Anatomic anterior cruciate ligament reconstruction: a changing paradigm
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CHAPTER 1

INTRODUCTION
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The History of the Anterior Cruciate Ligament

The anterior (ACL) and posterior (PCL) cruciate ligament were first mentioned in 3000 BC by an Assyrian in Egypt, who described the anatomy of the cruciate ligament\(^1\). In 460 - 370 BC, Hippocrates described cruciate pathology, for instance subluxation of the knee. The cruciates were thought to belong to the nervous system, not to the musculo-skeletal system. Claudius Galen, a Greek physician in the Roman Empire (150 AD), was the first to write about the origin of the “genu cruciate”\(^2\). Because he had both philosophical and medical training, Galen combined in his model of the body ideas of Hippocrates, Plato and Aristotle. His careful anatomic dissections showed the cruciates to be a supportive structure to the knee, preventing abnormal motion\(^1\)\(^2\).

Early Anatomy

It was not until much later in Germany that transection studies of the ACL were performed. In 1836, Weber and Weber from Göttingen described anterior translation of the tibia after cutting the ACL. They also discovered that it had different bundles, which tension at different flexion angles of the knee\(^3\).

![Figure 1: W. Weber and E. Weber, drawing of the two bundles of the ACL in extension and in 90° of flexion. Reprinted with permission of www.acta-ortho.gr](www.acta-ortho.gr)

A Frenchman, Amédée Bonnet (1809-1858), published two books\(^4\)\(^5\) on joint injuries and treatment, in which he described the high incidence of ACL ruptures,
the physical presentation of injury, the rupture pattern of the ACL and the concomitant injuries. In 1875, C. Noulis, a Greek, developed a physical exam to test for ACL rupture: “Fix the thigh with one hand; with the other hand hold the lower leg just below the knee with the thumb in front and the fingers behind. Then try to shift the tibia forward and backward. When only the anterior cruciate ligament is transected, this forward movement is seen when the knee is barely flexed”. This test is now known as the Lachman test and is part of the IKDC score, a popular scoring system currently used for ACL injuries. In 1879, a Frenchman named Paul Segond described a common fracture pattern that can accompany ACL injury, which was named the “Segond fracture” after his discovery. He also further specified the symptoms of an ACL rupture: the sound or sensation of a ‘pop’ at the time of injury, pain, joint effusion, and anterior instability.

First Treatment of ACL Injuries

Treatment of ACL ruptures was first described by Dr. Stark in 1850. He treated the injury with casting. Dr. Battle and Dr. Robson, both from England, repaired the ACL surgically in the early 1900’s with surprisingly good results. One of Dr. Robson’s patients worked eight-hour shifts in a mine during eight years after surgery and had a normal physical exam. Years later, however, Feagin and Curl had less good outcomes and concluded that primary repair of the ligament did not result in healing. This conclusion led the way towards reconstruction rather than repair of the ACL.

Shift toward Reconstruction instead of Repair

The first tissue transplanted for reconstruction of the ACL was the fascia lata. This technique was used for the first time by Dr. Giertz, the mentor of Ivar Palmer, in 1913. He harvested a strip of fascia lata that was fixed to the medial femoral epicondyle and the tibial tubercle. In 1917, Hey-Groves adopted a technique that is very similar to the predominant technique today, which used tunnels to fixate the graft. The femoral tunnel was drilled inside-out and aimed so that the tunnel aperture was located on the outer aspect of the notch in order to produce an oblique graft.

However, we must remember that those procedures were open, “arthrotomy” reconstructions. Today, almost all surgeries are done arthroscopically. The first arthroscopically assisted ACL reconstruction was performed in 1980 by Dr. Dandy. The efforts of Drs. Drez, Clancy and Rosenberg were largely responsible for the further development of this technique.

Another graft type that was suggested was meniscal tissue. Unfortunately, this turned out to be unsuccessful, due to the high failure rate. The hamstring tendon graft, consisting of the semitendinosus and gracilis tendon segments, was more
successful. Galeazzi from Italy developed a technique using the semitendinosus tendon\textsuperscript{15}. The German marine physician Zur Verth first applied the technique of using the patellar tendon as a graft for ACL reconstruction\textsuperscript{16}. In 1963, Dr. Jones from the United States described the use of the patellar tendon with a bone block, but in an extraordinary way: the patellar tendon bone block remained attached below the tibial tubercle. Without a tibial tunnel it was placed “beneath the fat pad” and a femoral drill hole was “placed in the intercondylar notch just posterior to the margin of the articular cartilage”\textsuperscript{7,17}. Another graft source that has recently become popular, also for reconstruction of the posterior cruciate ligament, is the quadriceps tendon.

Dr. Shino from Japan was the first surgeon that reported the use of allograft tissue for ACL reconstruction\textsuperscript{18}. Allografts are frequently used now, predominately in the United States.

\textit{Figure 2:} Jones’ ACL reconstruction technique in 1963. Reprinted with permission of www.acta-ortho.gr

\textbf{Development of the Double-Bundle Reconstruction Technique}

Even though the two-bundle anatomy was described as early as 1836 by Weber and Weber\textsuperscript{3}, all the above-mentioned techniques restore the ACL using a single graft. In 1938 the famous orthopedist Ivar Palmer from Sweden published his thesis on ligamentous injuries of the knee\textsuperscript{19}. He evaluated the anatomy and the current concepts and developed new reconstruction techniques. His thesis is still one of the most frequently cited orthopaedic references. However, his work was not appropriately accredited until the late 1970’s. He described the two-bundle anatomy and was the first to try and repair both bundles separately with his new suture technique. It was Girgis\textsuperscript{20} and later Arnockzy\textsuperscript{21} who named the two bundles: the anteromedial (AM) and posterolateral (PL) bundle. Mott\textsuperscript{22}, in 1982, was the
first to describe and publish a double bundle ACL reconstruction technique. He used two femoral and two tibial tunnels with arthrotomy and utilized a semitendinosus graft. Unfortunately, he did not report on the outcome of this technique. Zaricznyj\textsuperscript{23} did, however, by publishing two-year follow-up results of his double-bundle ACL reconstruction. He used one femoral and two tibial tunnels and reported on twelve patients with good to excellent results and two patients with fair results. In 1994, Rosenberg\textsuperscript{24} outlined a double bundle technique for arthroscopic surgery. He used two femoral tunnels and one tibial tunnel, with suspensory proximal fixation. Both Yasuda\textsuperscript{25} and Muneta\textsuperscript{26} should be accredited for their role in the research and development of double-bundle ACL reconstruction in its current form.


\textbf{Epidemiology}

Rupture of the anterior cruciate ligament (ACL) is one of the most frequent forms of knee trauma. It has a yearly incidence of 35 out of 100,000 people\textsuperscript{27}. Epidemiological analysis indicates that ACL injuries often occur in young athletes, especially women, who participate in sports that require pivoting and cutting, such as basketball, soccer, skiing or football\textsuperscript{28}.
Etiology

Injury to the ACL classically occurs in hyperextension and torsion or combined flexion, external rotation and valgus. Hyperextension of the knee initially results in tightening of the posterolateral bundle, which can lead to isolated posterolateral bundle injury and may progress to a combined anteromedial and posterolateral bundle injury of the ACL. The combination usually happens when an anterior force is exerted on an extended knee with a planted foot, especially in contact sports. Twisting injuries result from pivoting or cutting motions, and studies have revealed that over 70% of these injuries occur in non-contact situations. Landing on a flexed and externally rotated knee eccentrically loads the quadriceps, which can result in isolated anteromedial bundle tears. Dislocation of the knee, caused by high-speed motor vehicle accidents for instance, can also injure the ACL.

History and Physical Exam

A detailed history and physical examination to assess knee stability is the most powerful tool to clinically diagnose ACL rupture. Acute ACL ruptures often produce a “popping” sound at the time of injury, and patients experience pain and instability secondary to laxity of anterior translation in an ACL deficient knee. Physical examination includes the Lachman, anterior drawer and KT arthrometer testing for anterior stability and Pivot Shift for rotatory stability. A complete physical exam should take place to rule out multi-ligamentous injuries and other associated pathologies. The surgeon should evaluate what is ‘normal’ for the patient by comparing stability to the uninjured side. Another key component of the physical exam is the neurovascular assessment. Again, comparison to the uninjured side provides the surgeon with an estimate of a patient’s normal stability.

Imaging

X-ray imaging is the first modality for imaging the knee, to rule out any fractures or bony avulsions. It cannot be used to directly visualize soft tissue injury. On an anteroposterior view of the knee, a Segond fracture is an indicator of an
Acute anterior cruciate ligament injuries can be treated conservatively or surgically. There are studies that show a better outcome and higher patient satisfaction after surgical treatment. However, the treatment modality should be based on the patient’s wishes and characteristics, such as activity level. An appropriate conservative treatment strategy is based on a patient’s progress, as well as the healing phases of the ACL that permit the patient to increase activity at certain time points. In the first two to three weeks after injury the knee is immobilized in 40-45° flexion in a locked brace to allow reduction of pain and swelling. Partial weight bearing is allowed during this phase, followed by gradual increases in range of motion. Four to six weeks after injury the patient may return to daily activities and moderate exercise with full weight bearing without a brace. To strengthen the quadriceps and hamstring muscles a physical therapist can give isometric, isotonic, isokinetic and eccentric exercises. Non-pivoting and non-contact sports are generally allowed after three to six months. Pivoting and contact sports should not be performed until after one year. Surgical treatment consists of ACL reconstruction using a tendon graft. Historically, the single-bundle technique is the most widely used approach and restores the ACL using one femoral and one tibial tunnel and a single graft. Double-bundle reconstruction restores both the anteromedial and posterolateral bundle using two femoral and two tibial bone tunnels and two separate tendon grafts.

Prognosis

The single-bundle reconstruction has good results. However, about 15-25% of the patients still report pain and instability after reconstruction. In young athletes there is an increased risk of re-injury and injury to the contra-lateral side. This primarily occurs when they take up sports too soon and involve in strenuous sports and activities. A long-term complication after ACL injury is the development of early osteoarthritic changes.
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The Concept of Anatomic ACL Reconstruction

Anatomy is the basis of orthopaedic surgery. Anatomic ACL reconstruction strives to closely reproduce the native anatomy of the ACL. There are four fundamental principles in anatomic ACL reconstruction. The first is to restore the two functional bundles of the ACL. The second principle is to restore the native insertion sites of the ACL by placing the tunnels in their true anatomic positions. Tunnel and graft size are tailored to match the size of the native ACL insertion sites. The third principle is the correct tensioning pattern of each bundle. The AM bundle is taut throughout the knee range of motion, reaching a maximum of between 45° and 60°, whereas the PL bundle is tight primarily in extension. Therefore, the AM and PL bundles are fixated accordingly, to restore their native tensioning behaviors. The fourth and final principle is individualized surgery for each patient. Tunnel diameter and graft size are dictated by the native insertion sites. In addition, a single bundle graft can be a good option for patients with certain criteria. An anatomic ACL reconstruction may decrease the incidence of early osteoarthritic changes compared to the conventional single-bundle reconstruction. Another advantage of anatomic tunnel placement is that the graft is exposed to normal biomechanical stimuli and therefore is in a more favorable biological environment for healing and remodeling.
Relevance and Objectives of the Research of this Thesis

Recently, the double-bundle reconstruction technique has gained in popularity. The alleged benefits of double-bundle reconstruction follow from biomechanical studies that suggest that each bundle - AM and PL - makes a unique kinematic contribution to knee function. The two bundles function together, but the AM bundle provides the major anterior restraint, whereas the PL bundle functions at extension and contributes more to rotational stability. An in-vivo kinematics study has shown that conventional single-bundle ACL reconstruction, which most closely imitates AM bundle reconstruction, can successfully restore anterior knee stability but does not sufficiently bring back rotational stability. In addition, cadaveric biomechanical studies have shown that double-bundle ACL reconstructions better restore knee kinematics than single-bundle ACL reconstructions. The first research question of this thesis evaluates the theoretical benefits, drawbacks and considerations of double-bundle ACL reconstruction. Besides the ACL and its insertion site, the surrounding structures of the ACL play an important role in ACL reconstruction. The femoral intercondylar notch, for example, has long been thought to have a relationship with the ACL. A small intercondylar notch has been suggested to be associated with an increased risk of ACL rupture. Many different measurements of the notch have been used to assess this correlation, such as notch width index and notch area. In the medical literature conclusions about this relationship vary. Historically, during ACL reconstruction, notchplasty has been advocated as a method of preventing ACL impingement on the notch, which may provoke early graft failure. However, notchplasty conflicts with anatomic ACL reconstruction because in an effort to create more room for the graft, the surgeon distorts the native anatomy by the removal of bone. To determine the relation between notch volume and early graft failure a practical measure of the notch is required. Therefore, the second research aim of this thesis is to evaluate the frequently used “notch width index” as a measure of notch size, and to determine its correlations with overall notch volume. We hypothesized that there are no, or few correlations between the two-dimensional notch width index and the overall three-dimensional notch volume. The third research objective is to classify the intercondylar notch shape and dimensions in ACL injured patients. The hypothesis of this study was that it is possible to identify a particular notch shape that is correlated with the smallest notch dimensions and that this notch shape is more prevalent in females. The fourth research aim of this thesis is to determine if there is a difference in overall notch volume between subjects with and subjects without ACL injury and to determine the correlation between intra-operative two-dimensional notch measurements, patient demographic factors and overall notch volume. The hypothesis was that subjects with ACL injury have a smaller notch size than subjects without ACL.
injuries, and are therefore predisposed to ACL rupture (Chapter 5).

Other anatomic structures important in ACL reconstruction are the bony ridges. The femoral attachment of the ACL has two such ridges. The lateral intercondylar ridge (previously called “resident’s ridge”) runs from proximal to distal along the entire ACL femoral insertion. No ACL fibers are found anterior to the lateral intercondylar ridge. The other bony prominence found to be present in the anterior portion of the femoral footprint runs in an anterior to posterior direction, and is referred to as the lateral bifurcate ridge. During anatomic ACL reconstruction these osseous landmarks are preserved and may serve as guides for tunnel placement. In chronic cases, when the ACL stump has been resorbed or when only fibrous tissue remains, the bony ridges may provide a useful landmark in locating the ACL insertion site. However, it has been argued that the ridges may disappear after the ACL is torn and no longer exerts forces on the bone. These forces are thought to result in the formation of the ridges (Wolff’s law). The fifth research aim of this thesis is to evaluate this. The hypothesis was that the ridges are present less often with chronic ACL deficiency than with acute ACL ruptures (Chapter 6).

Many techniques for anatomic ACL reconstruction have been proposed. Because of the recent development of the anatomic concept, it remains unclear which technique yields the best outcome for the patient. In order to determine this, the different reconstruction techniques have to be evaluated and adequately reported in medical literature. The sixth research aim in this thesis is to systematically review and evaluate all studies published on anatomic ACL reconstruction. The hypothesis was that a substantial percentage of the reviewed surgical technique descriptions provides insufficient data required for proper interpretation of the technique and comparisons of reported outcomes (Chapter 7).

The anatomic ACL reconstruction principle can also be applied to revision surgery. The increasing number of ACL reconstructions will certainly lead to more failures and consequently to more revision surgeries. It is important to determine the causes of these failures, so that they may be avoided in primary and revision procedures. Therefore, the seventh research aim of this thesis is to establish the most common graft rupture patterns of double-bundle ACL reconstruction cases, seen at the time of revision surgery, and to compare the pattern of injury to that of the native ACL. Subsequently, the influence of certain factors such as age, gender, the period of time between the initial ACL reconstruction and re-injury, tunnel angle and etiology/mechanism of failure on the injury pattern is determined. The hypothesis was that there is a correlation between the factors mentioned above and the graft rupture pattern (Chapter 8).

Currently, both single- and double-bundle ACL reconstruction are performed, so there is a need to compare the results. Recent prospective, randomized, quasi-randomized and observational level I and level II studies have reported favorable clinical outcomes after double-bundle ACL reconstructions. This thesis includes a meta-analysis of all (quasi-) randomized and observational...
studies comparing single- and double-bundle ACL reconstruction. The hypothesis was that anatomic double-bundle ACL reconstruction has an advantage over anatomic single-bundle reconstruction in restoring anterior and rotational stability and knee range of motion (Chapter 9).

The ultimate aim of this thesis is to combine old and new research findings in order to improve the outcomes of ACL reconstructive surgery and raise the quality of patient care. Therefore, the last research objective is to develop a guideline for performing anatomic single- and double-bundle ACL reconstruction based on the studies in this thesis and previously reported studies (Chapter 10).

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