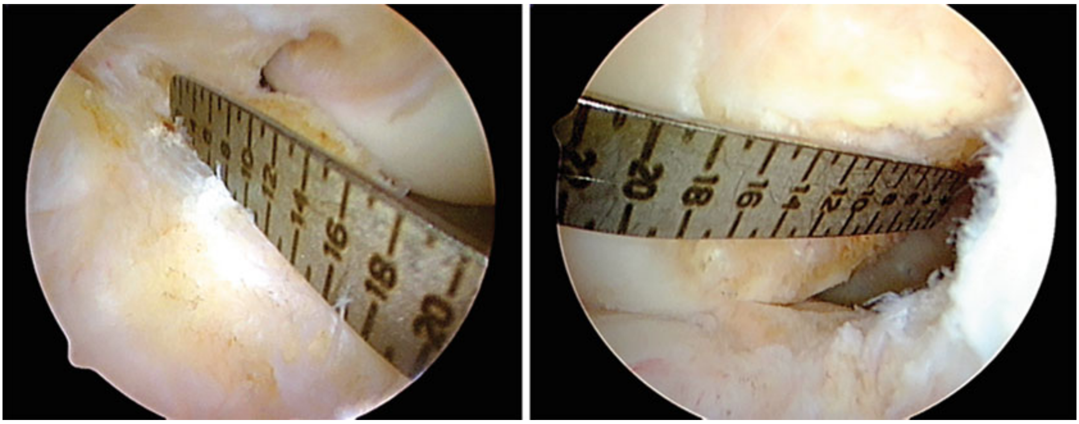

Fig. 12 Malleable ACL ruler is used to measure the length of the ACL tibial (*left*) and femoral attachment sites

tendon ACL reconstructions when the diameter of the hamstring tendon ACL graft is less than 8 mm (Magnussen et al. 2012; Park et al. 2012).

ACL Graft Placement

Proper placement of the ACL graft is critical to the success and clinical outcome of ACL reconstruction (Grood 1992; Wetzler et al. 1998; Getelman and Friedman 1999; Sommer et al. 2000; Loh et al. 2003; Jonsson et al. 2004; Musahl et al. 2005; Moisala et al. 2007; Ristanis et al. 2009; Marchant et al. 2010; Wright et al. 2010; Sadoghi et al. 2011; Trojani et al. 2011; Lind et al. 2012; Whitehead 2013). Malposition of the ACL bone tunnels is the most common technical error leading to recurrent instability and a failed ACL reconstruction (Wetzler et al. 1998; Getelman and Friedman 1999; Sommer et al. 2000; Marchant et al. 2010; Wright et al. 2010; Kamath et al. 2011; Trojani et al. 2011; Lind et al. 2012; Whitehead 2013). Proper placement of the ACL femoral tunnel is especially important because the length and tension of the ACL graft are most influenced by the position of the ACL femoral tunnel (Hefzy and Grood 1986; Hefzy et al. 1989; Grood 1992; Bylski-Austrow et al. 1993). Malposition of the ACL femoral tunnel can cause the ACL graft to undergo

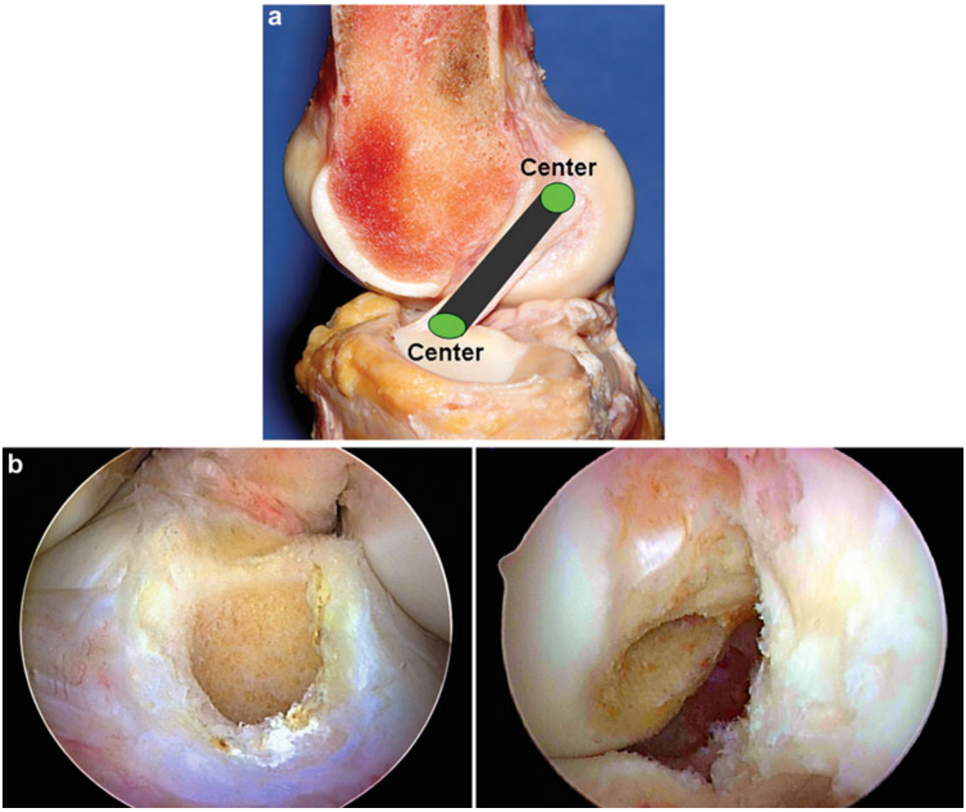

Fig. 13 (**a**), Center-to-center placement for single-bundle ACL reconstruction. (**b**), tibial (*left*) and femoral (*right*) bone tunnels for single-bundle ACL reconstruction are placed at the center of the native ACL attachment sites

excessive tightening or loosening with range of motion of the knee. Excessive loosening of the ACL graft can result in pathologic laxity of the knee, whereas excessive tightening may result in graft failure or loss of motion of the knee. Biomechanical and clinical studies have also shown that proper placement of the ACL femoral tunnel plays an important role in controlling tibial rotation (the pivot-shift phenomenon) and anterior translation of the tibia (Lachman and anterior drawer test) (Yagi et al. 2002; Loh et al. 2003; Scopp et al. 2004; Yamamoto et al. 2004; Musahl et al. 2005; Lee et al. 2007; Moisala et al. 2007; Ristanis et al. 2009; Steiner et al. 2009; Kato et al. 2010; Marchant et al. 2010; Bedi et al. 2011; Kondo et al. 2011; Sadoghi et al. 2011; Driscoll et al. 2012; Kato et al. 2013). It has been hypothesized that abnormal tibial rotation following ACL reconstruction, as well as in the ACL-deficient knee, plays an important role in the development of osteoarthritis (Jonsson et al. 2004; Andriacchi et al. 2006; Stergiou et al. 2007; Andriacchi et al. 2009; Wang et al. 2013). Proper placement of the ACL femoral tunnel is therefore critical to achieving a full range of motion and restoring stability to the knee and ultimately trying to prevent the long-term development of osteoarthritis.

This chapter will focus on recommendations for SB ACL reconstruction, as globally it is the most common surgical technique used to perform an ACL reconstruction (Chechik et al. 2013). For SB ACL reconstruction, it has been recommended that the bone tunnels be placed at the center of the native ACL femoral and tibial attachment sites (Karlsson et al. 2011; Kondo et al. 2011; van Eck et al. 2011; Hussein et al. 2012a, b; Brown et al. 2013; Fig. 13). This recommendation is based on biomechanical and clinical studies which demonstrate that compared to PL, high AM graft placement, or other matched ACL tunnel positions located within the native ACL attachment sites, a SB ACL graft placed at the center of the native ACL attachment sites is more effective at controlling anterior tibial translation and the pivot-shift phenomenon and more closely reproduces normal knee kinematics (Herbort et al. 2010; Kato et al. 2010; Kondo et al. 2011; Hussein et al. 2012a; Kato et al. 2013). Although, not all surgeons agree with the concept of center-to-center placement for anatomic SB ACL reconstructions, it is widely accepted that the bone tunnels for an anatomic ACL reconstruction should be placed within the native ACL attachment sites. Using the center of the ACL femoral attachment site as a defined anatomic reference point, surgeons may choose to place their ACL bone tunnels in the native ACL femoral attachment site according to different philosophies. Moving the center of the ACL femoral tunnel toward the center of the AM bundle will result in a more isometric, vertical ACL graft that experiences lower in situ graft forces. ACL grafts which experience lower in situ graft forces may be less likely to rupture. However, the lower rupture rate may come at the expense of inferior rotational control and increased shear forces on the articular cartilage which may predispose the development of early osteoarthritis. Moving the center of the ACL femoral tunnel toward the central region of the native ACL attachment site and the region of the PL bundle fibers will result in an anisometric ACL graft that undergoes larger length changes with flexion/extension of the knee. ACL grafts placed in this region will demonstrate rapid tightening in the last 20° of extension. Although placing the ACL graft in central and shallow region of the native ACL attachment site will result in greater length changes with flexion/extension of the knee, the resulting ACL graft will be more horizontally oriented and thus better aligned to control rotational laxity. However, the better rotational control of this graft placement may come at the expense of higher in situ ACL graft forces and possibly a higher graft rupture rate.

ACL Reconstruction Surgical Techniques

The two-incision, arthroscopically assisted intra-articular ACL reconstruction surgical technique was first introduced in the mid-1980s (Bach 1989; Schindler 2012; Chambat et al. 2013). In the two-incision surgical technique, the ACL femoral tunnel is drilled independent of the tibial tunnel from an outside–in direction through a small distal femoral incision. With independent drilling of the ACL femoral tunnel, it is possible to consistently position the ACL femoral tunnel within the native ACL femoral attachment site (Abebe et al. 2009; Chang et al. 2013; Kim et al. 2013; Robert et al. 2013; Shin et al. 2013). The only disadvantage to drilling the ACL femoral tunnel using an outside–in drilling technique is the need to make a second distal femoral incision. However, with the development of new drill guides and retro reaming drills, outside–in drilling of the ACL femoral tunnel can now be accomplished through a small stab incision. Long-term clinical studies of ACL reconstructions performed using the two-incision approach with outside–in drilling of the ACL femoral tunnel have demonstrated excellent subjective and objective clinical outcomes with a low percentage of knees having a positive pivot-shift test (Bach et al. 1998).

The transtibial surgical technique was developed in the early 1990s (Hardin et al. 1992; McCulloch et al. 2007; Schindler 2012; Chambat et al. 2013). In the transtibial surgical technique, the ACL femoral tunnel is drilled through the ACL tibial tunnel. For the past 20 years, this has been the most popular surgical technique for ACL reconstruction. There were many reasons for the popularity of the transtibial technique. It eliminated the need to make a second incision, thus decreasing operating time and surgical morbidity. The technique also allowed reliable and reproducible isometric femoral tunnel placement. Since only one skin incision was required, the procedure was more cosmetically acceptable to patients. Another reason for the popularity of the technique was that it utilized an offset ACL femoral aimer which made the surgical procedure reproducible in the hands of the average knee surgeon. Other reasons for the popularity of the transtibial technique were that there was no need to hyperflex the knee. During surgery the ACL femoral tunnel could be drilled with the knee at the more familiar 90° of flexion, and in fact the technique was capable of producing longer femoral tunnel lengths which was advantageous when using suspensory ACL femoral fixation devices. The major disadvantage and limitation of the transtibial technique is that the position of the ACL femoral tunnel is dependent on the position of the ACL tibial tunnel. Drilling the ACL femoral tunnel through a posteriorly positioned ACL tibial tunnel often resulted in the ACL femoral tunnel being located high and deep ("high AM" position), outside of the native ACL femoral attachment site. The combination of a posterior tibial tunnel position and a high, deep ACL femoral tunnel position often produced a vertical ACL graft which controlled anterior tibial translation but often failed to control the pivot-shift phenomenon (Yagi et al. 2002; Loh et al. 2003; Scopp et al. 2004; Yamamoto et al. 2004; Musahl et al. 2005; Heming et al. 2007; Lee et al. 2007; Moisala et al. 2007; Noyes 2009; Ristanis et al. 2009; Steiner et al. 2009; Herbort et al. 2010; Kato et al. 2010; Marchant et al. 2010; Bedi et al. 2011; Kondo et al. 2011; Sadoghi et al. 2011; Driscoll et al. 2012; Park et al. 2012; Inderhaug et al. 2013; Kato et al. 2013). A 10-year follow-up study of hamstring ACL reconstructions performed using the transtibial technique found that although 86 % of the patients had normal or near-normal anterior tibial translation, 20 % had a positive pivot-shift test and 42 % had a pivot glide (Inderhaug et al. 2013).

Advocates of the transtibial technique have claimed that it is possible to position the ACL femoral tunnel in the center of the ACL femoral attachment site (Piasecki et al. 2011). However, it has been shown that in order to position the ACL femoral tunnel in the center of the ACL femoral attachment site, a very medial and proximal starting position for the ACL tibial tunnel must be chosen (Heming et al. 2007; Piasecki et al. 2011). This starting position may result in a very short tibial tunnel which limits the length of the ACL graft available for healing in the tibial tunnel. A short tibial tunnel may also result in a graft–tunnel mismatch which can compromise fixation of bone–patellar tendon–bone grafts. In the transtibial technique, anatomic ACL femoral tunnel placement is facilitated by drilling a 10–11 mm diameter tibial tunnel (Piasecki et al. 2011). A large-diameter tibial tunnel may allow the offset femoral tunnel to be rotated down the lateral wall of the intercondylar notch, thus achieving a more anatomic placement of the ACL femoral tunnel. However, due to the smaller tibial tunnels used for hamstring tendon ACL reconstructions, the transtibial drilling technique does not allow the surgeon to position the ACL femoral tunnel for a hamstring tendon ACL reconstruction within the native ACL femoral attachment site (Strauss et al. 2011).

The medial portal surgical technique for ACL reconstruction was first developed to address the issues of ACL graft laceration, violation of the posterior wall of the ACL femoral tunnel, divergence of ACL femoral interference screws, and graft–tunnel length mismatch associated with bone–patellar tendon–bone autograft ACL reconstructions performed using a transtibial technique (Schindler 2012; Brown et al. 2013). In the medial portal surgical technique, the ACL femoral tunnel is drilled through an anteromedial (AM) or accessory anteromedial (AAM) portal with the knee flexed to 120° or higher. Hyperflexion of the knee is necessary to avoid having the femoral guide pin exit the lateral soft tissues too posteriorly. The peroneal nerve and posterior neurovascular structures are at risk for injury when the femoral guide pin exits the lateral soft tissues in a too posterior position (Hall et al. 2008; Lubowitz 2009; Nakamura et al. 2009; Otani et al. 2011; Brown et al. 2013). Drilling the ACL femoral tunnel through a medial portal provides several advantages compared to the traditional transtibial technique (Brown et al. 2013). First, the ACL femoral tunnel is drilled independently of the tibial tunnel which allows the femoral tunnel to be consistently placed within the native

ACL femoral attachment site (Bowers et al. 2011; Chang et al. 2013; Kim et al. 2013; Robert et al. 2013; Shin et al. 2013). Secondly, the intra-articular and the external starting positions for the tibial tunnel and the angle of the tibial tunnel do not have to be chosen to accommodate drilling of the ACL femoral tunnel. Therefore, the surgeon can position the tibial tunnel in the center of the tibial attachment site and is free to drill a steeper and thus longer tibial tunnel. A longer tibial tunnel minimizes the potential for graft–tunnel length mismatch. Thirdly, in the medial portal technique, femoral interference fixation screws are inserted through the same medial portal which was used to drill the ACL femoral tunnel, thus minimizing screw–tunnel divergence. Finally, the medial portal technique provides improved arthroscopic visualization during ACL femoral tunnel drilling since the ACL femoral tunnel can be drilled under ideal arthroscopic conditions without the loss of joint distention due to fluid extravasation out of the tibial tunnel. Disadvantages of drilling the ACL femoral tunnel through a medial portal include the need to hyperflex the knee and the potential for short femoral tunnels (Lubowitz 2009). Hyperflexion can potentially compromise arthroscopic visualization and lead to spatial disorientation in the notch compared to drilling at the more familiar 90° of knee flexion (Lubowitz 2009). The introduction of flexible drills allows the ACL femoral tunnel to be drilled at 90° of flexion, so this disadvantage no longer necessarily exists. Unless special attention is paid to proper portal placement, drilling the ACL femoral tunnel through a medial portal can result in short femoral tunnel lengths (Lubowitz 2009; Bedi et al. 2010; Chang et al. 2011; Brown et al. 2013). A short femoral tunnel can potentially compromise ACL graft fixation when using suspensory femoral fixation methods. However, with attention to detail, these potential issues can usually be overcome (Brown et al. 2013). The fact that this technique allows independent drilling of the ACL femoral tunnel and allows for consistent anatomic ACL femoral tunnel placement is viewed by most surgeons as outweighing the disadvantages or technical challenges of the technique. As a result, the medial portal technique has become the preferred surgical technique for performing ACL reconstruction (Chechik et al. 2013).

Comparison of the Transtibial, Medial Portal, and Outside–In Drilling Techniques

The different surgical techniques for drilling the ACL femoral tunnel primarily affect the following parameters: ACL femoral tunnel length, angulation of the ACL femoral tunnel in the coronal and sagittal planes, the ability of the ACL femoral tunnel to cover the native ACL femoral attachment site, and the ability to accurately place the ACL femoral tunnel within the native ACL femoral attachment site. Bedi et al. (2010) investigated the effect of transtibial versus AM portal drilling on ACL femoral tunnel length and coronal plane obliquity of the ACL femoral tunnel in human cadaveric knees. AM portal drilling was found to achieve slightly greater ACL femoral tunnel obliquity compared to transtibial drilling. However, there was a much higher risk of short femoral tunnel lengths (<25 mm) and posterior tunnel wall blowout with AM portal drilling. The authors concluded that AM portal drilling achieved slightly greater ACL femoral tunnel obliquity but cautioned that there was a substantially greater risk of obtaining a short (<25 mm) femoral tunnel length and posterior wall blowout.

Chang et al. (2011) compared modified transtibial and AM portal drilling techniques with respect to ACL femoral tunnel obliquity and femoral length in 105 patients who underwent ACL reconstruction with a four-strand hamstring tendon autograft. Obliquity of the ACL femoral tunnel was measured on postoperative tunnel-view radiographs, and femoral tunnel length was directly measured at the time of surgery using a depth probe. The mean coronal obliquity of the ACL femoral tunnel in the transtibial group was 61.7° compared to 55.9° for the AM portal group, and the mean femoral tunnel length was 43.3 mm in the transtibial group and 34.2 mm in the AM portal group. Both of these differences were statistically significant. Twenty-six percent of the knees in the AM portal group had a femoral tunnel length less than 30 mm versus 1.8 % in the transtibial group. Similar to Bedi et al. (2010), the authors concluded that AM portal drilling can achieve a more oblique ACL femoral tunnel position, but the resulting femoral tunnels can be substantially shorter than tunnels obtained using the transtibial technique.

Larson et al. (2012) compared four different femoral tunnel drilling techniques in human cadaveric knees. In group 1, the ACL femoral tunnel was drilled using a transtibial technique. In group 2, the femoral tunnel was drilling through the AM portal with a rigid drill. In group 3, the femoral tunnel was drilled through the AM portal with a flexible reamer. In group 4, the femoral tunnel was drilled using an outside–in technique. Measurements of the ACL femoral tunnel length, tunnel aperture, and tunnel placement were made from 3-D CT scans. Although there was no significant difference between the groups regarding the length or width of the resulting ACL femoral tunnel, there was a trend toward femoral tunnels in group 3 having a longer length and cross-sectional area. Mean femoral tunnel length was as follows: transtibial = 42 mm, AM portal-rigid drill = 38 mm, AM portal-flexible drill = 29 mm, and outside–in = 32 mm. Transtibial tunnels were significantly longer than AM portal-flexible reamer tunnels. The AM portal-flexible drill group was closest to the length obtained with transtibial drilling. Mean coronal obliquity for transtibial drilling was 63°, AM portal-rigid drill was 61°, AM portal-flexible drill was 52°, and outside–in was 45°. The difference in coronal obliquity between outside–in and transtibial and outside–in and AM portal-rigid drill was statistically significant. This study demonstrates that outside–in drilling produces the most oblique femoral tunnels and transtibial drilling the most vertical.

Chang et al. (2013) compared AM portal drilling in 63 knees versus outside–in drilling in 54 knees that had undergone primary ACL reconstruction with a four-strand hamstring tendon autograft. Femoral tunnel positions were compared on a postoperative tunnel-view radiograph. There was no significant difference in the femoral tunnel obliquity or femoral tunnel length between the AM portal and outside–in groups. However, the AM portal group had a greater percentage of knees (14 % versus 0 %) with a femoral tunnel length of less than 30 mm. The authors concluded that outside–in drilling of the ACL femoral tunnel can achieve similar ACL femoral tunnel obliquity in the coronal plane as AM portal drilling with a smaller risk of the femoral tunnel being less than 30 mm.

Hantes et al. (2009) evaluated differences in ACL graft orientation between four-strand hamstring tendon autograft ACL reconstructions performed using transtibial and AM portal drilling techniques. Postoperative MRI scans were used to measure ACL graft orientation in the coronal and sagittal planes. The mean coronal plane ACL graft obliquity was 71° in the transtibial group compared to 52° for the AM group. There was no difference in the sagittal plane obliquity of the ACL graft between the two techniques. However, neither group was able to reproduce the sagittal inclination angle of the normal ACL. The ability of AM portal drilling to achieve a more oblique orientation of the ACL graft in the coronal plane was attributed to the fact that the ACL femoral tunnel was drilled independent of the tibial tunnel, thus giving the surgeon the freedom to place the ACL graft in a more anatomical position.

These studies demonstrate that AM portal and outside–in femoral tunnel drilling techniques achieve greater obliquity in the coronal plane but shorter femoral tunnels compared to transtibial drilling. The issue of short femoral tunnels can be addressed by drilling the ACL femoral tunnel through a low accessory anteromedial (AAM) portal (Tompkins et al. 2012; Brown et al. 2013; Tompkins et al. 2013). The medial-lateral placement of the AAM portal determines both the length and aperture shape of the ACL femoral tunnel (Hensler et al. 2011; Brown et al. 2013). Positioning the AAM portal more medially results in a more perpendicular orientation of the drill bit with respect to the lateral wall of the notch and produces a shorter ACL femoral tunnel length and a more circular-shaped tunnel aperture (Hensler et al. 2011; Brown et al. 2013). Positioning the

AAM portal more laterally, toward the medial border of the patellar ligament, orients the drill bit more obliquely with respect to the lateral wall of the notch and produces a longer ACL femoral tunnel length and a more elliptically shaped ACL femoral tunnel aperture (Hensler et al. 2011; Brown et al. 2013).

The ability to achieve acceptable (longer) ACL femoral tunnel length by drilling the femoral tunnel through an AAM portal has been confirmed by Tompkins et al. (2013). In this study the authors measured the ACL femoral tunnel length in 106 consecutive patients undergoing primary ACL reconstruction with drilling of the femoral tunnel through an AAM portal with the knee in maximum hyperflexion. During surgery, the ACL femoral tunnel length was measured directly using a depth probe. The average femoral tunnel length was 37 mm (range 26–45 mm) with all but one tunnel longer than 30 mm. The authors concluded that the use of an AAM portal for independent drilling of the femoral tunnel with the knee in maximum hyperflexion was capable of consistently producing ACL femoral tunnel lengths greater than 30 mm without posterior tunnel wall fractures.

The ability of different ACL femoral drilling techniques to accurately place the femoral tunnel within the native ACL attachment site and the ability of the different techniques to restore the geometry of the ACL femoral attachment site has also been investigated. Kaseta et al. (2008) compared the ability of two different ACL reconstruction techniques to place a femoral guide pin near the center of the ACL femoral attachment site in a human cadaver knee model. Two different methods of femoral guide pin placement were compared, a transtibial technique in which the femoral guide pin was placed through a tibial tunnel and a two-incision technique in which the femoral guide pin was placed from an outside–in direction, independent of the tibial tunnel. The bony and cartilage geometry and the ACL femoral attachment site were recorded using a 3-D digitizing stylus and this data was used to generate a 3-D surface model of each knee. The 3-D models were used to establish anatomic coordinate systems to measure the position of the guide pins relative to the center of the native ACL. The independent (outside–in) technique allowed the guide pin to be placed closer to the center of the native ACL femoral attachment site compared with the transtibial technique. The transtibial technique placed the guide pin at a mean distance of 7.9 mm from the center of the ACL, whereas the guide pins placed using the independent outside–in technique were at a mean distance of 1.9 mm from the center of the ACL. The guide pins placed using the transtibial technique were 5.1 mm anterior (high) and 3.6 mm proximal (deep) from the center of the ACL compared to 0.3 mm anterior (high) and 1.0 mm distal (shallow) for the outside–in technique. This study demonstrated that independent drilling is able to position guide pins closer to the center of the native ACL femoral attachment site compared to the transtibial technique.

Abebe et al. (2009) performed an in vivo imaging analysis comparing transtibial and outside–in ACL femoral tunnel drilling in 16 patients following primary ACL reconstruction. There were eight patients in the transtibial group and eight patients in the outside–in group. 3-T MRI and 3-D modeling techniques were used to measure femoral tunnel placement of the ACL reconstructions relative to the native ACL femoral attachment site. The transtibial technique placed the center of the ACL femoral tunnel at a mean distance of 8.5 mm from the center of the ACL femoral attachment site compared to 3.2 mm for the outside–in drilling technique. The transtibial technique placed the tunnels anterior (high) and proximal (deep) in the notch compared to the outside–in technique. The center of the ACL femoral tunnel in the transtibial group was at a mean distance of 5 mm in the anterior (high) direction and 5.7 mm in the proximal (deep) direction from the center of the ACL femoral attachment site. The center of the ACL femoral tunnel in the outside–in drilling technique was at a mean distance of 0.9 mm in the posterior (low) direction and 1.7 mm in the proximal (deep) direction from the center of the ACL femoral attachment site (Fig. 14). The authors concluded that the outside–in drilling technique allowed for more anatomic femoral tunnel placement compared with the transtibial technique.

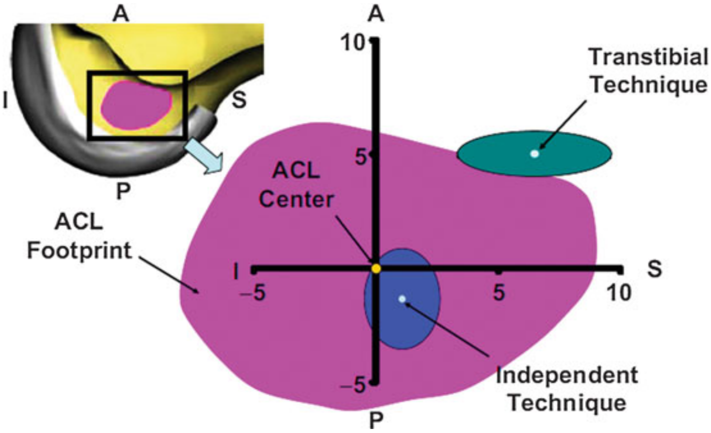

Fig. 14 The average position of the center of the tunnels using the transtibial and tibial tunnel-independent techniques relative to the center of the ACL in mm, mean ± standard deviation. Tunnel placement using the transtibial technique resulted in tunnels which were high and deep compared to the tibial tunnel-independent technique (with permission from the American Journal of Sports Medicine)

Silva et al. (2012) compared 20 patients that had a four-strand hamstring tendon autograft ACL reconstruction performed using a transtibial technique with 20 patients in which the ACL reconstruction was performed using AM portal drilling. The goal of the surgery was to place the femoral and tibial tunnels within the boundaries defined by the centers of the AM and PL bundle attachment sites. Postoperative CT scans were used to determine the position of the center of the ACL femoral and tibial tunnels in the sagittal plane. The position of the center of the ACL femoral tunnel was measured using the Bernard-Hertel (Bernard and Hertel 1996; Bernard et al. 1997) radiographic grid method, and the center of the tibial tunnel was measured using the method of Staubli and Rauschning (1994). There was no difference in the shallow–deep position of the ACL femoral tunnel between the two techniques. However, the center of the ACL femoral tunnel was significantly higher in the transtibial group. The center of the ACL tibial tunnel in the transtibial group was more posterior compared to the AM portal technique. Thirteen (65 %) of the tunnels in the transtibial group were posterior to the center of the PL bundle. In the AM portal group, 3 tunnels (15 %) were located anterior to the center of the AM bundle. This study demonstrated that the transtibial technique placed the femoral and tibial bone tunnels further away from the center of the ACL attachment sites, higher (anterior) on the femoral side, and more posterior on the tibial side compared to the AM portal technique.

Bowers et al. (2011) compared ACL tunnel position and ACL graft obliquity achieved with transtibial and AM portal drilling techniques. Thirty patients were prospectively studied after undergoing primary ACL reconstruction using a bone–patellar tendon–bone autograft. There were 15 patients in the transtibial group and 15 patients in the AM portal group. The ACL reconstructions were performed by 1 of 8 high-volume, fellowship-trained sports medicine surgeons who attempted to optimize femoral tunnel position and reproduce the graft obliquity of the native ACL. Tunnel location and ACL graft obliquity were accessed using 3-D knee models created with high-resolution MRI and imaging analysis software. No significant differences in the femoral centroid position were observed between the two groups. However, on the tibial side, the position of the tibial tunnel centroid in the transtibial group was significantly more posterior than the AM portal group and the native ACL. There was no significant difference in the medial-lateral tibial tunnel centroid position between the two groups. Sagittal plane obliquity in the AM group (52.2°) was closely restored to that of the native ACL

(53.5°), but the transtibial group was significantly more vertical (66.9°) than the native ACL. Coronal plane obliquity of both groups was significantly greater than that of the native ACL. There was 66.3 % overlap of the ACL graft with respect to the native ACL tibial attachment site in the AM portal group. The part of the ACL graft that did not overlap fell mostly medial to the native ACL tibial attachment site. The overlap for the transtibial group was 38 %, with 62 % of the tunnels positioned predominantly posterior and slightly medial to the native ACL tibial attachment site. The authors concluded that although both techniques could reproduce the native ACL femoral attachment site with similar accuracy, the transtibial technique required significantly greater posterior placement of the tibial tunnel which resulted in decreased ACL graft obliquity in the sagittal plane. One factor not accounted for in this study was the fact that the ACL reconstructions were performed using bone–patellar tendon–bone autografts. Piasecki et al. (2011) have shown that it is possible to position the ACL femoral tunnel near the center of the ACL femoral attachment site using a transtibial technique with a 10–11 mm diameter tibial tunnel and a proximal and medial external starting position for the tibial tunnel. However, using this same external starting position, it is not possible to position the ACL femoral tunnel near the center of the ACL femoral attachment site with a transtibial technique using smaller tibial tunnels necessary for hamstring tendon ACL grafts (Strauss et al. 2011). Therefore, the findings of this study apply only to the situation where the ACL reconstruction is performed with a bone–patellar tendon–bone ACL graft. For a hamstring ACL reconstruction, an alternative to the transtibial approach must be used to place the ACL femoral tunnel near the center of the ACL femoral attachment site (Strauss et al. 2011).

Tompkins et al. (2012) compared the ability of traditional transtibial and AAM portal drilling to place the ACL femoral tunnel within the native ACL femoral attachment site in ten matched paired cadaveric human knee specimens. Tunnel placement was documented by dual-energy CT scanning with a technique optimized for ligament evaluation. The AAM portal technique placed significantly more of the ACL femoral tunnel aperture within the native ACL femoral attachment site (98 %) compared to 61 % for the transtibial technique. The AAM portal technique also placed the center of the ACL femoral tunnel significantly closer to the center of the native ACL femoral attachment site (3.6 mm) than the transtibial technique (6 mm). Average femoral tunnel lengths were shorter for the AAM portal technique (37.8 mm) compared to the transtibial technique (41.1 mm). However, this difference was not statistically significant. The authors concluded that drilling the ACL femoral tunnel through an AAM placed more of the ACL femoral tunnel aperture within the native ACL femoral attachment site and placed the femoral tunnel closer to the center of the ACL femoral attachment site than the traditional transtibial technique.

Gadikota et al. (2012) investigated the relationship between femoral tunnels created by the transtibial, AM portal, and outside–in techniques in a controlled laboratory study using human cadaveric knees. The femoral tunnels for each technique were created using an 8 mm reamer. No significant difference was observed between the three groups in the total coverage of the ACL femoral footprint (AM = 55.0 %, outside–in = 56.8 %, transtibial = 51.0 %). Coverage of the PL bundle area of the ACL femoral footprint by the transtibial technique (26.4 %) was significantly lower than the AM portal (42.2 %) and outside–in (61.5 %) techniques. No significant differences were observed between the three groups in terms of coverage of the AM bundle area of the femoral footprint. On average, 72.9 % the transtibial tunnel was inside of the native ACL femoral attachment site. This was significantly less than the AM portal (86.4 %) and outside–in (89.2 %) tunnels. There was no significant difference in the percentage of the ACL femoral tunnel inside of the ACL femoral attachment site between the AM portal and outside–in techniques (Fig. 15). In summary, the study found that similar coverage of the ACL femoral attachment site can be achieved by tunnels created by the transtibial, AM portal, and outside–in techniques. However, tibial tunnel-independent techniques were able to cover a

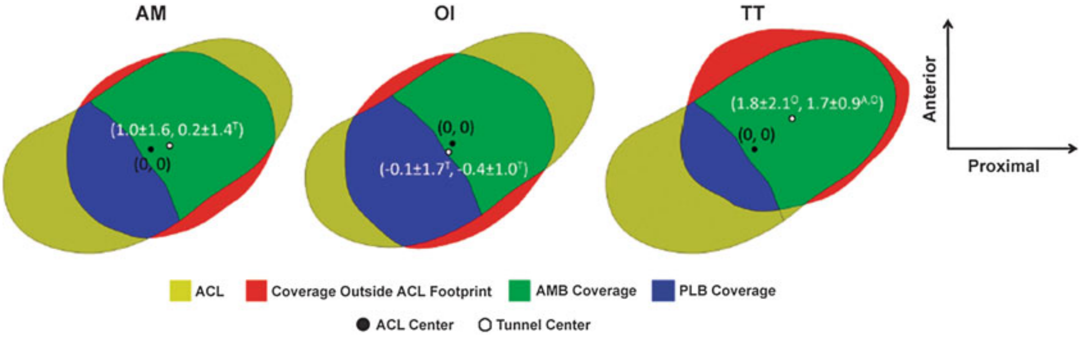

Fig. 15 Average native ACL and femoral tunnel footprints. The *white circles* represent the location of the femoral tunnel for the different surgical techniques. *AM* anteromedial portal technique, *OI* outside–in technique, *TT* transtibial technique (with permission from the American Journal of Sports Medicine)

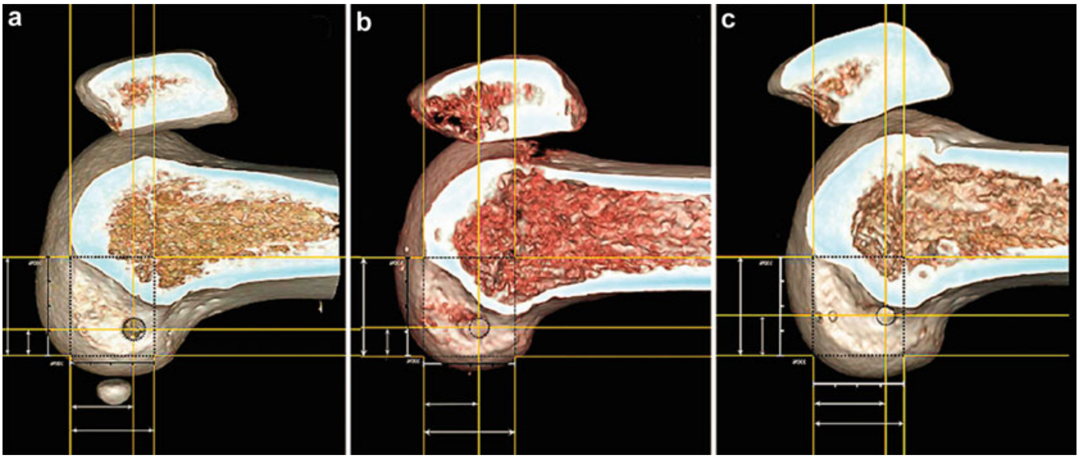

Fig. 16 Illustrations of the (**a**) outside–in, (**b**) anteromedial portal, and (**c**) transtibial surgical techniques. The transtibial technique resulted in a higher femoral tunnel placement than either the anteromedial or outside–in techniques (with permission from the American Journal of Sports Medicine)

larger portion of the PL bundle area of the ACL femoral attachment site.

Shin et al. (2013) prospectively evaluated 153 patients who underwent four-strand hamstring tendon graft ACL reconstruction using the AM portal ($n = 73$), outside–in ($n = 38$), and transtibial ($n = 42$) techniques. The ACL femoral tunnel position for each patient was determined using a 3-D CT scan. There was no significant difference in the shallow-to-deep ACL femoral tunnel position among the three groups. However, the ACL femoral tunnel for the transtibial group was significantly higher than the AM portal or outside–in techniques in the high–low direction (Fig. 16). There was no significant difference in the high–low position between the AM portal and outside–in groups. The authors concluded that the transtibial technique positioned the ACL femoral tunnel higher (more anterior) than the AM portal and outside–in techniques.

In vivo video motion analysis has recently been used to investigate the effects of ACL reconstruction surgical technique on knee joint kinematics. Zampeli et al. (2012) evaluated the effect of coronal and sagittal plane ACL graft obliquity on tibial rotation range of motion during dynamic pivoting activities after bone–patellar tendon–bone autograft ACL reconstruction. The study population involved 19 ACL-reconstructed patients (mean age, 29 years; mean time interval postoperatively, 19.9 months) and 19 matched control subjects (mean age, 30.6 years). Both groups were evaluated using motion analysis during descending a stairway and pivoting and landing from a jump and pivoting. MRI was used to measure the coronal and sagittal ACL graft angles. Although the ACL reconstruction group was unable to restore tibial rotation range of motion back to that of the normal contralateral knee or the healthy control knees, there was a highly significant positive correlation between ACL graft obliquity in the coronal plane and tibial rotation range of motion. No correlation was found between tibial rotation range of motion and sagittal ACL graft angle. The findings of this study show that tibial rotation range of motion was better restored in ACL-reconstructed patients with a more oblique ACL graft orientation in the coronal plane.

Wang et al. (2013) compared the effectiveness of the transtibial and AM portal ACL reconstruction techniques in restoring knee joint kinematics during normal gait. There were 12 patients in the transtibial group and 12 patients in the AM portal group. The control group consisted of 20 healthy participants with no history of lower extremity injuries. The ACL reconstructions were performed by a single surgeon using 4-strand hamstring tendon autografts. When the diameter of the 4-strand hamstring autograft was less than 8 mm, the graft construct was augmented with a single semitendinosus allograft to increase the size of the combined graft to 9 or 10 mm. A video motion capture system was used to record the motion data. The peak femoral external rotations during level walking were greater for both the reconstructed groups (transtibial = 5.7°, AM portal = 4.9°) compared with the controls (3.2°), but the differences were statistically significant for only the transtibial group. The transtibial group had significantly greater average femoral anterior–posterior translation on the tibial plateau during the stance phase compared to the AM portal and control groups (transtibial = 23.8 mm, AM portal = 16.2 mm, controls = 16.9 mm). The transtibial group was also found to have significantly greater average femoral anterior–posterior translation after toe off compared to the AM portal and control groups (TT = 22.2 mm, AM portal = 12.3 mm, control = 13.2 mm). This study demonstrated that surgical technique has an effect on knee kinematics. The AM portal technique improved anterior–posterior stability of the knee during the swing phase as well as axial rotational stability at midstance compared with the transtibial technique.

There are few published clinical studies comparing the results of the transtibial and AM portal techniques. Alentorn-Geli et al. (2010) compared the outcomes of ACL reconstruction performed with bone–patellar tendon–bone autograft using transtibial or AM portal drilling of the femoral tunnel in a homogeneous group of soccer players. All operations were performed by the senior surgeon and differed only in the drilling technique of the femoral tunnel. There were 21 patients in the transtibial group and 26 in the AM portal group. All patients were evaluated 2–5 years after the index surgical procedure. The patients were evaluated with standard outcome measures. Compared with the transtibial group, there was a significant reduction in recovery time in the AM portal group. Manual maximum anterior tibial translation as measured by a KT-1000 arthrometer was significantly reduced in the AM portal group (transtibial = 1.9 mm, AM portal = 0.2 mm). The objective IKDC score, Lachman test, and pivot-shift test were significantly better in the AM portal group. Seventy-nine percent of the patients in the AM portal group had a negative pivot shift compared to 41 % in the transtibial group. The authors concluded, "the AM portal technique significantly improved the anterior–posterior and rotational knee stability, and overall IKDC scores compared to the transtibial technique."

Kim et al. (2011) compared the clinical results of 33 patients who underwent SB ACL reconstruction with an autograft or allograft bone–patellar tendon–bone graft using a 3-portal technique with a control group of 33 patients that had undergone a similar procedure using a transtibial technique. Both groups were evaluated with standard clinical outcome measures. Femoral tunnel obliquity was measured on a postoperative knee view x-ray. There was no significant difference in the Lachman test or KT-1000 arthrometer measurements between the two groups. However, there was a significant difference in the results of the pivot-shift test between the two groups, with 90 % of the patients in the AM portal group having a negative pivot-shift test compared to 79 % in the transtibial group. Although the Lysholm and IKDC scores were higher for the AM portal groups, this difference did not reach statistical significance. Femoral tunnel obliquity was significantly greater in the transtibial group (59°) compared to the AM portal group (31°). The authors concluded that ACL reconstruction using two anteromedial portals was effective in restoring the anatomy of the ACL and obtaining good clinical results, because the technique allowed for a better field of view and lower ACL graft obliquity compared to the transtibial technique.

Recently, Chalmers et al. (2013) performed a systematic review of the literature for biomechanical and clinical studies directly comparing the ability of the transtibial and AM portal ACL reconstruction techniques to achieve rotational stability of the knee. They identified five clinical (Level II or III studies) and four cadaveric studies that directly compared the transtibial and AM portal techniques. Two clinical studies and two cadaveric studies demonstrated superior rotational stability with the AM portal group, whereas one clinical and two cadaveric studies showed no difference. Clinical outcomes were similarly mixed with some studies showing a significantly quicker return to play and better IKDC and Lysholm scores with the AM portal technique, whereas other studies showed no difference. However, no study showed significantly better results with the transtibial technique. According to the authors, “This study shows that the AM portal technique of ACLR may be more likely to produce improved clinical and biomechanical outcomes but that the TT technique is capable of producing similar outcomes.”

To summarize the AM portal and outside–in ACL reconstruction techniques can be expected to achieve similar femoral tunnel lengths, while the transtibial technique can be expected to achieve femoral tunnel lengths significantly longer than either the AM portal or outside–in techniques. There are significant differences in the ACL femoral and tibial tunnel positions achieved with the AM portal, outside–in, and transtibial techniques. Transtibial drilling is more likely to position the ACL femoral tunnel significantly higher and deeper along the lateral wall of the notch, and the tibial tunnel more posteriorly in the native ACL tibial attachment site. Biomechanical and clinical studies have demonstrated that positioning an ACL graft in a high-deep femoral tunnel and a posterior tibial tunnel results in a vertical ACL graft in both the coronal and sagittal planes. Vertical ACL grafts may control anterior tibial translation but often fail to control the pivot-shift phenomenon. There does not seem to be a significant difference in the femoral or tibial tunnel positions achieved using the AM portal and outside–in techniques, and both of these techniques can consistently place the ACL femoral and tibial tunnels near the center of the native ACL attachment sites. As a result, vertical ACL grafts are less likely to be achieved using these techniques. There are also differences in the ability of the ACL femoral tunnel created by the three techniques to achieve coverage of the ACL femoral attachment site. Coverage of the PL part of the ACL femoral attachment site is lowest with femoral tunnels drilled using the transtibial technique. There does not appear to be any differences in coverage of the PL area of the ACL femoral attachment site between the AM and outside–in techniques. The three techniques have equal ability to produce a femoral tunnel which covers the AM part of the ACL femoral attachment site. The transtibial technique has the largest percentage of the femoral tunnel outside of the ACL femoral attachment site.

Obliquity of the ACL graft is an important issue since biomechanical and clinical studies have demonstrated that greater coronal obliquity of the ACL graft is associated with better rotational stability, better clinical outcomes, and better restoration of normal knee kinematics. The AM portal and outside–in techniques have been shown to achieve greater femoral tunnel and ACL graft coronal plane obliquity compared to the transtibial technique. Kinematic studies have shown that greater coronal plane obliquity of the ACL graft better restores tibial rotation and knee kinematics (Zampeli et al. 2012; Wang et al. 2013). One of the objectives of anatomic ACL reconstruction is to prevent the development of osteoarthritis. Abnormal tibial rotation in the ACL-deficient and ACL-reconstructed knee has been related to inferior functional outcomes and patient satisfaction and a lower rate of return to sports and has also been considered a predominant etiologic factor for the development of osteoarthritis (Jonsson et al. 2004; Kocher et al. 2004; Andriacchi et al. 2006; Stergiou et al. 2007; Andriacchi et al. 2009). The ability of the AM portal and outside–in techniques to achieve greater coronal plane obliquity of the ACL graft is a significant advantage over the transtibial technique.

Based on the best available biomechanical, clinical, and kinematic studies, there appears to be little advantage to the transtibial technique. Although that it is possible to position a bone–patellar tendon–bone ACL graft near the center of the native ACL femoral and tibial attachment sites using a transtibial technique, numerous modifications including the use of an accessory transpatellar tendon portal for placement of the tibial aimer, use of a external tibial tunnel starting position at the junction of the pes anserinus and medial collateral ligament fibers, adequate rotation of the 7 mm offset femoral aiming device to improve lateralization of the tunnel, and adjustment of the tibial aimer to achieve 55–60° of angulation of the tibial tunnel in the coronal plane are necessary (Piasecki et al. 2011; Chalmers et al. 2013). Even with these modifications it is impossible to position a hamstring tendon ACL graft within the native ACL femoral attachment site (Strauss et al. 2011). Given these limitations, transtibial drilling of the ACL femoral tunnel has a limited role when performing anatomic ACL reconstruction.

Summary

Anatomic ACL reconstruction is defined as “the functional restoration of the ACL to its native dimensions, collagen orientation and insertion sites” (van Eck et al. 2011). Biomechanical and clinical studies have demonstrated that an anatomic ACL reconstruction with the bone tunnels placed at the center of the native femoral and tibial attachment sites is more effective at controlling anterior tibial translation and anterolateral tibial rotation compared to a nonanatomic ACL reconstruction. Anatomic ACL graft placement has been demonstrated to improve rotational stability and produce better clinical outcomes and better restore normal knee kinematics. Different surgical techniques such as the transtibial, anteromedial portal, and outside–in technique are used to perform an ACL reconstruction. The anteromedial portal and outside–in techniques can be used to consistently place the ACL femoral tunnel within the native ACL femoral attachment site and have become the preferred surgical techniques when performing an ACL reconstruction.

Cross-References

- ▶ Anatomic Double-Tunnel Anterior Cruciate Ligament Reconstruction: Evolution and Principles
- ▶ Anterior Cruciate Ligament Graft Selection and Fixation
- ▶ Different Techniques of Anterior Cruciate Ligament Reconstruction: Guidelines
- ▶ Personalized Treatment Algorithms for Anterior Cruciate Ligament Injuries
- ▶ Revision Anterior Cruciate Ligament Reconstruction
- ▶ Single Versus Double Anterior Cruciate Ligament Reconstruction in Athletes

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