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Surgery for anterior cruciate ligament deficiency: a historical perspective

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Abstract The anterior cruciate ligament (ACL) has entertained scientific minds since the Weber brothers provided biomechanical insight into the importance of the ACL in maintaining normal knee kinematics. Robert Adams described the first clinical case of ACL rupture in 1837 some 175 years to date, followed by Mayo-Robson of Leeds who performed the first ACL repair in 1895. At that time, most patients presented late and clinicians started to appreciate signs and symptoms and disabilities associated with such injuries. Hey Groves of Bristol provided the initial description of an ACL reconstruction with autologous tissue graft in 1917, almost as we know it today. His knowledge and achievements were, however, not uniformly appreciated during his life time. What followed was a period of startling ingenuity which created an amazing variety of different surgical procedures often based more on surgical fashion and the absence of a satisfactory alternative than any indication that continued refinements were leading to improved results. It is hence not surprising that real inventors were forgotten, good ideas discarded and untried surgical methods adopted with uncritical enthusiasm only to be set aside without further explanation. Over the past 100 years, surgeons have experimented with a variety of different graft sources including xenograft, and allografts, whilst autologous tissue has remained the most popular choice. Synthetic graft materials enjoyed temporary popularity in the 1980 and 1990s, in the misguided belief that artificial ligaments may be more durable and better equipped to withstand stresses and strains. Until the 1970s, ACL reconstructions were considered formidable procedures, often so complex and fraught with peril that they remained reserved for a chosen few, never gaining the level of popularity they are enjoying today. The increasing familiarity with arthroscopy, popularised through Jackson and Dandy, and enhancements in surgical technology firmly established ACL reconstruction as a common procedure within the realm of most surgeons' ability. More recently, the principle of anatomic ACL reconstruction, aiming at the functional restoration of native ACL dimensions and insertion sites, has been introduced, superseding the somewhat ill-advised concept of isometric graft placement. Double-bundle reconstruction is gaining in popularity, and combined extra- and intra-articular procedures are seeing a revival, but more accurate and reliable pre- and post-operative assessment tools are required to provide customised treatment options and appropriate evaluation and comparability of long-term results. Modern ACL surgery is united in the common goal of re-establishing joint homoeostasis with normal knee kinematics and function which may ultimately assist in reducing the prevalence of post-operative joint degeneration. This review hopes to provide an insight into the historical developments of ACL surgery and the various controversies surrounding its progress.
Level of evidence V.

Keywords Anterior cruciate ligament · ACL · History · ACL reconstruction · ACL deficiency

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Anatomy and basic science: from ancient history to the twentieth century

The history of ACL surgery is also the history of the discovery of the ligament's function, the recognition of its injury pattern and the development of reliable methods in

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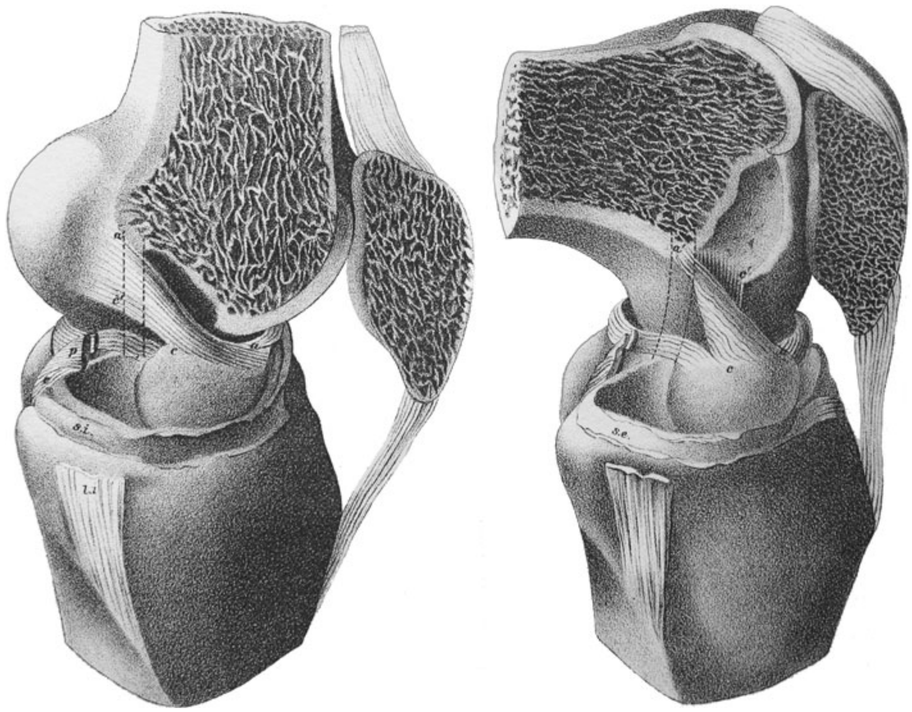


Fig. 1 Illustration from 'Mechanics of the human walking apparatus' by the Weber brother's published in 1836 clearly showing the appearance of the ACL in extension and flexion. The Weber brothers were the first to describe the existence of two distinct ACL fibre bundles and their respective tension pattern (with kind permission of Springer Science, Berlin) [297]

assessing and diagnosing ACL injury. Hippocrates of the Greek island of Kos (460–370 BC) although unaware of the cruciate ligaments as such, was the first to suggest that knee instability following trauma may be attributable to torn internal ligaments [116]. Galen of Pergamon in Greece (131–201 BC) is credited for providing the cruciate ligaments with their name, when, based on their appearance of crossing over, he coined the term 'ligamenta genu cruciata' [92]. Over the following 2000 years, the cruciate ligaments occupied a Cinderella status by receiving little attention in scientific circles. In 1836 Wilhelm Weber (1804–1891) Professor of Physics in Göttingen and Eduard Weber (1806–1871) Professor of Anatomy and Physiology in Leipzig were also able to show that sectioning of the anterior cruciate ligament resulted in abnormal anterior–posterior movement of the tibia, thereby providing an early description of the anterior drawer sign [297]. They also described the exact anatomic position of the cruciate ligament complex and demonstrated that the anterior cruciate ligament consists of two distinct fibre bundles which are tensioned at different times during knee motion (Fig. 1) In 1858 Karl Langer, anatomist at the University of Vienna (1819–1887), not only confirmed earlier findings by the Weber brothers, but provided the first detailed description of cruciate kinematics and the ligaments torsional behaviour pattern [171].

The first description of a clinical case of ACL injury in the English literature was provided by the Irish surgeon Robert Adams of Dublin (1791–1875) [2]. In December of 1837, he observed the case of a drunken 25-year-old man who injured his knee wrestling and died 24 days later. Autopsy of the knee revealed that the knee had become septic and that the ACL had torn off the tibia with a portion of bone still attached to the ligament (Fig. 2). Many more

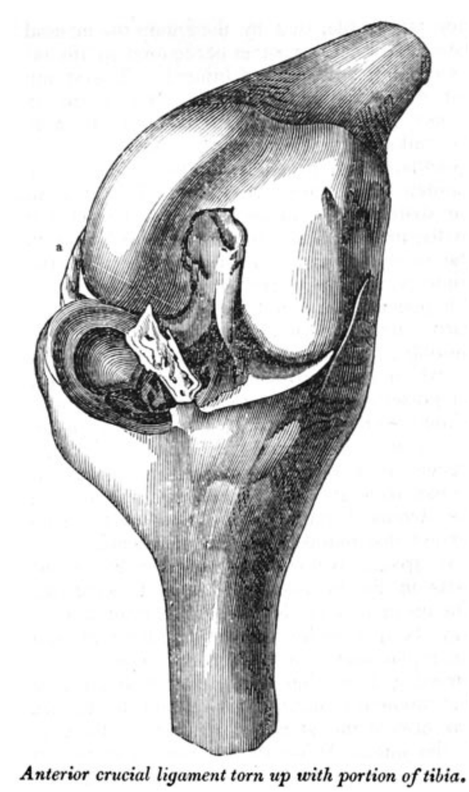


Fig. 2 Earliest recorded drawing of a cruciate ligament tear (avulsion injury), observed by Robert Adams [2]

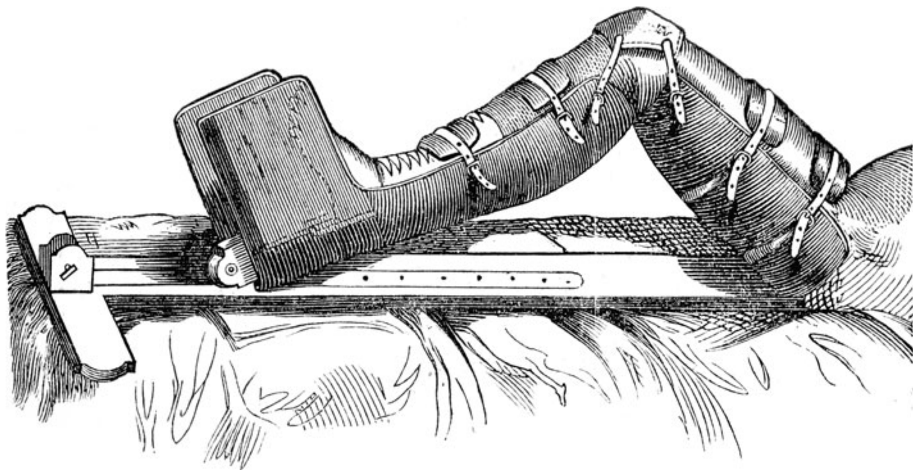


Fig. 3 Sliding frame designed by Bonnet in 1853 as part of his conservative treatment approach to prevent stiffness and enable early mobilisation following internal derangement of the knee [24]

ACL ruptures are likely to have occurred before then, but failure to recognise clinical signs and the absence of reliable assessment tools prevented their discovery.

In 1845, Amedeé Bonnet (1809–1858) Professor of Surgery at the Lyon University published his Traité des maladies des articulations [23]. He described three essential signs indicative of acute ACL rupture, "In patients who have not suffered a fracture, a snapping noise, haemarthrosis, and loss of function are characteristic of ligamentous injury in the knee", and thought that the pain that accompanied ACL rupture was due to the stretching of its nerve supply. Through cadaver experiments, Bonnet became aware that the anterior cruciate ligament (ACL) was more likely to tear close to its femoral insertion. He also described the subluxation phenomenon, which later became known as the pivot-shift. Although a surgeon, Bonnet advocated conservative management for ligamentous injuries with application of cold packs in the acute stage. Through his own experiments, he was aware of the detrimental effects prolonged immobilisation has on articular cartilage and hence encouraged early motion exercises using a sliding frame [24] (Fig. 3). For patients who continued to suffer from instability, he suggested wearing of a long-leg hinged brace not dissimilar in principle to modern stabilising braces used following injury or surgery (Fig. 4). His ideas and suggestions on the treatment of acute ligamentous injuries were far ahead of his time but received little recognition in the English speaking world, as most of his work remained un-translated.

James Stark, a general practitioner from Edinburgh (1811–1890), observed two cases of cruciate ligament tears in 1839 and 1841, respectively, describing some of the typical signs of ligament rupture "… and felt something gave way with a snap in the left knee; when raised, she found she had lost all command over the leg" [274]. Stark believed that damage to the cruciates would render the knee "utterly useless". He treated both of his patients conservatively, but despite 3 months of immobilisation, and a further 10 months using a semi-rigid brace made of a "finely fitting laced stocking, made of Saxony broad cloth, and a broad flat steel spring was sewed to the back of it", neither patient regained entirely normal knee function. Stark is often quoted as the first clinician to describe cases of ACL deficiency in the English literature. Wagner however pointed out, that the excessive hyperextension and

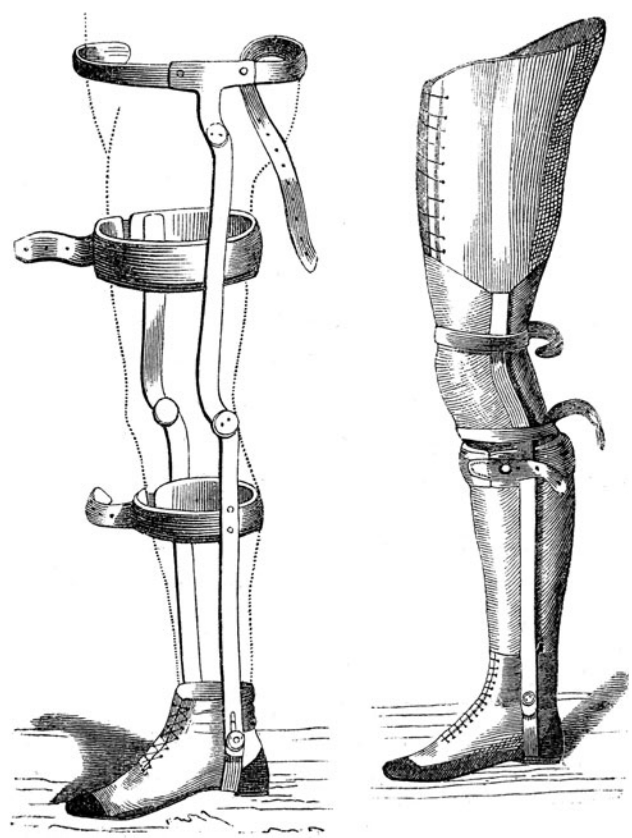


Fig. 4 Early design of a knee brace/walking apparatus introduced by Bonnet to enable patients with chronic knee instability to ambulate [24]

instability seen in Stark's patients most probably suggests that both suffered combined ACL and PCL injuries.

In 1875, the Greek Georgios C. Noulis (1849–1915) gave a detailed description of what is now known as the Lachman test, when he wrote, "… 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" [219]. Stirling Ritchey of Washington DC rediscovered the test in 1960, but it was not until 1976 when Joseph Torg, in appreciation of his mentor John Lachman of Philadelphia (1956–1989), described it as the 'Lachman test' and popularised its value in assessing ACL function [246, 285].

Clinicians, curious as to how cruciate damage occurs, were hoping to find answers through cadaver experiments [23, 60, 120]. In 1876, Leopold Dittel of Vienna (1815–1898) published on the examination results of a number of knee specimens which he had previously exposed to extremes of motions [60]. Like Bonnet and later Hönigschmied, he observed that the ACL most commonly tore close to its femoral insertion, but occasionally avulsed with a fragment of bone off the tibia, leaving the ligament essentially intact [23, 120] (Fig. 5). Notwithstanding Dittel's observation that ACL tears may occur in isolation following unidirectional force applied to the tibia in postero-anterior direction, he was the first clinician to become aware of the strong association between injuries of ACL, medial collateral ligament and medial meniscus.

Three years later in 1879, the French surgeon Paul Segond of Paris (1851–1912) provided a detailed description of signs and symptoms accompanying the rupture of cruciate ligaments, including "strong articular pain, frequent accompanying pop, rapid joint effusion and abnormal anterior-posterior movement of the knee on clinical examinations" [259]. Segond also described the so-called Segond fracture, a small bony avulsion on the lateral tibial plateau which if present is commonly combined with an ACL tear. He commented that "This lesion is pathognomonic of torsion of the knee in internal rotation and slight flexion of the lower leg and is associated with rupture of the anterior cruciate ligament". To fully appreciate Segond's discovery, one should bear in mind that he was unable to rely on radiographs, as Röntgen rays had not been discovered.

Between 1853 and 1917, physiologists and anatomists such as Hermann von Meyer (1815–1892) and Hermann Zuppinger of Zürich, and Hans Straßer of Bern (1852–1927),

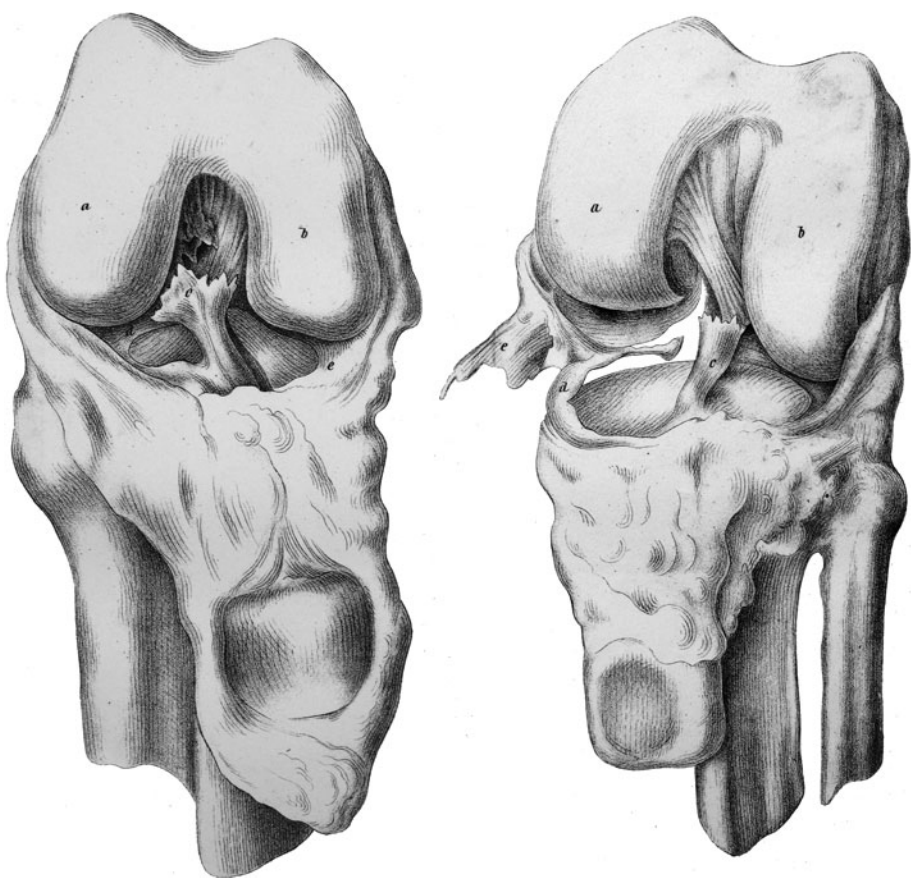


Fig. 5 Illustration of two cadaver specimens drawn following Dittel's experiments published in 1876. The left illustration is showing the ACL (**c**) being torn off its femoral insertion whilst on the right a combined injury to ACL (**c**), MCL (**e**) and medial meniscus (**e**) can be depicted [60]

further advanced our knowledge on the function of the cruciates and their interplay with other internal and external knee structures [204, 277, 313]. These scientists recognised the importance of the functional unit of ACL and PCL, known as the 'four-bar-linkage', in providing normal rolling, gliding and sliding motion of femur on tibia, and that any disturbance of this unit (e.g. ACL tear) would invariably disrupt this mechanism and create un-physiological movement patterns.

In 1911 Rudolf Fick of Leipzig (1866–1939) described in detail the tension pattern of the two ACL bundles and recognised that parts of the ACL were tensioned at all times, a finding that later led to the creation of the concept of graft isometry [79]. In 1927 Bruno Pfab of Graz was able to demonstrate the blood supply to the cruciates [237]. In the following decades, further studies on the functional anatomy of the ACL were produced by Otto Brantigan and Allan Voshell of Baltimore in 1941, LeRoy Abbott of San Francisco (1890–1965) in 1944, Fakhry Girgis of New York in 1975, and Lyle Norwood and Mervyn Cross of Columbus in 1979, defining the ACL as the primary anterior stabiliser and secondary rotatory stabiliser of the knee [1, 28, 99, 218] (Fig. 6).

In the early 1970s, Victor Frankel of New York, Frank Noyes of Cincinnati and Jack Kennedy of London, Ontario provided further insight into injury pattern and biomechanics of ACL failure by assessing the effect of a number of variables including age, and stress and strain upon the physical ligament properties [84, 149, 151, 220]. By the end of the twentieth century, the orthopaedic community had hence gained a sophisticated understanding of the functional behaviour of the cruciate ligaments.

Direct repair of the torn ACL: 1895–1990

In the ninetieth century when morbidity and mortality associated with surgery was still high and antimicrobial agents to combat sepsis not yet discovered, surgeons showed general reluctance to offer surgery for a condition as obscure as ligament disruption. This era was described by Edgar Bick of New York as a time "when the [knee] joint was considered a matter beyond the pale of the ordinary rules of surgery" [17]. Injuries to ligaments often remained unrecognised and symptoms of knee instability rarely attributed to a torn ACL [1]. In 1915 Richard Warren of London (1876–1957) well aware of the ignorance of some of his colleagues wrote in his 'Textbook of Surgery', "Such cases are likely to be regarded as bad sprains, but when the abnormal mobility persists the joint should be explored and the ligaments sutured with chromic gut" [295].

Although William Battle of St. Thomas in London (1855–1936) was the first to publish the successful results of a single case of open ACL repair with a silk suture in 1900, it was in fact Sir Arthur Mayo-Robson of Leeds (1853–1933, Fig. 7) who had performed a similar surgical procedure on a 41-year-old miner 5 years earlier [14, 200]. Here too the ligaments were torn off the femoral side and secured via catgut ligatures. The patient was discharged after

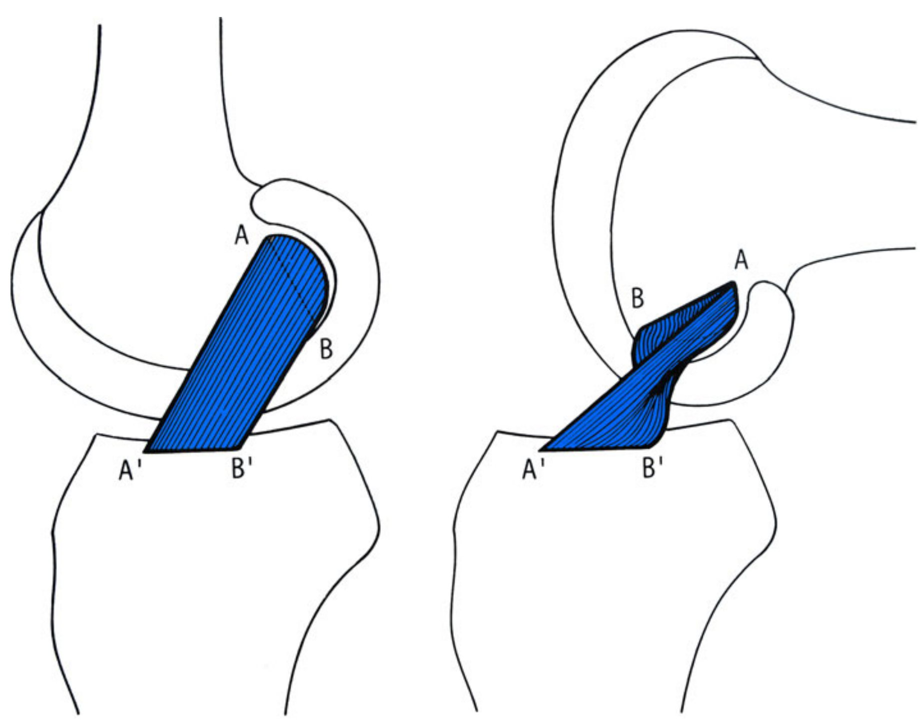


Fig. 6 Schematic drawing representing changes in the shape and tension of the ACL components in extension and flexion according to Girgis 1975 (With kind permission of Lippincott Williams & Wilkins, Philadelphia) [99]

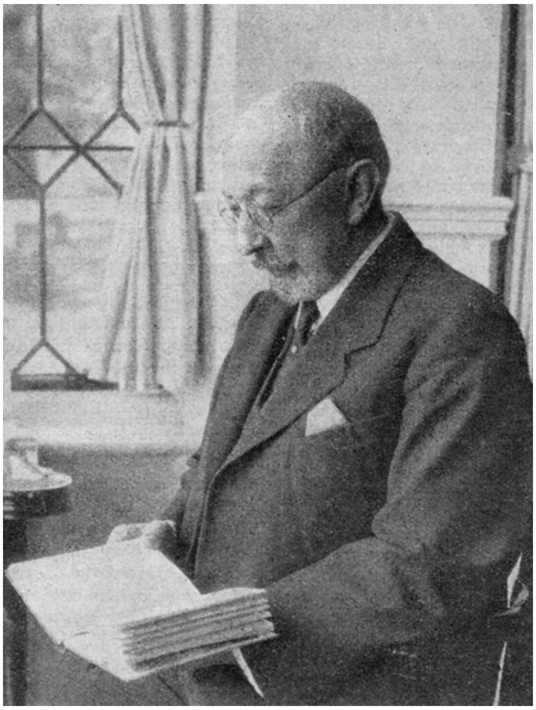


Fig. 7 Sir Arthur Mayo-Robson (1853–1933) of the Leeds General Infirmary performed the first repair of a torn ACL in 1895 (with kind permission of BMJ Publishing Group Ltd, London) [315]

3 weeks with a plaster of Paris, which was removed after a month. When reviewed 6 years later, the patient considered his leg "perfectly strong" and Mayo-Robson remarked, "He walks well without a limp and can run. No abnormal mobility whatever present. Extension to the straight line is perfectly free. Flexion is somewhat limited".

By 1913 Hubert Goetjes of Cologne was able to trace a total of 23 cases of ACL rupture in the available scientific literature [102]. In his comprehensive paper, he elegantly summarised all knowledge on the function, biomechanics and treatment of cruciate ligaments of his day. He reported in detail on each single case and added a further 7 from his own hospital. Goetjes concluded that suture repair should be recommended in all acute and chronic cases if associated with abnormal knee function. He was also the first surgeon to suggest examination under anaesthesia of the knee when the clinical diagnosis was uncertain.

The results of ACL repair, however, remained unpredictable, due to difficulties encountered in trying to obtain reliable suture fixation of the often tethered and shredded ligament remnants. Hence surgeons like Sir Robert Jones of Liverpool (1857–1933) continued to advocate conservative management [144, 145]. He expressed disbelief that suture repair would yield advantage over plaster immobilisation when he remarked that "… stitching the ligaments is absolutely futile. Natural cicatricial tissue … is the only reliable means of repair". Jones's view was echoed by Ernest Hey Groves of Bristol (1872–1944) who in 1920 commented that "… in all my cases the ligaments have been so destroyed … that direct suture would have been utterly impossible" [114].

Georg Perthes of Tübingen (1869–1927), better known for his description of femoral head necrosis in children, was aware of the difficulties in connecting the torn ACL fibres with sutures, since he realised that the ACL almost always tore off its femoral attachment leaving not enough proximal ligament to facilitate repair [236]. He devised a new technique whereby a suture loop of aluminium-bronze wire was connected to the distal ligament remnant and both ends of the wire pulled through separate drill holes entering the femoral foot print of the ACL and exiting at the outer aspect of the femoral metaphysis (Fig. 8). The ligament was pulled tight and the wire twisted over the bony bridge to achieve secure fixation. He reported excellent results with this technique at 1–4 years in three patients. Animal studies provided further evidence on the suitability of his technique, by confirming complete reconstitution in all cases following Perthes' repair [238]. Perthes, however, was concerned that most of his colleagues only considered ACL repair once it became clear that conservative management had failed and patients suffered from ongoing instability [236]. He believed that the level of knee laxity and associated symptoms of swelling and discomfort are likely to

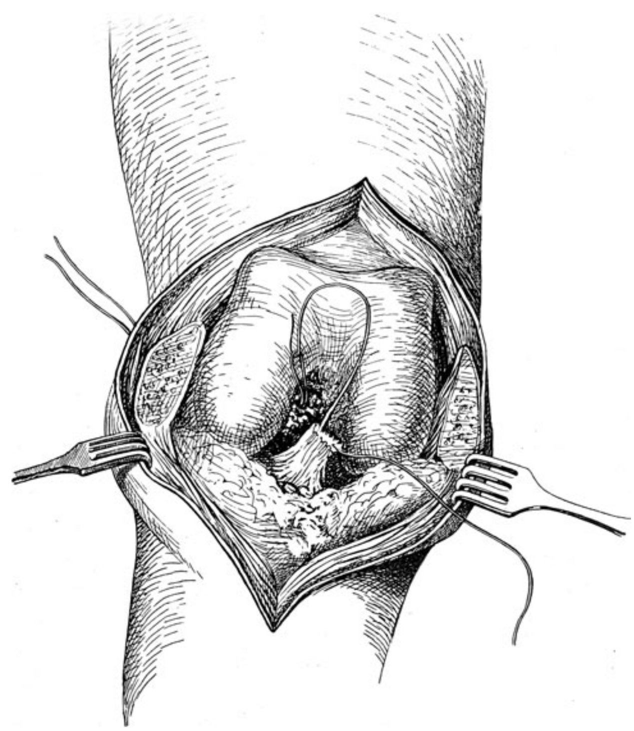


Fig. 8 Perthes' technique of ACL repair using transcortical wire suture. Please note the longitudinal division of the patella, according to Robert Jones, to gain access to the joint (with kind permission of Hüthig Jehle Rehn, Heidelberg) [236]

increase with time and therefore suggested that patients should be examined as soon as pain and swelling have subsided and that surgical repair should follow in all cases where rupture of the cruciate ligament is strongly suspected.

Erwin Payr of Leipzig (1861–1946) took a different approach to repairing the ACL from Perthes [233]. Aware of the insufficient length of the proximal ligament remnant he designed a procedure that was essentially a partial ACL reconstruction. A fascia loop was threaded through a semicircular tunnel, positioned at the femoral origin of the ACL, and sewn against the tibial ACL stump (Fig. 9). In 1938 Ivar Palmer published his thesis 'On the Injuries to the Ligaments of the Knee Joint', a detailed study on anatomy, biomechanics, pathology, and treatment [232]. He advocated operating "at an early stage when it is generally possible to restore anatomic conditions". Palmer used the Perthes' technique and emphasised the importance of repairing both bundles separately.

Don O'Donoghue of Oklahoma (1901–1992), a key figure in Orthopaedic Sports Medicine, popularised ACL repair in the United States in the 1950 and 1960s [225, 226]. O'Donoghue had already gained experience with the reconstruction of neglected ACL-deficient knees in 29 athletes using a modified Hey Groves technique [227]. Although his results were acceptable, he felt that "the rate of success is not sufficiently high to warrant the attitude that acute ruptures of the anterior cruciate need not be repaired under the misapprehension that the ligament can be satisfactorily reconstructed at a later date if the patient has sufficient disability. On the other hand, after successful repair of an acute rupture I have no hesitation in recommending return to active athletics, including football". It becomes clear that O'Donoghue did "not recommend routine reconstruction" but instead proposed that in an "acute injury, cruciate repair should be done routinely" and that "the time of the repair is vastly more important than the severity of the injury". Through emphasising the need for early intervention following ligament injury if return to sport activities is desirable, O'Donoghue gave ACL surgery an unexpected boost in the USA.

Suture repair continued to be practised way into the early 1980s and supported by good clinical results published by David MacIntosh of Toronto and John Marshall of New York [186, 193]. Both devised a variation on the Perthes technique with sutures being passed behind the lateral femoral condyle in a so-called 'over-the top' repair. In 1976 John Feagin of the Keller Army Hospital in West Point, New York presented his 5-year results of 32 army cadets who had undergone direct ACL repair [77]. Although initially 84% did well and returned to sporting activities, at 5 years almost all patients suffered some degree of instability, two-thirds experienced pain and 17 of the 32 had sustained a re-injury during the follow-up period. Feagin concluded that "long-term follow-up evaluations do not justify the hope … that anatomic repositioning of the residual ligament would result in healing". His views

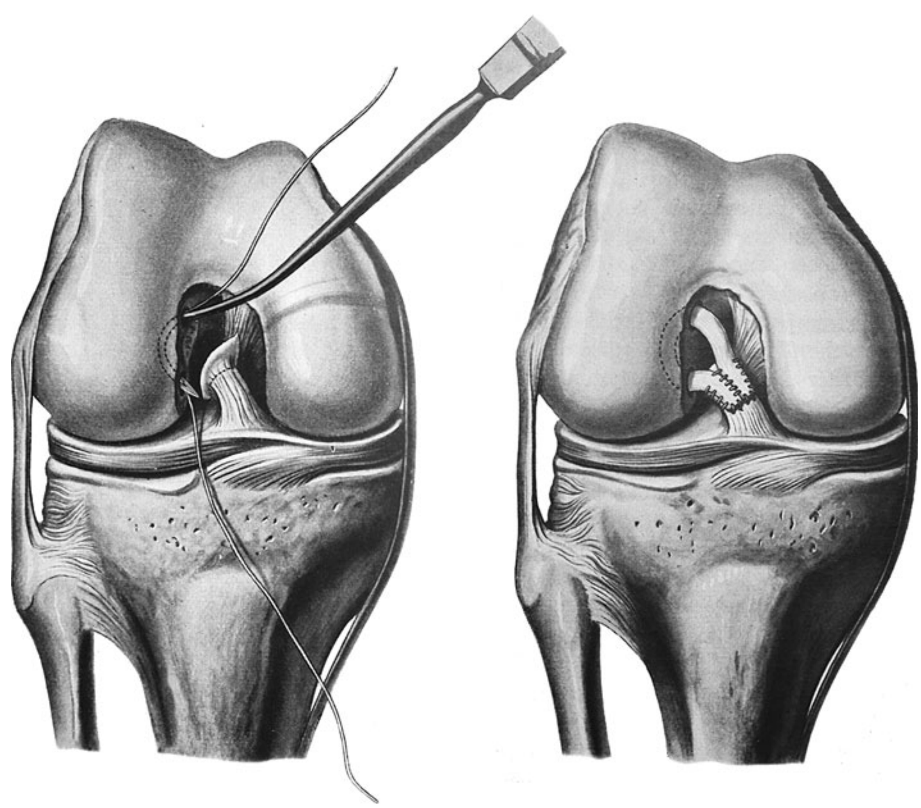


Fig. 9 Payr's technique to repair the proximally torn ACL with a trans-osseous fascia lata loop (with kind permission of Springer Science, Berlin) [233]

were shared by Werner Müller of Bale who believed that "success in these cases may well have been due to extensive adhesions among the intra-articular folds, greatly reducing joint play and restraining anterior translation while still permitting recovery of knee motion in flexion–extension" [214]. Damaging long-term results published by Engebretsen and associates in the 1990s sealed the fate of primary suture repair, which was all but abandoned by the end of the century [73].

Pioneers of ACL reconstruction: 1914–1920

Clinicians eventually realised that a number of patients developed ongoing instability due to chronic knee laxity. These patients required a different solution other than repair which subsequently led to the concept of replacing the ACL with some form of graft material [166, 292]. The clinical indications for ACL reconstruction were later defined by O'Donoghue as "… anterior cruciate instability sufficiently severe to interfere with a person's normal everyday living" [227]. John Insall, however, recognised that "… the ability to perform at some level, in some kind of sport is highly desirable and must be recognised as a true indication for ligament reconstruction", whilst bearing in mind that "surgery is not indicated to cure a physical sign without symptom nor should the end result be judged solely on the basis of the stability examination alone" [129].

In 1913 Paul Wagner of Leipzig wrote a thesis on the 'Isolated rupture of cruciate ligaments' [292]. He suggested the use of fascia for the reconstruction of the ACL in cases where the ligament is so badly damaged that suture repair has become impossible, but did not refer to any clinical experience. Erich Hesse, surgical assistant to Ivan Grekov (1867–1934) in St. Petersburg, reported in 1914 on what is believed to be the first attempt of an anatomic reconstruction of the cruciate ligaments performed on a 40-year-old man who had fallen from the 3rd floor dislocating his knee [111]. The operation was performed by Grekov, who used a free fascia graft which he routed through drill holes in the femur and stitched against the ligament remnants on the tibia. The functional results were thought to be "exceptionally good with no side to side laxity".

The first complete reconstruction of the ACL was performed 3 years later by Ernest William Hey Groves at the General Hospital in Bristol [113] (Fig. 10). He was disenchanted with the standard of treatment of ACL injuries of his day when he wrote in 1917, "while the frequency and importance of this injury is becoming more widely known, there have not been any corresponding advances in the method of treatment. A rigid plaster or leather cast to be worn for a year, followed by a hinged apparatus represents the generally accepted method". Hey Groves utilised the entire fascia lata which he detached from its tibial insertion and "threaded through new canals bored in femur and tibia" where it was sown onto the periosteum (Fig. 11). Leaving the tendon attached to the muscle belly was believed to maintain tendon blood supply and nutrition. Hey Groves was clearly aware that proper knee joint function could only be re-established if the reconstructed ligament graft is placed in the exact anatomic position of the original ACL "in contradistinction to a mere passage of new ligaments across the joint" [114]. He also recognised the importance of graft obliquity, as "any new ligament which is used to replace them should be given this oblique direction, even in an exaggerated degree, because an anterior ligament will be efficient in preventing anterior tibial displacement in proportion to its obliquity". The mechanical principle behind Hey Groves's notion of graft obliquity, however, remained unrecognised for almost a century, until Loh and colleagues from Pittsburgh published their biomechanical study on tunnel placement in 2002 [179]. They discovered that increased graft obliquity achieved through a low femoral tunnel placement within the notch, provided for improved rotational stability of the knee compared to a graft placed in a more vertical position. Their findings were later confirmed in clinical studies and subsequently became accepted practice [257].

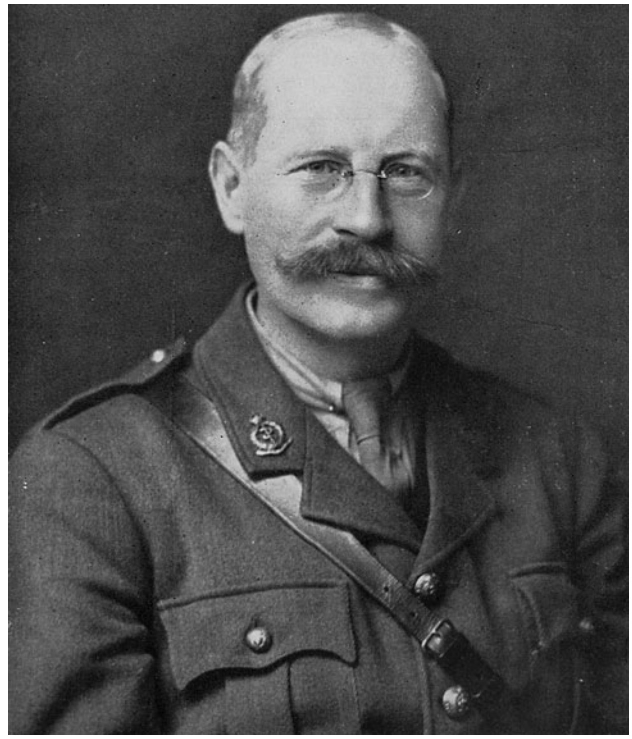


Fig. 10 Photograph of Ernest William Hey Groves (1872–1944) of Bristol in the year 1916 (with kind permission of John Wiley & Sons, Hoboken) [115]

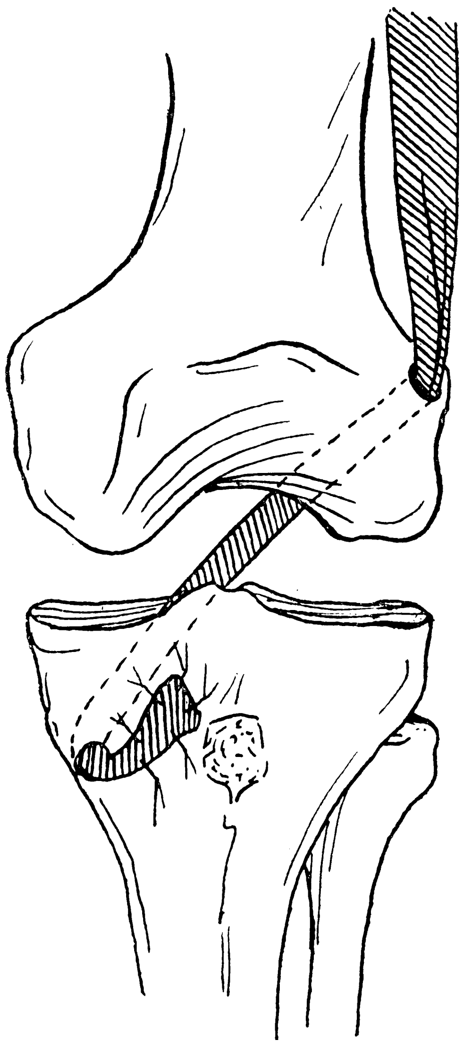


Fig. 11 Original Hey Groves ACL reconstruction technique of 1917 (With kind permission of The Lancet) [113]

Hey Groves was also the first clinician who described antero-lateral subluxation of the tibia in the ACL-deficient knee when he commented that "In active exercise, when the foot is put forward and the weight of the body pressed on the leg, then the tibia slips forward; sometimes this forward slipping of the tibia occurs abruptly with a jerk …" [114]. His description leaves little doubt that Hey Groves, like Bonnet 70 years earlier, had identified the pivot shift phenomenon, which indicated that the anterior half of the ilio-tibial band had become an extensor rather than flexor and hence was unable to prevent subluxation of the lateral tibial plateau when the knee was close to extension. This phenomenon was later used by Galway & MacIntosh to devise the 'pivot-shift-test', a sensitive diagnostic assessment tool to identify ACL incompetence [94].

In 1918, Alwyn Smith of Cardiff (1884–1931) reported on nine cases treated with Hey Groves' technique, criticising the incomplete nature of the construct, "as it does not attempt to strengthen in any way the internal lateral ligament, so that the new fascial strip has to bear the entire strain of abduction of the knee as well as of anterior sliding and internal rotation" [268, 269]. Smith's report would suggest that he had encountered a more complex injury pattern also involving the MCL which would later become known as antero-medial instability. He therefore proposed a modification to the Hey Groves technique suggesting the use of only a section (strip) of the fascia lata (1 ½″ wide and 10″ long) which should be detached proximally from its muscle belly (Fig. 12). The tendon is then routed through femoral and tibial tunnels and looped through a superficial drill hole around the medial femoral epicondyle, to provide additional reinforcement to the MCL. Smith also described using massage and electrical stimulation to decrease quadriceps atrophy.

For other reasons than Smiths's, Hey Groves had also became disenchanted with his original technique using proximally based fascia, as it provided a relatively short graft and weakened the knee by depriving it of one of its main lateral supporting structures. In his second publication on ACL surgery in 1920, Hey Groves presented results of 14 cases of ACL reconstruction using a modification of his original technique [114]. Of his 14 cases, "None were made worse, 4 showed no benefit, 4 benefitted to some degree, 4 were cured and 2 were only operated 6 months ago" but "promise to be successful". Hey Groves appeared rather self-critical and his refreshing honesty in conveying his results deserves credit and has to be considered unusual for his time. He continued using the revised technique for the remainder of his career and documented each case thoroughly and often added artistic drawings (Fig. 13). Hey Groves and Smith had laid down the basic principles of anatomic ACL reconstruction and although the surgical community followed various pathways in the coming years it eventually started to appreciate their achievements and ingenuity.

Despite the excellent work of these early pioneers however, the debate over the following 50 years was less over primary ligament repair versus reconstruction, but whether any procedure should be performed at all [199]. Conservative management of ACL-deficient knees was fostered by the improvements in orthotics and physiotherapy. Timbrell Fisher of London (1888–1967) strongly believed in the benefits of conservative management and in his view "operations should be reserved for cases who suffer grave functional disability, which persist in spite of increasing the power of the quadriceps, and other thigh muscles, or the wearing of a well-planned and accurately fitting mechanical support" [80].

Amedeé Bonnet had already experimented with off-set hinges for knee orthoses in the early 1850s [24]. Staudinger

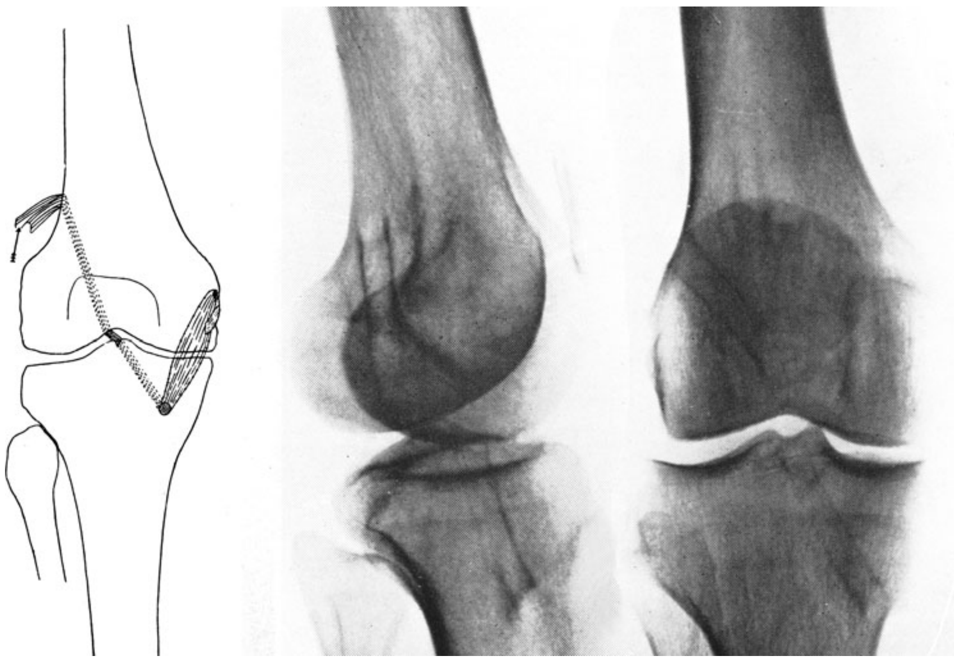


Fig. 12 Smith of Cardiff re-routed a distally based strip of fascia, through lateral femoral condyle and medial tibial plateau and attached it onto the medial femoral epicondyle, thereby combining reconstruction of the ACL with MCL augmentation (with kind permission of John Wiley & Sons, Hoboken) [268]

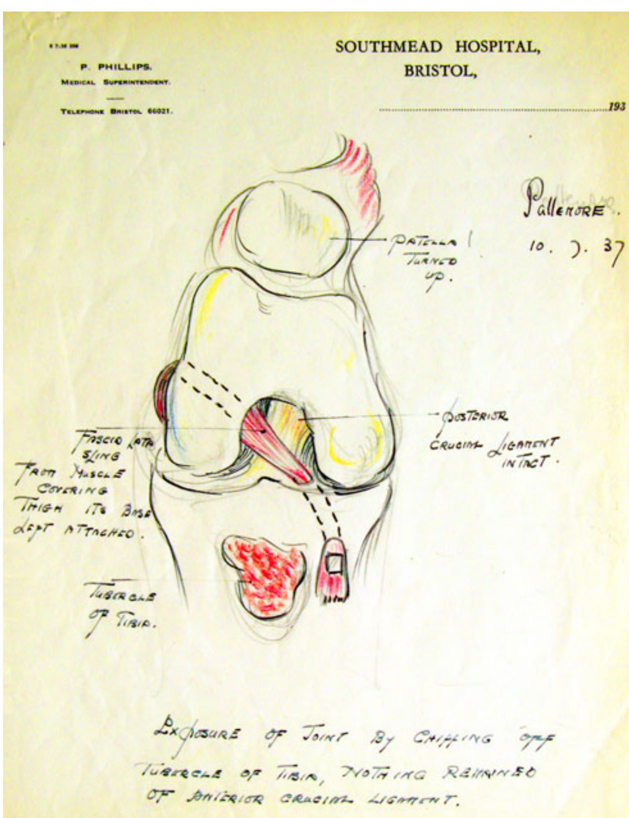


Fig. 13 Original drawing by Hey Groves in 1937 showing the revised technique of using proximally detached pedicled fascia lata as described in 1920. Tibial tubercle osteotomy was performed for enhanced exposure and the graft secured with an ivory nail (author's archive)

Fig. 14 Knee brace introduced by Staudinger in 1931 using a 'parallelogram hinge' to accommodate the changes in the centre of rotation during knee flexion (with kind permission of Ferdinand Enke, Stuttgart) [276]

of Frankfurt, aware of the disadvantages of traditional hinged knee braces, introduced his “parallelogram hinge brace” in 1931 [276] (Fig. 14). The mechanism, which was based on a design by Schede & Habermann used in leg prosthesis, tried to emulate the changes of instant centre of rotation and thereby accommodating the natural rolling and gliding motion of femur on tibia [255, 276]. In 1945 Thomas DeLorme of Chicago introduced the concept of muscle strengthening through heavy resistance exercise and reported that “most dramatic results have been obtained in cases of instability of the knee” [59].

Critics of ACL surgery were not only mindful of the extensile exposure necessary to facilitate surgery, but believed that it was essentially wrong to allow the dynamic play of forces in the knee, which had lost stability, to depend on a relatively fragile, isolated graft, running freely through the joint (Fig. 15). Constantine MacGuire of New York believed that reconstruction “could not give any benefit other than that derived from the period of immobilisation following operation” [184]. Such objections, however, did not dampen the overall enthusiasm, confirmed by an ever increasing number of publications on the topic, focussing on modifications of surgical technique and graft selection [13, 45, 68, 103, 137]. The mood was echoed by LeRoy Abbott who in 1944 wrote “The application of a splint or plaster cast until such time as the lesion is judged to have healed, satisfies the attendant, if not always the patient. Rest and fixation, although sound in principle,… often prove disastrous in those patients in whom the supporting ligaments of the knee have been severely damaged” [1]. Even Sir Robert Jones, one of the great promoters of conservative management, conceded in the 1923 edition of Jones & Lovett’s ‘Orthopaedic Surgery’ that “the writers have examined several of these cases (of ACL reconstruction) without having seen a perfect result, but several have been much improved” [146]. Both authors, however, were mindful that such surgery should not be performed indiscriminately when they concluded that “the operations are usually grave and require the highest craftsmanship, and should never be undertaken without a sense of grave responsibility”.

Fig. 15 Intra-operative photograph taken from Janik’s treatise on cruciate ligament injuries published in 1955, which highlights the extensive exposure used at the time to perform ACL reconstruction with fascia lata (with kind permission of Walter De Gruyter, Berlin) [137]

With changes in life style especially towards the second half of the twentieth century, patients expectations rose and as evidence emerged on the relatively high failure rate of conservative management, reconstructive surgery gradually gained wider acceptance. A major impetus towards a more pro-active approach in the treatment of ACL injuries was provided by Frank Noyes of Cincinnati in 1983 following his publication on ‘the rule of thirds’ in patients treated non-operatively [221]. He concluded that “one-third of the patients with this injury will compensate adequately and be able to pursue recreational activities, one-third will be able to compensate but will have to give up significant activities, and one-third will do poorly and will probably require future reconstructive surgery”.

ACL graft materials

Fascia lata (ilio-tibial band): 1914–1990

Fascia lata remained a popular choice of graft for the best part of the twentieth century. In 1927 Charles F Eikenbary of Seattle (1877–1933) followed Grekov to become only the second surgeon to use a free tissue graft to reconstruct the entire ACL [68]. The procedure was “suggested as an improvement over the Hey Groves or the Putti method” and utilised a medial para-patellar approach thereby avoiding patellar tendon detachment or splitting which was standard at the time [68, 114, 243]. Drill holes were placed through the anterior surface of femur and tibia to simplify graft introduction (Fig. 16). First clinical results of free tissue grafts for ACL reconstruction were provided by Wilhelm Jaroschy of Prague (1886–1938) in 1929 [138]. He reported on two successful cases where grafts remained competent and joint stability was maintained 9 months after surgery, thereby diminishing concerns of impaired biological viability thought to be associated with free tissue grafts.

William Cubbins and James Callahan of Chicago became the key promoters of the Hey Groves procedure in the United States. Both published extensively on their technique of simultaneous ACL and PCL reconstruction during the 1930s [45, 46]. In 1978 John Insall (1930–2000) presented the ‘bone block ilio-tibial band transfer’, a procedure based on Jeffrey Minkoff’s and James Nicholas’s ‘ilio-tibial band pull-through’ (ITPT) technique, first used at Lennox Hill Hospital in 1971 [128, 129, 217] (Fig. 17).

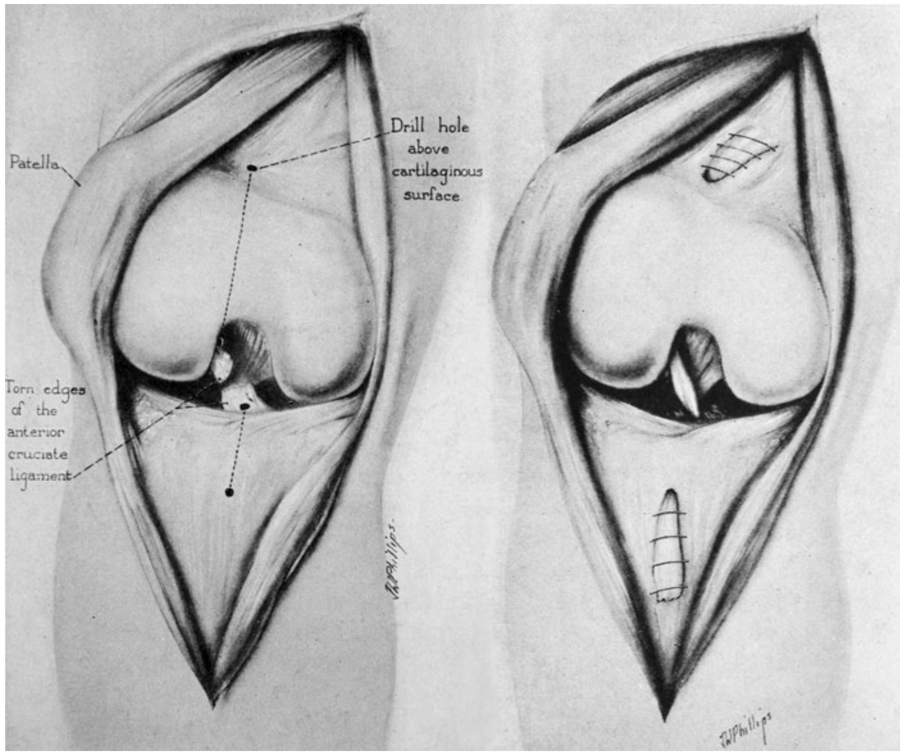


Fig. 16 One of the first ACL reconstruction using a free tissue graft through a medial para-patellar approach as designed by Charles Eikenbary in 1927 (with kind permission of Elsevier, Philadelphia) [68]

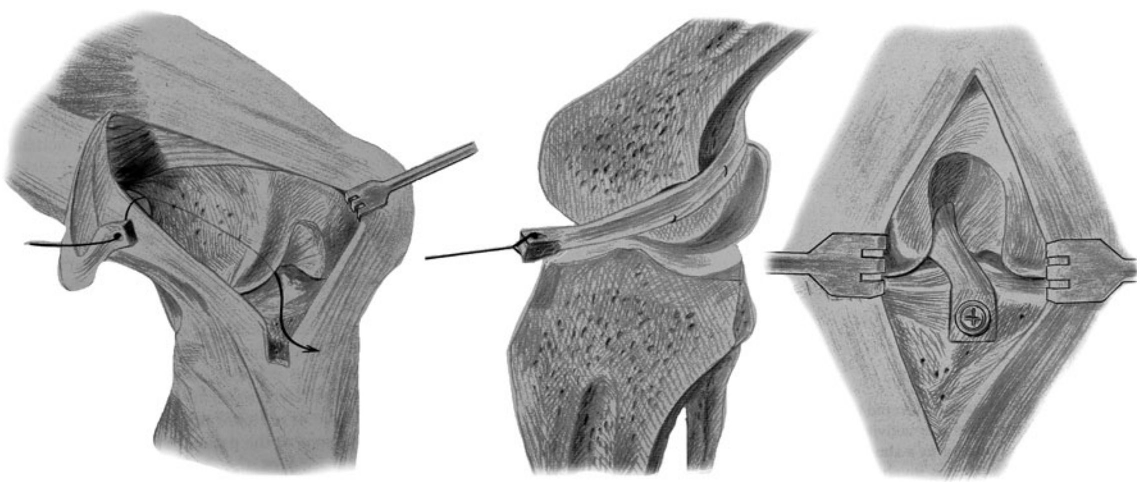


Fig. 17 John Insall's 'bone block ilio-tibial band transfer' first published in 1981 (with kind permission of Elsevier, Oxford) [129]

Insall detached the central portion of the fascia lata with its osseous insertion from Gerdy's tubercle, re-routed the graft over-the-top of the postero-lateral femoral condyle through the joint and secured the bone block with a screw just below the tibial plateau. At a minimum of 2 years follow-up, Insall reported that "although the results of the post-operative anterior drawer test are disappointing if one hopes to restore the knee to normal, the improvement in the patients' functional capacity is quite dramatic … and most of these patients were engaging in strenuous sports without brace protection." Insall conceded however that "normal stability rarely if ever is restored" as he believed it to be "impossible to duplicate the original anatomy exactly with any form of graft" [128].

Meniscus: 1917–1990

Even at the beginning of the twentieth century, surgeons were already aware of the strong association between rupture of the ACL and meniscal damage. The treatment of choice for a torn meniscus was its removal and since it was known that meniscal tissue consisted of avascular fibro-cartilage nourished by synovial fluid, it appealed to many as an almost ideal and readily available substitute for the

ACL. In 1917 Hölzel, assistant to Max zur Verth of Hamburg (1874–1941), reported on a patient with cruciate deficiency, who was seen on a hospital ship during the war [119]. Zur Verth replaced the ACL with the torn lateral meniscus, which he left attached distally, and sutured against the ligament remnants proximally. He commented that "As far as the replacement of the ligaments are concerned free fascia lata graft would have been available. Instead it was preferred to use the remaining aspect of the meniscus which was well anchored on the tibia. This spared the trouble of trying to attach the fascia to the tibia which is not a very simple task". From his account, it would appear that zur Verth had already used the technique of grafting the torn ACL with fascia lata before Hey Groves but without formally publishing on it.

In 1927 Pfab was able to confirm through experiments on sheep, that healing and integration of meniscal tissue occurred when used in replacing the ACL [238]. Meniscus was seen as a suitable ACL replacement graft until the late 1970s and promoted by a number of well-known Orthopaedic Surgeons on both sides of the Atlantic [40, 131, 177]. Their view is reflected by Bengt Tillberg of Linköping in Sweden who, after having performed the surgery on 43 patients concluded that "The use of a meniscus for the reconstruction of either cruciate ligament is considered to be simple, safe and effective" [284].

Although Max Lange of Munich (1899–1975) had experimented with meniscal tissue graft in the early 1930s, he remained critical upon its use. He upheld the view that meniscal tissue was "functionally unsuitable to replace a ligament" as it was primarily designed to withstand compression rather than tension and shear [169]. In histological studies, Lange was able to confirm mucoid and cystic degeneration of meniscal implants and concluded that "a degenerative meniscus appears to be too poor to be considered for reconstruction, whilst a healthy meniscus would appear to be too good" [93, 169].

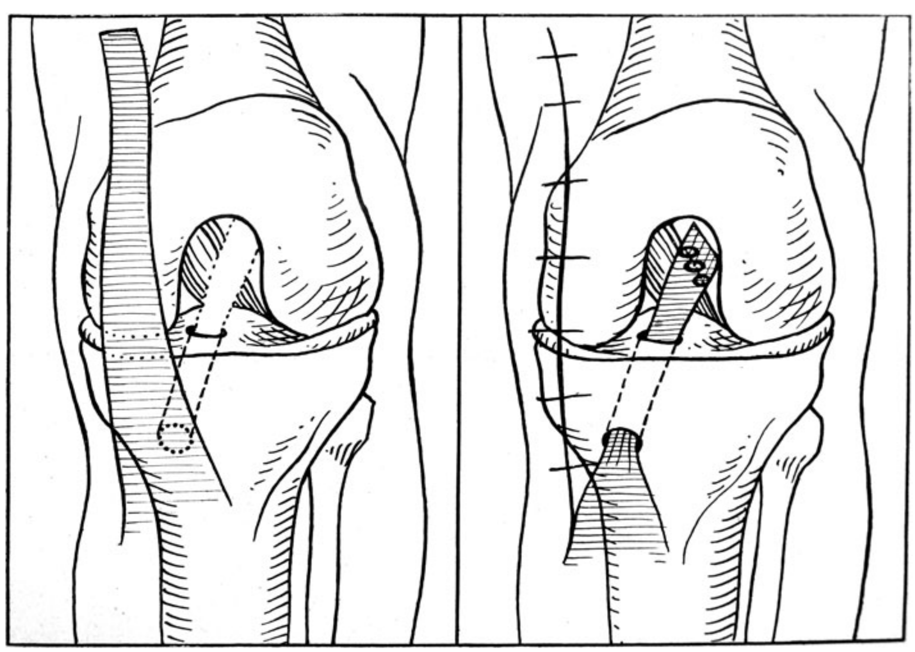
Knowledge of the importance of the meniscus, the consequences of its removal and reports on clinical failures gradually prompted a shift in opinion [294]. This was led by publications of Jack Hughston of Columbus, Georgia (1917–2004) in 1962 who recognised the contribution of the meniscus to knee stability and those of Peter Walker of New York in 1975, who defined the role of the meniscus in the force transmission across the joint [76, 123, 124, 188, 258, 293]. Meniscus was finally abandoned as grafting material by the end of 1980s.

Extensor retinaculum and patellar tendon: 1927—today

Mitchell Langworthy of Spokane, Washington (1891–1929) is reported to have been the first surgeon to replace the ACL using part of the ligamentum patellae [68]. Langworthy never published on his method and suffered an untimely death when he became the victim of a bullet from an unhappy patient in his private practice in 1929.

In 1928 Ernst Gold of Vienna presented the case of a 27-year-old lady hampered with knee instability, who had torn her ACL skiing 2 years earlier [103]. Gold used a distally based strip of extensor retinaculum and medial border of the patellar tendon, brought into the joint through a tibial tunnel, and secured against the anterior–superior aspect of the PCL with interrupted locking sutures (Fig. 18). At 7 months, the patient resumed normal

Fig. 18 ACL reconstruction according to Gold, using medial patellar retinaculum and tendon attached to the posterior cruciate ligament (with kind permission of Springer Science, Berlin) [103]



activities including cross country walking with little pain. Clinically her knee was stable and bending beyond 90°. In 1932 Max zur Verth reported on the treatment of chronic ACL-deficient knees with a pedicled section of patellar tendon [314]. Zur Verth never presented his clinical results, but Arnold Wittek of Graz (1871–1956), who had adopted the 'zur Verth' technique, presented 16 successfully operated cases in 1935 [303]. Just like Gold, he did not strive for true anatomic reconstruction as he attached the proximal end of the graft to the PCL.

In 1936 the American surgeon Willis C. Campbell of Memphis (1880–1941), who coined the term 'giving way' in summarising the distressing signs of knee instability, published the first of two articles in which he described the use of extensor retinaculum containing "very strong tendinous tissue from the medial border of the quadriceps and patellar tendons" [32] (Fig. 19). This strip was threaded through tibial and femoral tunnels drilled in accordance to Hey Groves and sutured against the periosteum of the distal femur. Campbell, like Dittel before him, noticed that ACL injuries are commonly associated with injury to the medial meniscus and medial collateral ligament, a situation he called 'terrible triad', thereby predating O'Donoghue's description of the 'unhappy triad' [32, 33, 60, 225]. Campbell was mindful that isolated reconstruction of the ACL in such cases might not provide the desired level of knee stability and hence promoted combined reconstruction of ACL and MCL, just as Smith had done several years before him.

In 1963 Kenneth Jones of Little Rock, Arkansas, suggested a new surgical technique which he "considered simpler and more physiological than those previously described" [141] (Fig. 20). He used the central third of the patellar tendon which he left attached distally. The proximal part of the tendon was removed from the patella together with a small block of bone. He then passed the graft "beneath the fat pad" into a femoral tunnel "placed in the intercondylar notch just posterior to the margin of the articular cartilage". To overcome the problem of insufficient graft length associated with a pedicled patellar tendon graft, Jones had to move the attachment of the anterior cruciate ligament forward within the roof of the intercondylar notch. This resulted in an extremely non-anatomical and vertical graft position and contradicted Jones' earlier claims that his procedure may be "more physiological".

Modern biomechanical understandings and the principle of the 'four-bar-linkage', however, suggested that anterior positioning of the femoral tunnel away from its anatomic foot print would, as shown by Müller, increase tension forces within the ligament graft in proportion with knee flexion and hence was likely to cause graft attenuation or failure long-term [27, 203, 213] (Fig. 21). In addition, Wirth and Artmann of Munich studied 100 knee specimens and found that distally based patellar tendon grafts were simply not long enough with only 13% reaching the anatomical insertion site of the native ACL on the femur [300]. Although Jones claimed generally good results at 2 years with none of his patients "regarded the knee as unstable", 50% of patients nevertheless presented a positive anterior drawer sign. When Jones reviewed 83 of his patients in 1980, almost 30% were lacking confidence and

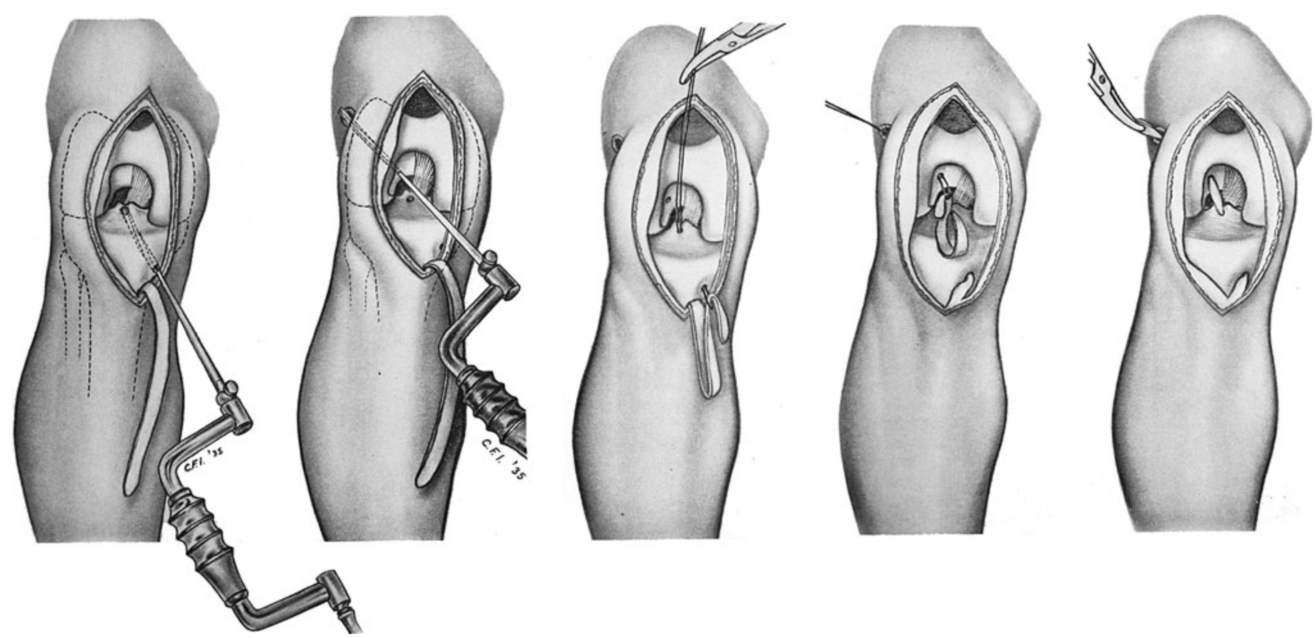


Fig. 19 Illustrations taken form Willis Campbell's publication on knee ligament repair published in 1936. He became the first American to use extensor fascia and part of the patellar tendon to reconstruct the ACL (with kind permission of Elsevier, Philadelphia) [32]

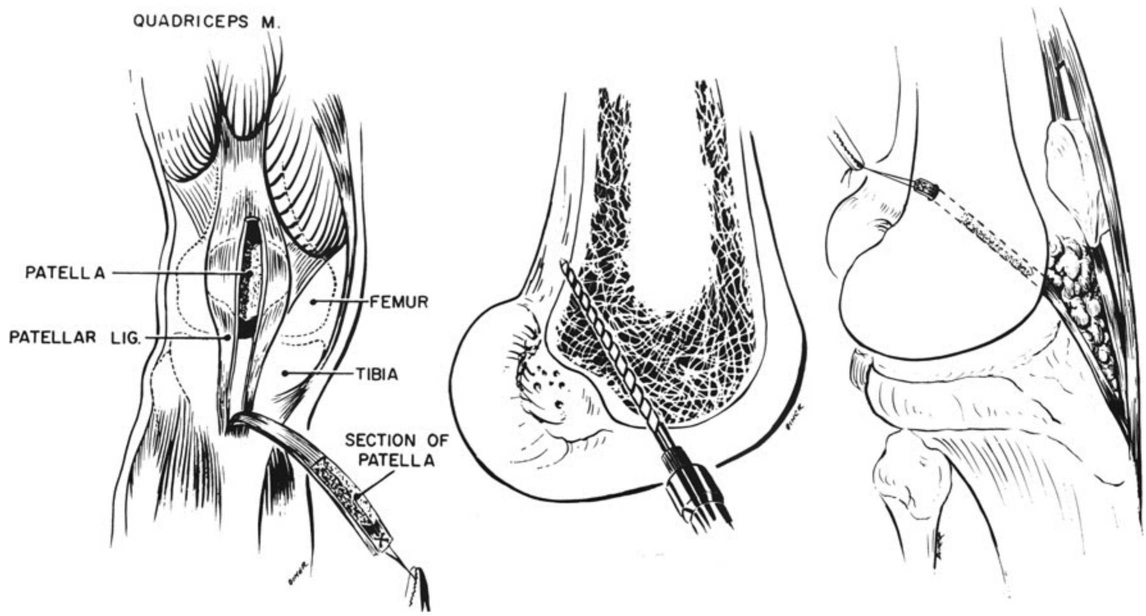


Fig. 20 Illustrations of the original 'Jones Procedure' as described by Kenneth Jones in 1963. Of note is the non-anatomical femoral tunnel placement through the inferior part of the femoral trochlea (with kind permission of the Journal of Bone & Joint Surgery, Boston) [141]

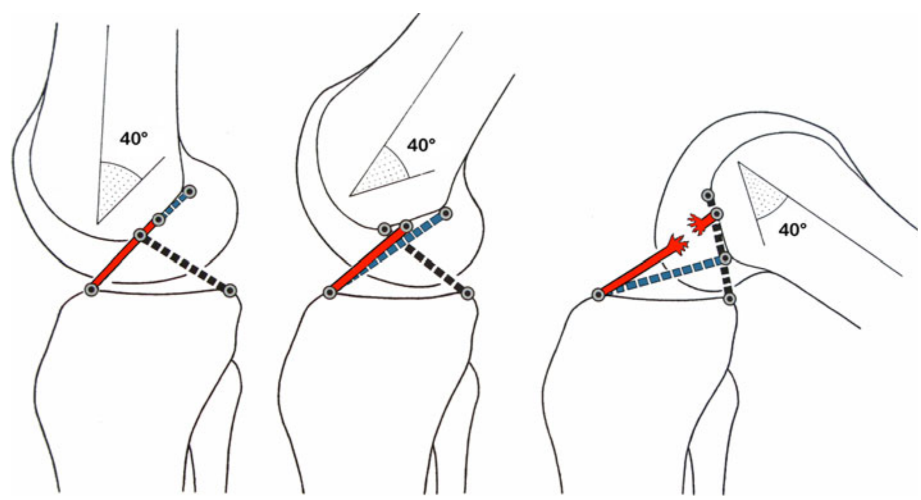


Fig. 21 Werner Müller's model of the 'Four-bar-linkage', first developed by Zuppinger of Vienna and later refined by Strasser and Menschik, demonstrating the detrimental effect of anterior mal-positioning of femoral tunnel in relation to the anatomical foot-print of the native ACL (with kind permission of Springer, Berlin) [213]

suffered residual symptoms [143]. Despite its shortcomings, Jones's technique gained widespread popularity particularly in the United States and reconstruction of the ACL with patellar tendon graft became known as the 'Jones procedure'.

In 1966 Helmut Brückner of Rostock, Germany described the use of the medial 1/3 of the patellar tendon which he left attached distally, whilst the proximal part was lifted off the patella together with a thin sliver of bone [30] (Fig. 22). To overcome problems of insufficient graft length, which had forced Jones to compromise on the femoral tunnel position, Brückner re-routed the patellar tendon graft through a tibial tunnel, thereby essentially shortening the distance between graft attachment and entry into the joint. This allowed Brückner to position a blind ending femoral tunnel closer to the anatomic foot print of the ACL in the intercondylar notch creating a more physiological reconstruction and improved graft isometry. The graft was pulled tight into the femoral tunnel and with the knee positioned at about 40° of flexion, and secured with wire sutures tightened over a small metal button. As an alternative technique Brückner recommended the use of a free central strip of bone-patellar tendon-bone graft (B-PT-B) taken from the contra-lateral knee in cases where the ipsi-lateral patellar tendon was compromised through previous surgery. By 1969 he had performed 35 reconstructions, 90% of which regained normal stability and 25% experienced minor discomfort after strenuous activities

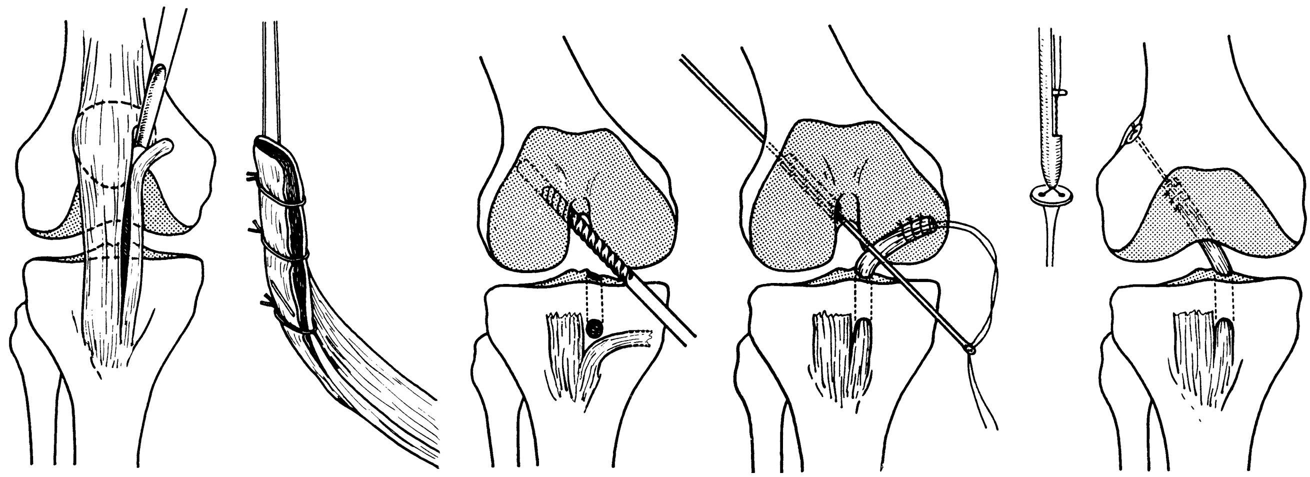


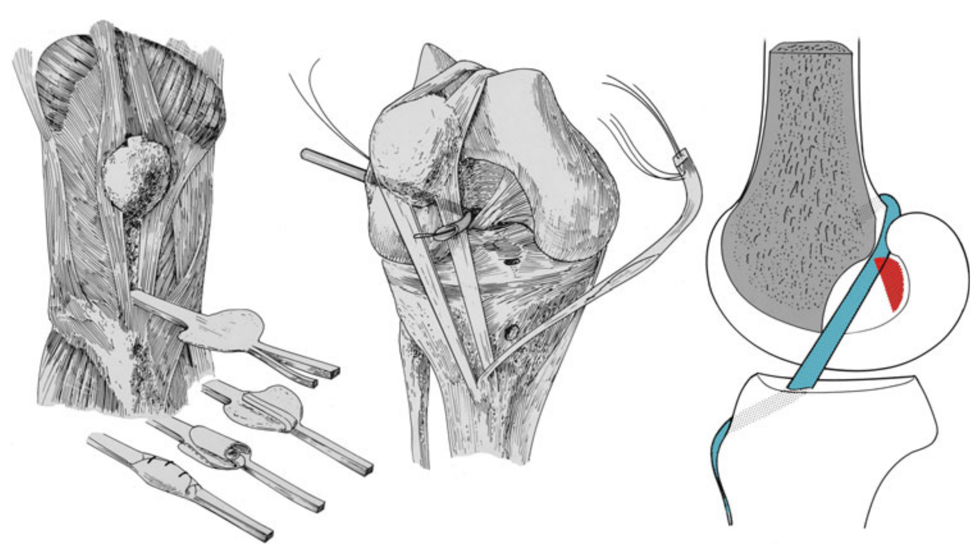
Fig. 22 ACL reconstruction utilising the pedicled medial section of a patellar tendon graft as devised by Brückner in 1966 (with kind permission of Springer Science, Berlin) [30]

[239]. The Brückner technique remained relatively unknown at first but received wider attention through Enjar Eriksson of Stockholm, who in 1976 presented a series of 72 patients, of whom 80% were stable at 1 year [74]. Emerging evidence on changes of patellar kinematics resulting in an increased tendency to patellar subluxation and subsequent degeneration brought an end to utilising the medial 1/3 of the patellar tendon in favour of a central strip [196, 301].

William Clancy of Madison, Wisconsin became a major proponent of patellar tendon for ACL reconstruction in the United States [37]. Unaware of Brückner's original work, Clancy initially described an almost identical technique using a pedicled patellar tendon graft. Although he reported encouraging clinical results with this technique, he eventually converted to using a free tendon graft [38]. John Marshall and associates chose a different approach to overcome problems of insufficient graft length with their 'Quadriceps tendon substitution' technique published in 1979 [193]. They utilised the distally attached central third of the patellar ligament, the pre-patellar expansion and part of the quadriceps tendon as a single graft, which they pulled through a tibial tunnel and looped 'over-the-top' of the lateral femoral condyle (Fig. 23).

In 1976 Kurt Franke of Berlin presented his experience of 130 ACL reconstructions using a free graft of the central third of the patellar tendon as previously described by Brückner [30, 83]. This was the first publication on clinical long-term results with a free bone-patellar-tendon-bone (B-PT-B) graft in a large patient cohort, providing good functional outcome in combination with a reliable and reproducible technique. Following Franke's publication, B-PT-B was to become one of the most popular graft sources and was further popularised through the work of Eriksson in Europe and Clancy in the United States [38, 74].

Fig. 23 Quadriceps tendon substitution technique devised by Marshall and associates in 1979. The graft was placed in the 'over-the-top' position close to the proximal aspect of the foot-print of the ACL (*red area*) (with kind permission of Elsevier, Oxford) [129]



Quadriceps tendon: 1984—today

With time however, it became apparent that harvesting autogenous patellar tendon graft was not an entirely benign procedure but associated with postoperative problems such as patellar fracture [264], patellar tendon rupture [195], flexion contracture, patellar tendonitis and anterior knee pain [3, 222, 230, 253]. Mindful of the potential morbidity associated with patellar tendon harvest some surgeons started experimenting with using a central section of the quadriceps tendon. In 1984 Walter Blauth of Kiel became the first to publish on the use of quadriceps tendon for chronic ACL deficiency [21]. The graft was harvested with a triangular-shaped bone block distally whilst the proximal part was divided into two strands thereby facilitating a double-bundle reconstruction. Blauth positioned one bundle trans-femorally and the other 'over-the-top' of the lateral femoral condyle (Fig. 24). Between 1982 and 1984, he operated on 53 patients with apparently good results. In the United States John Fulkerson of Farmington, Connecticut became the key promoter of quadriceps tendon which he considered to be superior to any other graft source [90]. Quadriceps tendon, however, never gained the same level of popularity as patellar tendon or hamstrings despite experimental studies confirming their excellent mechanical properties as a tendon graft [275]. Today the use of quadriceps graft continues to occupy a fringe position and remains a suitable alternative in the revision setting or when other graft sources are compromised [54, 96, 271].

Hamstring tendons: 1927—today

In 1927 Alexander Edwards of Glasgow suggested an operation he had performed on a cadaver whereby both cruciate ligaments were replaced with the proximally based hamstring tendons [66]. He was not concerned with anatomic reconstruction, since he used a single femoral tunnel drilled through the medial femoral condyle and two tibial tunnels placed in the anterior aspect of the tibial spines. No clinical cases using his technique were ever reported.

In 1934 Riccardo Galeazzi (1866–1952) of Milan pioneered anatomic ACL reconstruction with semitendinosus tendon which he left distally attached to the pes anerinus [91]. Using a three incision technique, he threaded the tendon through 5-mm tunnels, placed according to Hey Groves' original description (Fig. 25). Patients were immobilised in a cast for 4 weeks and remained partially weight bearing for 6 weeks. All three patients in his series fared well even though follow-up was very short. Despite being forward thinking, Galeazzi's surgical ingenuity remained obscured by language barriers as most of his work was published in lesser known Italian journals.

Harry Macey (1905–1951) staff surgeon at the Mayo Clinic in Rochester, unaware of Galeazzi's earlier publication, presented a similar but simplified 'two-incision' technique for the use of semitendinosus tendon [183]. The knee was exposed via an S-shaped lateral para-patellar approach whilst the hamstring tendon was severed through a small stab incision at its musculo-tendinous junction (Fig. 26). He did not report on any clinical cases. A variation on Macey's technique was offered by James McMaster of Pittsburgh in 1974 [201]. He reported on using pedicled gracilis instead of semitendinosus tendon, which he fixed to the lateral condyle with a staple.

In 1950 Kurt Lindemann of Heidelberg (1901–1966) developed the concept of 'dynamic reconstruction' by attempting to take advantage of the stabilising effect of the muscle–tendon unit, a principle first explored by Hey Groves in 1917 [113, 176]. Lindemann utilised proximally

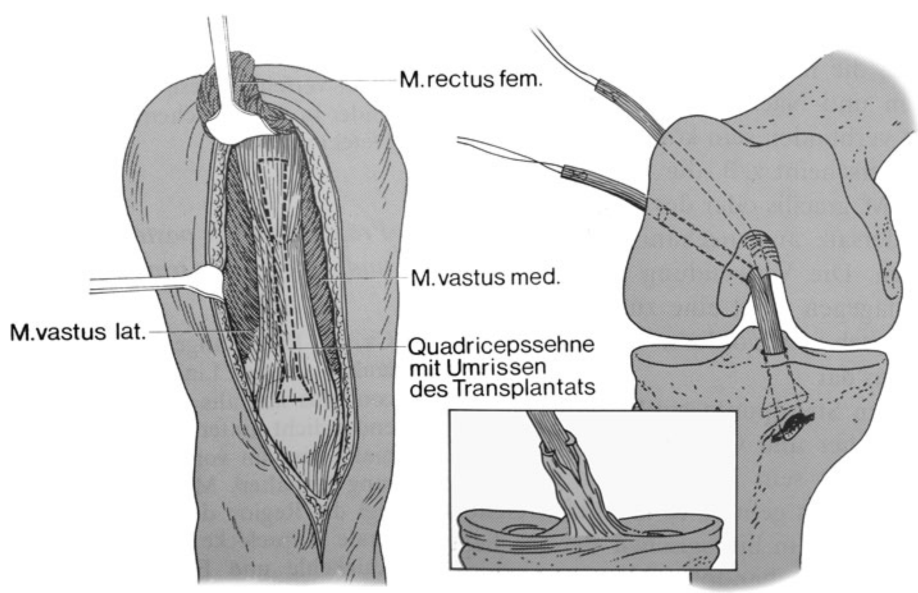


Fig. 24 Double-bundle ACL reconstruction using quadriceps tendon graft according to Blauth. Of note are the preservation of the ACL stump and the press-fit fixation of the graft via bone block in the tibial tunnel (with kind permission of Springer Science, Berlin) [21]

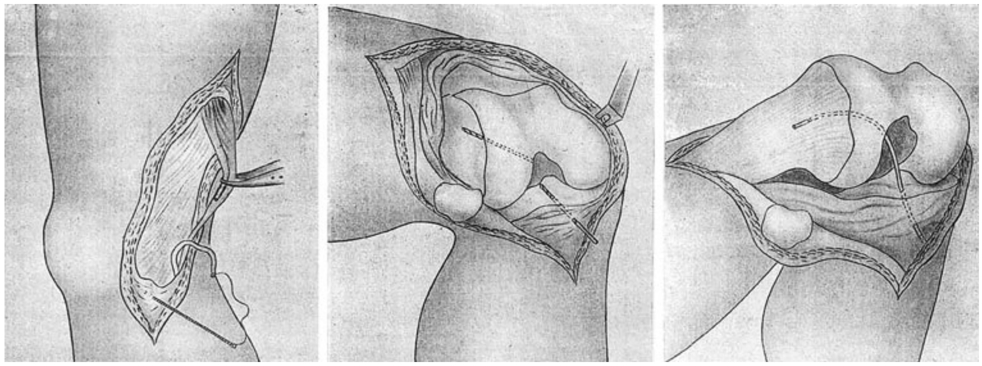


Fig. 25 Riccardo Galeazzi became the first surgeon to publish on the clinical use of hamstrings in the reconstruction of the ACL in 1934. A distally based semitendinosus tendon was threaded through near anatomically placed bony tunnels in tibia and femur [91]

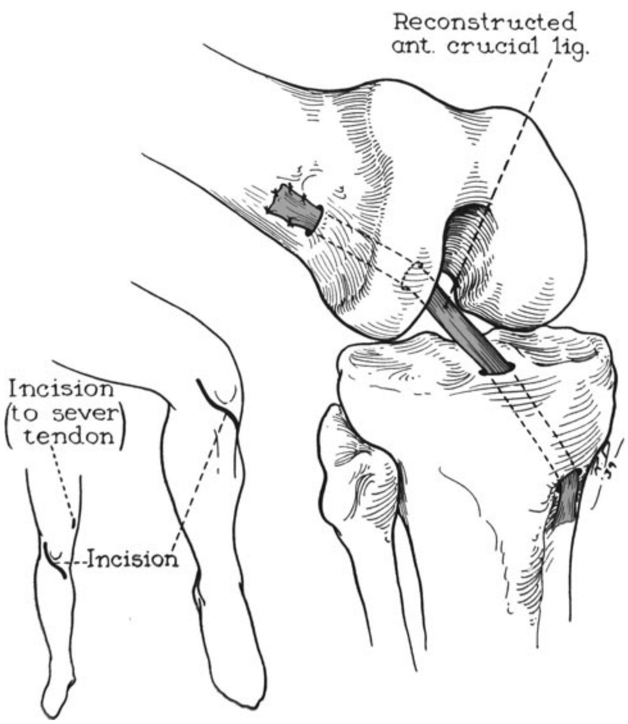


Fig. 26 Harry Macey introduced his two-incision technique using pedunculated semitendinosus tendon in 1939. He utilised a small stab incision to cut off the tendon at the musculo-tendinous junction (with kind permission of Elsevier, Philadelphia) [183]

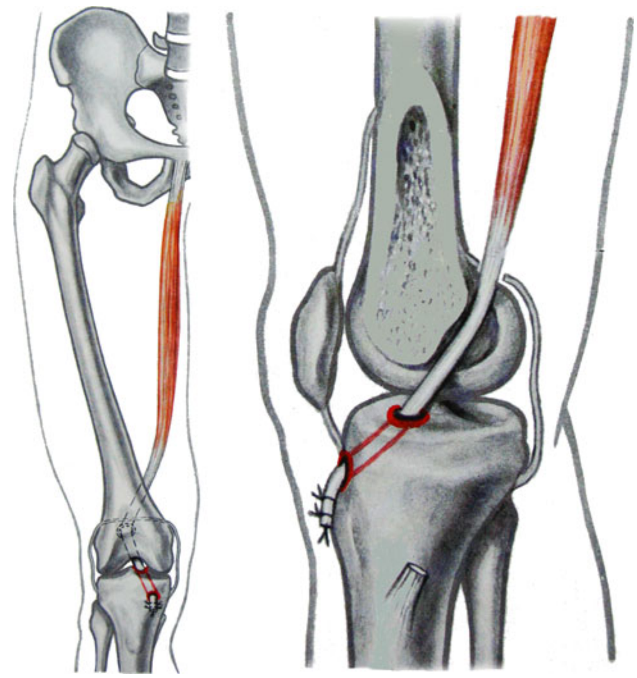


Fig. 27 The Lindemann 'dynamic reconstruction' technique introduced in 1950, was believed to reduce knee instability through the actively stabilising effect of the gracilis muscle/tendon unit (with kind permission of Springer Science, Berlin) [291]

based gracilis tendon, passed through an opening in the postero-lateral capsule into the inter-condylar notch, and threaded through a tibial tunnel positioned at the foot print of the ACL (Fig. 27). At an average follow-up of 2 years, all 6 patients, originally affected by isolated ACL deficiency, regained normal knee function and were able to return to work.

Robert Augustine of Madisonville, Kentucky suggested an almost identical technique to the one proposed by Lindemann 6 years earlier but instead of gracilis chose a pedicled semitendinosus graft [13]. Like Lindemann, he believed in the dynamic effect of the operation to "stabilise the tibial plateau on the femur in conjunction with the PCL when the hamstrings are contracted". Augustine, however, expressed doubts that any reconstructive effort of a chronic cruciate ligament rupture would result "in return to a normal state" and that such knees are "possible of improvement but not cure". His views were echoed by other investigators including O'Donoghue and Insall and summed-up by Kenneth Jones in 1963, who commented that "Anatomical normalcy of the structure is, by the nature of the situation, beyond expectation" [128, 141, 227]. Nevertheless, dynamic reconstructions gained relative success for some time, as surgeons believed that with intact proprioceptors and attachment to active muscle, tension in the transfer would be maintained and anterior subluxation of the tibia prevented [65, 283].

Merle d'Aubigné of Paris (1900–1989) described his techniques and results of ACL reconstruction with distally based semitendinosus tendon graft in 1957 [52]. He was followed by Max Lange, who had used the original Hey Groves technique since the 1940s and was one of the first surgeons to publish clinical long-term follow-up results [93, 169]. Out of 50 isolated ACL tears, he reported excellent outcomes in 82% following early reconstruction and in 62% when surgery was delayed. Although Lange was satisfied with his results achieved with fascia, he changed over to using hamstrings as the operation required less exposure and soft tissue dissection and therefore reduced the surgical trauma to the patient [170]. In the United States, Kenneth Cho of Washington DC also adopted distally attached semitendinosus as graft source and in 1975 reported overall good results and no residual anterior drawer sign in 5 out of 7 patients [36]. Cho believed that "the preservation of the tendon sheath and its intact distal insertion may help to retain some of the vascularity, rendering it more compatible with the intra-synovial environment".

In 1982 Brant Lipscomb of Nashville started using both semitendinosus and gracilis tendon as a double-strand left attached to the pes anserinus [178]. Six years later, following on from Lipscomb's experience, Marc Friedman of Los Angeles pioneered the use of an arthroscopically assisted four-strand hamstring autograft technique, which, despite several smaller modifications, set the standard for ACL reconstruction with hamstrings for the next 25 years [86]. Long-term follow-up studies have since confirmed almost equivalent results regarding knee function and prevalence of osteoarthritis, independent of the choice of graft tissue [118, 247].

Allografts: 1929—today

Allograft reconstruction of the ACL was an attractive proposition as it avoids the need of graft harvest and associated donor site morbidity and prevents weakening of external ligament and tendon structures which contribute to overall joint stability. Eugene Bircher of Arau in Switzerland (1882–1956), better known for his pioneering work on arthroscopy, conveyed his experience with kangaroo tendon as an augment as well as a sole graft in 1929 and was followed by Micheli from Italy who published his results 4 years later [18, 19, 206]. Kangaroo tendon, however, remained a rare choice, and like other xenografts, never gained any real popularity. Bircher was also one of the first clinicians to promote a more progressive rehabilitation regime following surgery, just like Bonnet had done for the conservative management in the previous century [18, 24]. He used a sliding frame during the initial 10-day period instead of the then traditional plaster of Paris, and encouraged early mobilisation thereafter. The idea of early mobilisation was later expanded upon by Donald Shelbourne of Indianapolis, who, in 1992, created his concept of "accelerated rehabilitation" [260, 261].

Reports on the use of human allografts in other areas of Orthopaedics were able to confirm their mechanical, biological and functional comparability to autologous tissue grafts [130, 234, 298]. In 1984 Konsei Shino of Osaka studied the mechanical properties of both allografts and autografts in a dog model without finding any significant differences [262]. Two years later, his group became one of the first to publish clinical results of 31 patients who had received allogenic reconstruction of the ACL utilising mainly anterior tibial and calcaneal tendon grafts [263]. After a minimum follow-up of 2 years, all but one patient had been able to return to full sporting activities. Further publications by Richard Levitt and associates of Miami who reported excellent results in 85% of cases at 4 years with patellar and Achilles tendon allografts and Jacques Defrere & Anne Franckart of Liege who had similar results in their group of 70 patients at 4.5 years with patellar grafts, paved the way for allografts to achieve relative popularity particularly in the United States [55, 174].

Unfortunately, the increased risk of viral disease transmission (e.g. HIV, Hepatitis C) associated with allografts in the 1990s created a significant setback for this technology. Sterilisation methods were developed to reduce this risk, but radiation in particular affected the collage structure and with it the mechanical properties of the graft [244, 270]. Allograft reconstruction has only recently regained some of its ground through the introduction of improved 'graft-friendly' sterilisation techniques, although it is still not possible to definitively eliminate the risk of viral disease transmission [209, 245]. Today allograft tissue remains an attractive and reliable alternative to autograft in the primary and revision setting despite the rather considerable cost implications [107].

Synthetics: 1903—today

The use of synthetic materials has intrigued surgeons for over 100 years. It was hoped that readily available 'off-the-shelf' synthetic grafts could be developed which are stronger than soft tissue equivalents, and simplify the operation by avoiding graft harvest and associated donor site morbidity. Themistokles Gluck of Berlin (1853–1940), pioneer of joint arthroplasty, successfully bridged tendon defects with plaited catgut in 1881, but did not take his discovery further [100]. Fritz Lange of Munich (1864–1952) suggested silk sutures as prosthetic ligaments to stabilise 'wobbly' knees in 1903 [165]. Lange had already used silk as early as 1895 for the treatment of paralytic feet and in 1907 reported on 4 cases of ACL deficiency, which he stabilised by using "artificial ligaments made of silk" in conjunction with the tendons of semitendinosus and semimembranosus placed extra-articularly [166] (Fig. 28). The silk was slowly surrounded by fibrous tissue, and Lange praised the "wonderful ability of the silk to produce fibrous tissue under functional stress", a finding confirmed through histological investigations by Max Borst a few years earlier [25].

Alwyn Smith of Cardiff was critical of silk after a patient suffered with synovitis which only settled once Smith had removed all silk from the joint [268]. A similar experience prompted Max Herz in 1906 to declare that "The silk ligaments were too beautiful an idea; the attempts to copy something from nature had failed" [110]. Although both Herz and Smith realised that silk cannot survive when used in isolation within the intra-articular environment, they failed to appreciate the fibrogenic potential of silk when placed in direct proximity to collagen rich tissue. Fritz Lange's grandson Max (1899–1975), who also became Professor of Orthopaedics in Munich, achieved clinical success by utilising silk augmented with fascia in ACL reconstruction [167, 168]. Lange was mindful that joint stability could not be achieved by silk alone, which he saw merely as a foreign body scaffold providing initial strength whilst inducing a process of ligament healing and re-growth. Karl Ludloff of Frankfurt (1864–1945) had followed a similar approach when in 1927 he used a strip of fascia wrapped around a thick central silk suture to replace the ACL in a 23-year-old farmer who had come off his motorbike [182] (Fig. 29). He was meticulous in trying to place both tunnels at the centre of the anatomical foot prints of the ACL and kept tunnel diameters small enough to obtain a tight fitting graft. Ludloff refrained from any form of graft fixation as he believed that the graft should be allowed to establish equilibrium of tension. Like Bircher, Ludloff encouraged early mobilisation from day 14 and walking from day 25 onwards. The patient was reviewed at 5 months, after having gone back to his duties as a farmer, presenting minimal loss of flexion and a negative anterior drawer sign.

Edred Corner of St Thomas in London (1873–1950) presented the case of a 29-year-old man, who injured his

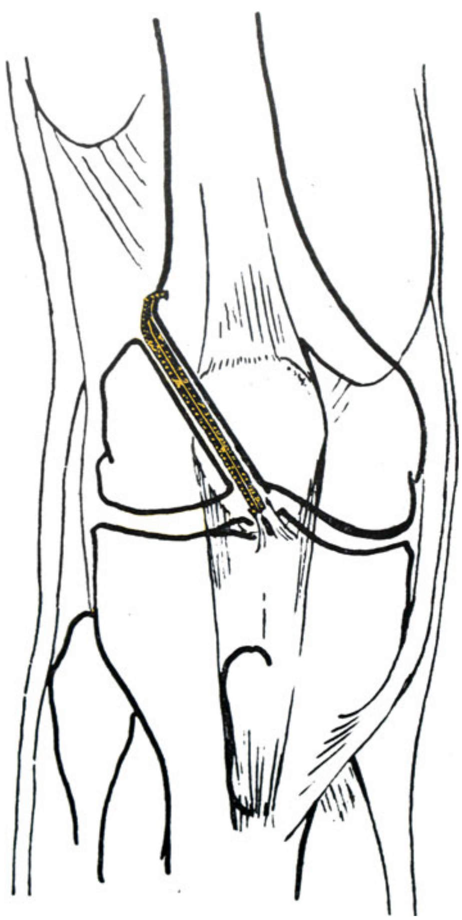


Fig. 28 Fritz Lange's early attempt to reconstruct the torn ACL with silk sutures placed trans-femorally (with kind permission of Georg Thieme, Stuttgart) [168]

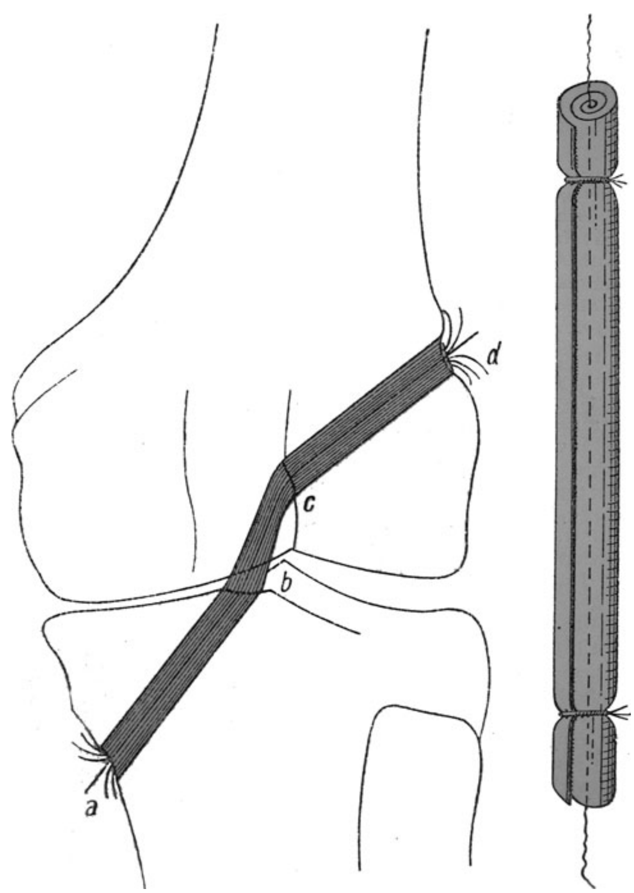


Fig. 29 The first ACL augmentation device as presented by Ludloff in 1927. The fascia lata graft is wrapped around a thick silk suture and placed through tight fitting bony tunnels without additional fixation (with kind permission of Hüthig Jehle Rehn, Heidelberg) [182]

knee playing football and subsequently complained "of pain, and weakness in the knee joint, which gives way suddenly, letting him down" [43]. Corner employed a novel technique by passing a loop of silver wire through the lateral condyle which was interlaced with a similar loop brought through the tibia to form a new ACL (Fig. 30). Post operatively the patient was advised to wear an apparatus "to limit his knee movement". The latter broke and with it the wire loops, but no information was disclosed upon the patient's fate.

The second half of the twentieth century saw a myriad of different synthetic ligament graft materials appear. In 1949 Rüther of Germany reported disappointing results following the implantation of a synthetic ACL made of Supramid®, a polyamide derivative [252]. Olav Rostrup of Edmonton, Alberta started using synthetic grafts in humans in 1959 after having successfully implanted Teflon grafts into dogs knees [72, 249]. He saw synthetics primarily as augmentation devices to support fascia or tendon and felt that Teflon® or Dacron® were "not the ideal material" and hence did "not recommend its wide-scale or indiscriminate use". Stryker nevertheless made Dacron® as a ligament replacement device commercially available in the 1980s. Richard Wilk of Burlington and John Richmond of Boston reviewed 50 patients following ACL reconstruction with the Stryker Dacron® ligament in 1993 and recorded a significant deterioration of ligament failure rate from 20% at 2 years to 37.5% at 5 years [299]. Wolfgang Maletius and Jan Gillquist of Sweden reported their 9-year follow-up results in 55 patients in 1997 [189]. By that time, 44% of grafts had failed, 83% had developed radiographic signs of osteoarthritis and only 14% presented with acceptable stability. The production of the Dacron® ligament device was finally discontinued in 1994.

In 1973 Proplast®, a porous Teflon graft claiming to offer enhanced fibrogenic properties, became one of the first synthetic graft materials to receive FDA approval, but clinical performance was disappointing [305]. David Jenkins of Cardiff began to use flexible carbon fibres to reconstruct the ACL in the mid-1980s [140]. The carbon was thought to act as a temporary scaffold, encouraging the ingrowth of fibroblastic tissue and the production of new collagen. More often than not however, fragmentation of carbon occurred creating unsightly staining of the synovium and foreign body reaction. Not unsurprisingly in the hands of most investigators, carbon fibre ACL reconstruction provided for rather inconsistent and often unreliable results especially when used in isolation [251]. Angus Strover of South Africa demonstrated more promising results with collagen-coated carbon fibre which he published in 1985 [279]. He noticed that when placing "carbon fibres either within the remnants of the original ligament or within a sheath of fascia and maintained in the retro-synovial situation, no carbon debris appears within the joint cavity, and a normal-looking cruciate ligament results".

Awareness of the potential biological and biomechanical shortcomings of using a single type of synthetic material prompted attempts to combine materials of favourable characteristics. Strover and associates developed the ABC® (Activated Biological Composite) ligament in the mid-1980s, which combined the advantages of polyester in terms of durability, based on the success of Dacron® vascular grafts, and those of carbon in terms of its fibrogenic

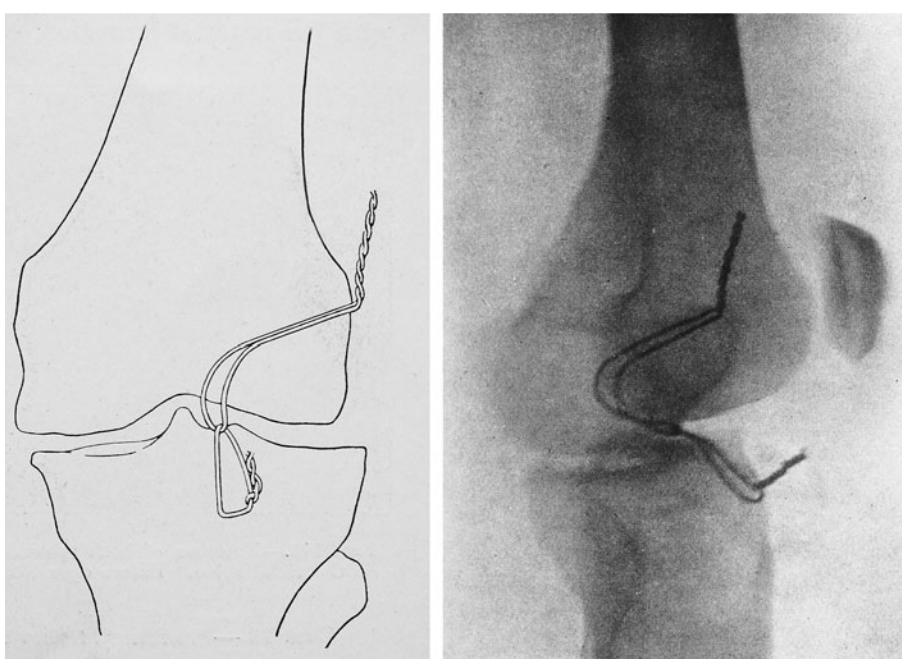


Fig. 30 Corner's attempt of ACL reconstruction with interlaced silver wire in 1914 (With kind permission of John Wiley & Sons, Hoboken) [43]

potential [280]. Carbon and polyester were interwoven in a type of plaited arrangement, positioned through a tibial tunnel distally and over-the-top proximally and secured with bollards placed through prefabricated ligament loops. The ABC® ligament enjoyed a period of relative success in the 1980 and 1990s but like all other synthetic grafts eventually became obsolete.

In the late 1970s, Jack Kennedy of London, Ontario introduced a ligament augmentation device made of polypropylene, which became known as the 'Kennedy-LAD®' [150] (Fig. 31). The concept arose from observations that biological grafts are affected by temporary degeneration and loss of strength before being fully incorporated and that the LAD would protect the biological graft during this vulnerable phase. Kennedy created the notion of load sharing, as he was hoping the LAD® would reduce stresses and strains on the natural graft and prevent early graft failure [153]. Lars Engebretsen and associates of Trondheim in Norway commenced a large randomised controlled study in 1990 to assess the merits of the LAD compared to acute repair and reconstruction with autologous B-PT-B [73]. He enrolled 150 patients into the three treatment arms and produced follow-up results of up to 16 years. Both acute repair and repair with the LAD provided for failure rates of up to 30%, and the authors hence discouraged any form of repair other than autograft reconstruction [64]. The Kennedy-LAD® together with the Leeds-Keio® and the LARS® ligament became nevertheless one of the very few synthetic grafts which gained more widespread popularity and which have remained in use as augmentation devices up to this day.

Various other synthetic ACL grafts, including Gore-Tex®, PDS®, Eulit®, and Polyflex®, were introduced during the same period [136] (Fig. 32). Clinicians, however, became over-optimistic regarding the clinical long-term performance of most of these materials, as their in vitro behaviour showed fatigue resistance on cyclic loading beyond the limit of human endurance [250]. The hope of finding a reliable and durable off the shelf ACL replacement was soon dampened by a flood of reports on an increasing amount of fatigue failures, including graft re-rupture, chronic synovitis, tunnel widening through osteolysis, foreign body reaction, and poor incorporation of the synthetics into host bone [127, 265, 304]. In 1981 Wolfgang Plitz of Munich examined the mechanical properties of 51 different commercially available polymer ligaments under physiological conditions and found only one type to meet basic testing requirements [241, 242]. It was eventually conceded that in vivo functional stresses applied on the knee exceed the biomechanical properties of the new ligaments in the long term [22, 136]. Improved results with intra-articular reconstruction using autologous grafts finally saw the end of synthetics in ACL reconstruction, a trend Ejnar Eriksson of Stockholm had already anticipated in 1976 by saying synthetics are "like shoestrings, they eventually break" [75].

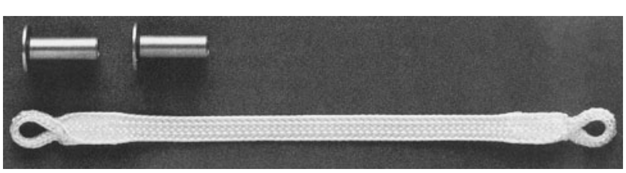


Fig. 31 Ligament Augmentation device (PROLAD®) with fixation lugs (Courtesy of Prof. W. Plitz, Munich)

Extra-articular ACL reconstruction: 1913—today

The complexities of intra-articular reconstructions were often fraught with peril and clinicians were eager to find ways to simplify stabilising procedures for ACL deficiencies without opening the joint. This idea was fostered by Henry Milch of New York (1895–1964) who in the early 1930s promoted the principle that "a torn ACL left little if any disability whilst the medial or tibial collateral ligament is of the utmost importance in the stability of the knee" [207, 208].

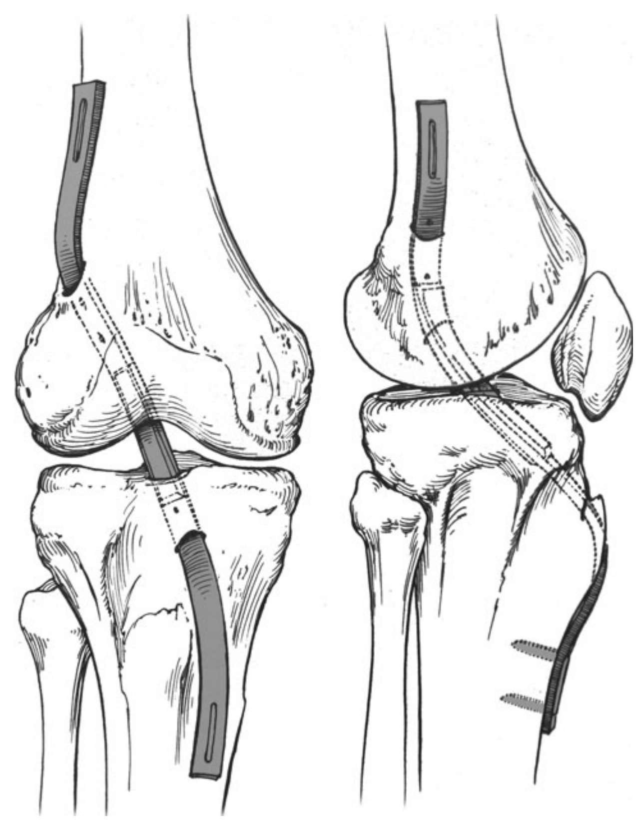


Fig. 32 Synthetic anterior cruciate ligament stent in situ according to James in 1979 (With kind permission of Lippincott Williams & Wilkins, Philadelphia) [136]

The first account of an extra-articular procedure was published in 1907 by Fritz Lange who successfully placed silk sutures across the joint space in an attempt to treat knee instabilities (see chapter 4.7) [166]. Encouraging results of free tissue transfer obtained between 1910 and 1913 by Martin Kirschner of Königsberg (1879–1942) and John Davis of Baltimore (1842–1946) persuaded the Swedish surgeon Knut Giertz (1876–1950) in 1913 in attempting to stabilise the knee of a 13-year-old girl who had lost her cruciates as a result of septic arthritis during childhood [53, 97, 154, 155]. He succeeded by augmenting both collateral ligaments with sections of fascia lata and the child regained good function albeit with slight restrictions in motion.

In 1918 Hermann Matti of Bern (1879–1941) published his paper entitled 'Replacement of the torn anterior cruciate with extra-articular free fascia graft', where he describes the application of an obliquely placed doubled-up fascia strip running from the posterior aspect of the medial femoral condyle towards the antero-medial aspect of the tibia [197]. For PCL insufficiencies, he simply reversed the alignment of the fascial strip. A number of similar procedures focussing on strengthening of the MCL and antero-medial capsule were introduced over the next 20 years, based on the general believe, that rupture of the ACL would commonly occur in conjunction with injury to the medial structures [20] (Fig. 33).

Granville Bennett of Boston described an almost identical procedure to Matti, whereby the medial ligament was tightened and reinforced with a free strip of fascia woven along the medial joint line [16]. In 1936 David and Bordman Bosworth of New York presented three successful clinical cases of extra-articular joint reinforcement using strips of fascia arranged in a fan shape across the joint space [26]. In the same year, Page Mauk of Richmond, Virginia proposed sub-periosteal advancement of the distal MCL attachment to cure recurrent instability whilst Emil Hauser of Chicago (1897–1981) utilised part of patellar and quadriceps tendon which he left attached to the patella and secured in a criss-cross fashion onto the antero-medial capsule [108, 198]. In 1973 Dolanc of Basel advocated opening wedge tibial osteotomy above the distal MCL attachment to treat knee instabilities with concomitant axial mal-alignment [61]. This idea was further developed by Roland Jakob of Berne and Henri Dejour and Phillipe Neyret of Lyon who saw a particular indication for osteotomy in cases of residual instability following soft tissue procedures or in established knee instability where osteoarthosis had already developed [58, 135].

In 1937 Frank Strickler of Louisville championed lateral extra-articular substitution which he combined with intra-articular reconstruction [278]. A long strip of fascia was routed through the joint and across the antero-lateral capsule

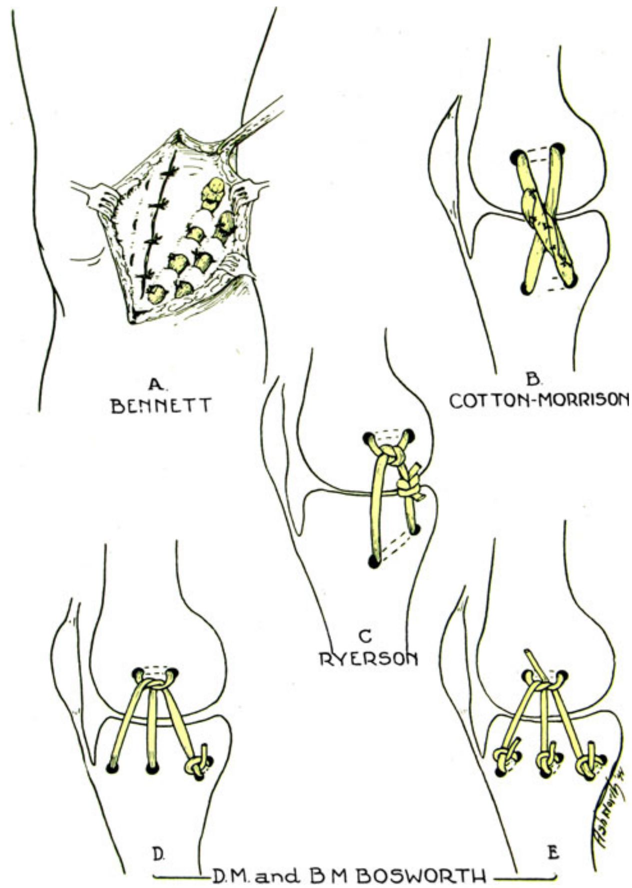


Fig. 33 Various types extra-articular reconstructions introduced between 1920 and 1940 aimed at stabilising the medial capsule and collateral ligament thereby primarily addressing antero-medial instability (with kind permission of Elsevier, Philadelphia) [20]

and fastened to itself at the entry point into the femur, thus forming a complete loop (Fig. 34). Strickler believed such a single loop could service both ACL and PCL insufficiencies. The principle of this idea was rediscovered and modified in the 1980s by a number of surgeons who believed that intra- or extra-articular reconstruction performed in isolation were more likely to fail longer term [37, 311].

Arthur Jacob Helfet of Cape Town (1907–1989) provided further impetus for what became a period which inspired surgeons particularly in the United States to explore extra-articular stabilisation procedures [109]. In 1963 Helfet published his treatise on the management of internal derangement of the knee in which he conveyed his theory on the function of the ACL. "If we consider that the cruciate ligaments act as check-straps which prevent anteroposterior movement of the tibia on the femur and that resulting instability after rupture of these ligaments is due to the absence of these check-straps, then the only logical course of treatment is anatomic replacement. On the other hand, if the cruciate ligaments are guide ropes which keep the tibia in its normal helicoid track on the medial condyle

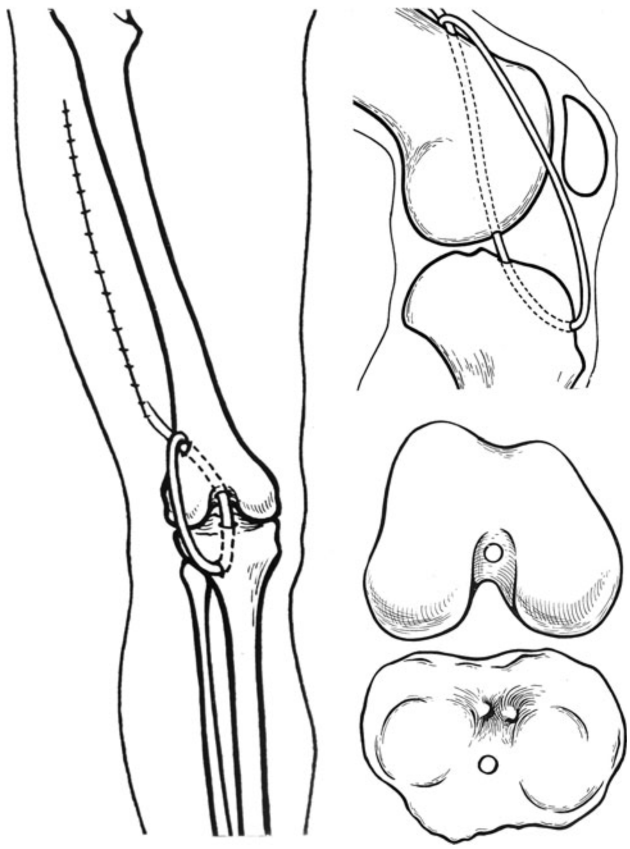


Fig. 34 Combined intra- and extra-articular reconstruction with fascia loop as suggested by Strickler in 1937 which was designed to cater for both ACL and PCL deficiencies (with kind permission of Lippincott Williams & Wilkins, Philadelphia) [278]

of the femur, it is possible to replace this function by extra-articular tendon transplant" [109]. Helfet made a case for the latter and his views were echoed by Arthur Ellison of Williamstown, Massachusetts (1926–2010), who considered the ACL to be "located virtually at the axis or pivot of the knee and as such it is at the hub of the wheel" [71]. This, so Ellison believed, "places it in a superb location to guide rotational movement but at a very disadvantageous position to restrict rotation". He saw distinct advantages in stabilising the knee on the outside rather than to reconstruct the ACL, based on his thinking that "it is easier to control rotation of a wheel at its rim than at its hub". Subsequently extra-articular procedures became fashionable and enjoyed a period of popularity until the late 1990s.

Marcel Lemaire of Paris (1918–2006) started using a lateral extra-articular augmentation in 1960 which became particularly popular in Europe and Canada [172]. His procedure was based on the then accepted wisdom "that the role of the ligament was to control external rotation", and that "people thought that ruptures of the anterior cruciate happened through a combination of valgus-flexion-external rotation". Lemaire used a distally attached central fascia lata strip which he positioned underneath the lateral collateral ligament, threaded through a bony tunnel slightly posterior to the lateral femoral epicondyle, folded back and sutured against its origin at Gerdy's tubercle. By 1975, he had operated on 328 isolated ACL ruptures of which he rated 87% as good [173]. Lemaire was aware that, although his procedure was ill-equipped to control the anterior drawer, it controlled some of the rotational instability associated with ACL deficiency, which in clinical practice appeared to be enough to allow patients to resume sporting activities.

In 1968 Donald Slocum and Robert Larson of Eugene, Oregon introduced the notion of rotatory laxity, citing, as the usual cause, an injury to the ACL and the medial ligament complex [266]. This was thought by many to be insufficiently addressed by ACL reconstruction alone and demanded extra-articular reinforcements either in combination as 'belt-and-braces' or as independent procedures [37, 41, 311]. Initially, the emphasis was placed on anterior medial rotatory instability [41, 125, 228]. This produced a myriad of extra-articular procedures most notably the 'pes anserinus transfer' of Slocum and Larson and the 'five-in-one repair' of Nicholas, which were designed to hold the tibia in an internally rotated position [215, 267]. Anatomical studies by Kennedy and Fowler, and the establishment of the 'pivot shift phenomenon' as pathognomonic for ACL deficiency, prompted Hughston to incorporate these findings into his 'anterior lateral rotatory instability' theory [94, 126, 149]. A subsequent move towards laterally based procedures limiting primarily antero-lateral subluxation of the tibia followed and was led by MacIntosh, who devised his 'lateral substitution reconstruction' in the mid-1970s [185, 186]. This was essentially a variation on the Lemaire technique, avoiding the use of a bony tunnel and instead threading the fascia through the lateral intermuscular septum (Fig. 35). Depending on the level and type of knee laxity, this procedure could be used either on its own or in addition to an intra-articular stabilisation. If significant laxity was present, MacIntosh suggested to combine extra with intra-articular reconstruction. In this technique, which was not too dissimilar to what Strickler's had described 40 years earlier, he routed the pedicled facia sling 'over-the-top' of the condyle, through the intercondylar notch and into a tibial tunnel exiting close to Gerdy's tubercle [133].

Various other extra-articular substitution procedures became popular around the same time, most of which addressed antero-lateral instability, trying to control the pivot-shift phenomenon by using methods of capsular tightening, various tendon and fascial slings to re-route the ilio-tibial tract and repositioning of ligament attachments [42, 62, 71, 216]. Those included most notably the ones described by Albert Trillat of Lyon (1972), Arthur Ellison [69], Michael Jäger & Carl-Joachim Wirth of Munich (1976), Ronald Losee of Ennis, Montana (1978), and

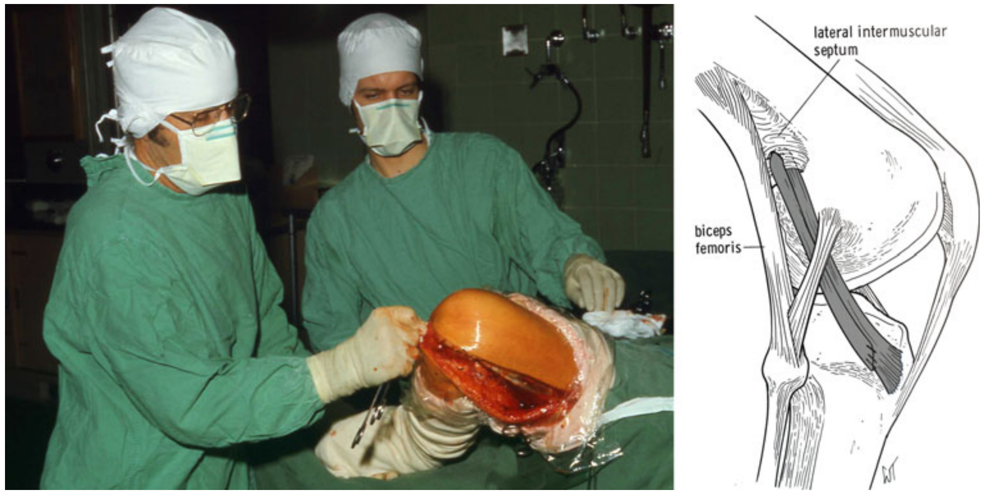


Fig. 35 David MacIntosh of Toronto (on far left) performing his extra-articular fascia lata tenodesis. The procedure was popular with surgeons during the 1980 and 1990s and was used in isolation or in combination with intra-articular reconstructions (photograph courtesy of David Dandy; Illustration with kind permission of Elsevier, Oxford) [129]

Werner Müller [70, 133, 181, 213, 286, 287] (Fig. 36). Conscious of the notion of isometry and the failure of most extra-articular procedures to provide stability throughout a full range of motion, James Andrews of Columbus, Georgia devised his "mini reconstruction" in 1983 [10]. He formed an anterior and posterior bundle of the ITB which he tenodesed against the lateral femoral epicondyle so that the anterior part would be tight in flexion and the posterior in extension. In 1981 Jakob described the 'reverse pivot shift sign' introducing the concept of postero-lateral rotatory instability [134]. By this time, clinicians had created a classification of all variations of straight and rotatory knee instabilities, appropriate tests to define them, and a plethora of surgical remedies to treat them [56, 129, 213].

Although most extra-articular procedures diminished or obliterated pivot shift and Lachman manoeuvres, they provided for temporary stability only, as the repairs eventually stretched-out [62]. Extra-articular reconstructions gradually fell out of favour when reports emerged about their unpredictability to satisfactorily decrease tibial subluxation [82, 152, 212, 296]. In a landmark paper, Jack Kennedy reported in 1978 on 52 patients following extra-articuar stabilisation with only 47% achieving good to excellent results [152]. This was echoed in the same year by Russell Warren and John Marshall of the Hospital of Special Surgery in New York, who, after reviewing the results of 86 patients, concluded that "as a general rule, extra-articular surgery without attention to the cruciate ligaments

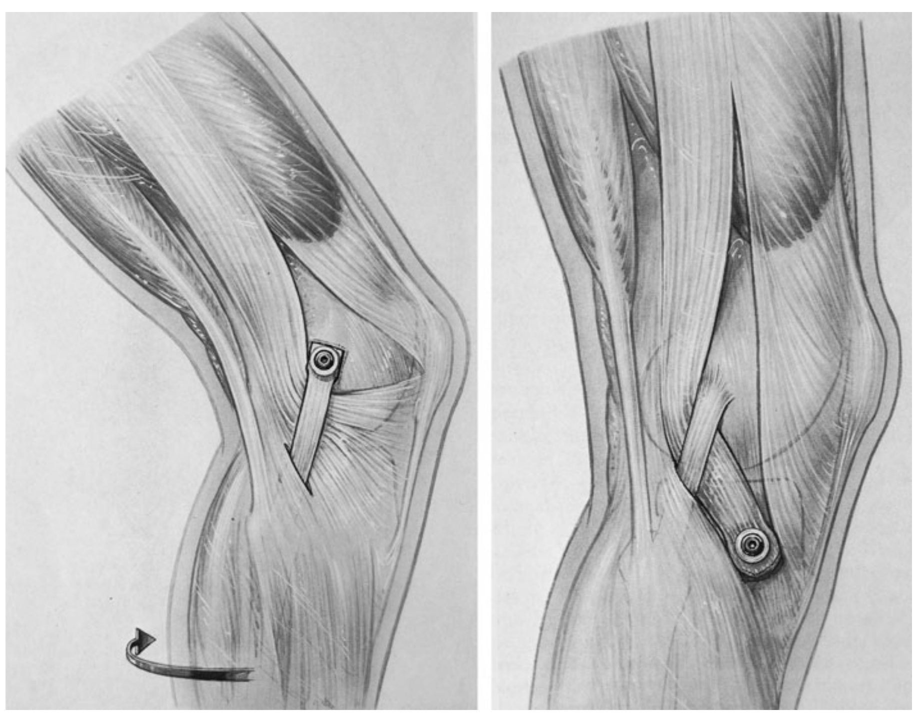


Fig. 36 Lateral extra-articular reconstruction through re-routing of the ilio-tibial band according to Jäger and Wirth (*left*) and Ellison (*right*) (with kind permission of Thieme, Stuttgart) [133]

will often result in failure" [296]. In their biomechanical study in 1993, Andrew Amis and Brigitte Scammell of London found no basis for combining intra with extra-articular reconstruction in isolated ACL deficiency, where the main aim was to control anterior drawer [7]. This however, so they conceded, "does not affect the role of extra-articular procedures in controlling complex rotatory instabilities, such as those resulting from combined injuries of the ACL and peripheral structures affecting pivot shift more than anterior drawer". Their findings were echoed by clinical reports suggesting that intra-articular reconstruction of the ACL would be sufficient in the treatment of knee instability following isolated ACL tear and extra-articular procedures added little to the overall functional out-come [9, 222, 281]. Although this view was not shared uniformly, most additional extra-articular procedures had vanished by the end of 1990s [37, 63, 311].

The last few years have seen a renewed interest in combined ACL reconstruction with extra-articular augmentation, based on the notion that the additional repair will not only protect the ACL graft from excessive loads especially during the healing process, but also improve lateral rotational control [190, 309]. The advantage of inhibiting pivot shift appears particularly desirable due to emerging evidence that residual rotatory mobility might be associated with an increase in post-surgical osteoarthritis [147]. In 2009 Marcacci and associates from Bologna presented 11-year follow-up results of 54 patients who received double-stranded hamstring ACL reconstruction and lateral augmentation, a technique not dissimilar to MacIntosh's 'over-the-top' repair [191, 192]. Over 90% presented with good to excellent IKDC scores and 97% had less 5 mm antero-posterior movement on arthrometer testing (Fig. 37). Although it is generally conceded that most cases of ACL deficiency are suitable for isolated ACL reconstruction, those with "associated ligamentous lesions of a subclinical nature" as quoted by Hughston, which often fail if standard reconstruction techniques are applied, might be suitable candidates for combined procedures. To achieve this reliably, more specific quantitative assessment tools to define thresholds of laxity are necessary, in order to tailor the most appropriate treatment option to the individual [310].

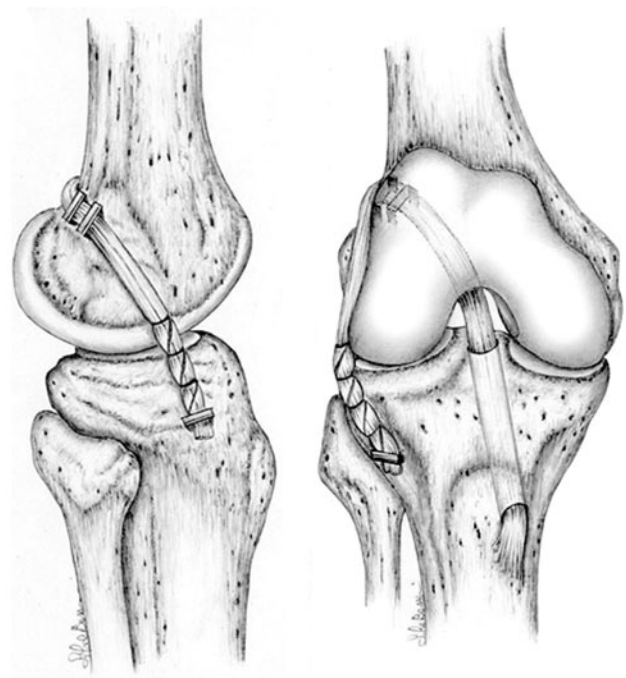


Fig. 37 Maurillio Marcacci's combined extra and intra-articular reconstruction using double-strand hamstring graft (with kind permission of SAGE Publications, London) [190]

The concepts of isometric and anatomic reconstruction

The biomechanical concept of graft isometry was developed in the 1960s and was based on the notion that the ideal anterior cruciate ligament graft should be isometric, either in part or in the mechanical summation of its parts [44, 163, 224]. Isometric placement of the ACL hence referred to the concept that a full range of knee motion can be achieved without causing ligament elongation and plastic deformation (a status whereby structural changes make it impossible for the ligament to return to its original length). Reproducing the ACL bundles and their tension pattern with a single tubular graft composed of parallel fibres posed difficulties to most surgeons, as they were unsure where to place the ideal tibial and femoral tunnels within the functionally important fan-shaped foot prints of the native ACL. Orientation was usually accomplished through bony landmarks such as the lateral intercondylar ridge or 'resident's ridge', first described by William Clancy Jr., which is located immediately anterior to the ACL attachment [78]. It is often mistaken as the 'over-the-top position' by inexperienced surgeons in training, and likely to lead to gross anterior graft misplacement, which is one of the most common causes of graft failure in ACL reconstruction [139].

In 1974 Artmann and Wirth were able to define isometric points within the ACL origins, thus showing little or no change in distance of linear separation as the knee was flexed and extended [12] (Fig. 38). In their experiments, the femoral tunnel was best placed within the postero-superior portion of the anatomic foot print, close to the 'over-the-top' position, whilst the position of the tibial tunnel appeared to be less critical. Based on their results, Artmann and Wirth concluded that reconstruction of the ACL should aim to primarily replace the antero-medial bundle. Their findings were later confirmed through experimental studies conducted by other investigators [202, 224, 235].

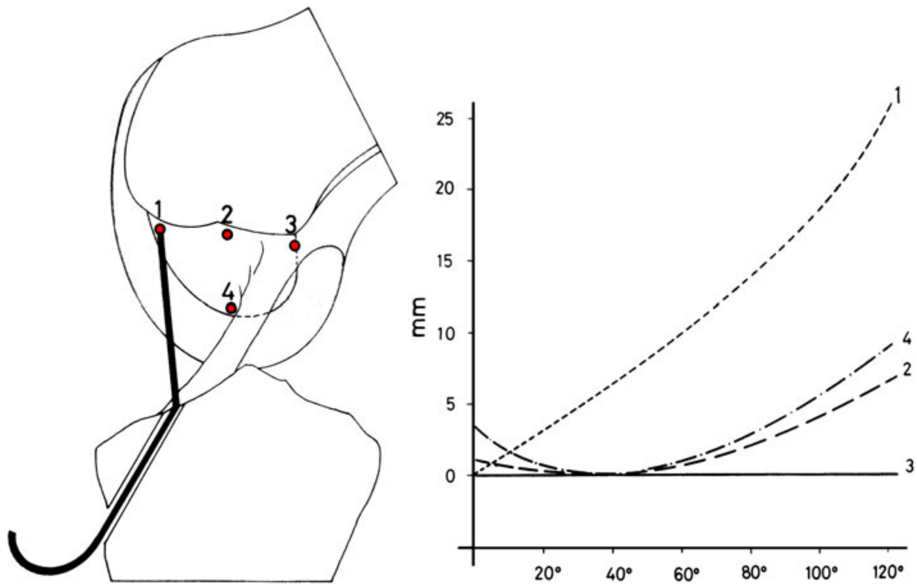


Fig. 38 Illustration taken from Artmann & Wirth experimental study on the definition of isometric attachment points of the ACL. Changes in distance between the common origin on the tibia and various attachment points on the lateral wall of the inter-condylar notch are demonstrated (with kind permission of Springer Science, Berlin) [12]

To achieve greater surgical precision and reliable graft placement, improved surgical equipment was required. The first specific femoral drill guide was presented by Ivar Palmer of Stockholm (1897–1985) in 1938 but received little attention [232] (Fig. 39). More refined guiding instruments were introduced in the 1960 and 1970s by Soli Lam of London, Enjar Eriksson of Stockholm and George Hewson of Tuscon [75, 112, 163]. Dale Daniel (1939–1995) and Richard Watkins of San Diego, best known for their creation of the KT-1000® Knee Ligament Arthrometer, developed the tension Isometer® in 1986 [50, 51] (Fig. 40). This was to become the first commercially available instrument to define points of equidistance for isometric graft placement and to provide improved precision in obtaining tension and displacement measurements prior to graft fixation. Enthusiasm for using tension isometers however started to wane towards the end of the 1990s when it became apparent that they lacked accuracy compared to off-set guides which allowed for the positioning of the femoral tunnel at a set distance from the posterior condyle, hence providing more reliable and reproducible tunnel placements [81, 256] (Fig. 41). Advances in surgical equipment proved crucial in improving surgical accuracy and gave clinicians the necessary tools to achieve reproducible results making ACL reconstruction a more reliable operation which even the average orthopaedic surgeon could tackle.

By the 1990s, surgeons started to recognise that the goal to achieve isometry within a single or double tubular graft proved an elusive one, and which, if achievable, would create un-physiological conditions, as none of the identifiable native ACL bundles are isometric in their own right [6, 162]. Through biomechanical investigations it became apparent that the majority of ACL fibres are not positioned

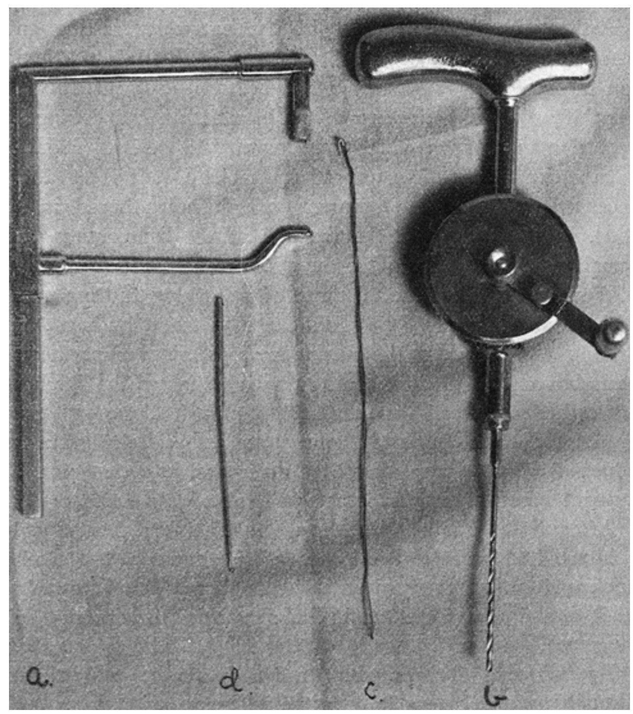


Fig. 39 Photograph of Ivar Palmers original femoral tunnel preparation equipment which included the first aiming and drill guide as seen on the left (with kind permission of Acta Orthopaedica Scandinavica, Stockholm) [232]

at an isometric point within the notch but posterior to it [85]. Pierre Chambat of Lyon believed that these fibres should not be ignored as they display "favourable non-isometry", contributing to the rotational stability to the knee near extension [34]. In 1988 Friederich and O'Brien conceived the notion of 'functional isometry' as they recognised that "only a limited number of fibres can directly interconnect isometric points" [85]. Whilst the

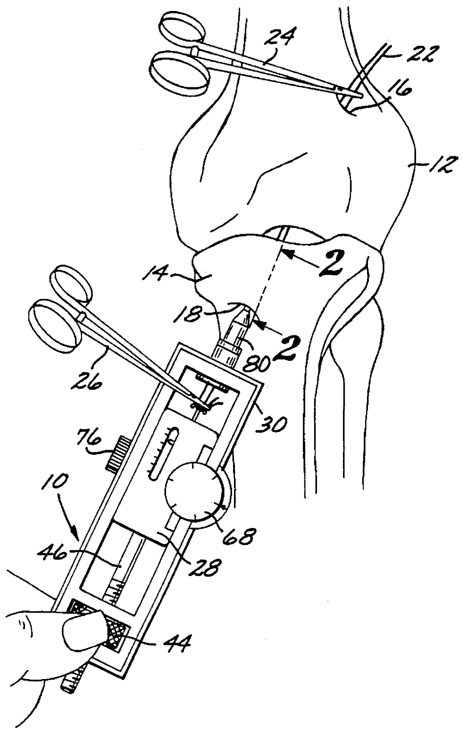


Fig. 40 Illustration of patent application for a system for establishing anterior cruciate ligament graft orientation and isometry, designed by Daniel in 1986 (US patent No. 4.712.542) [51]

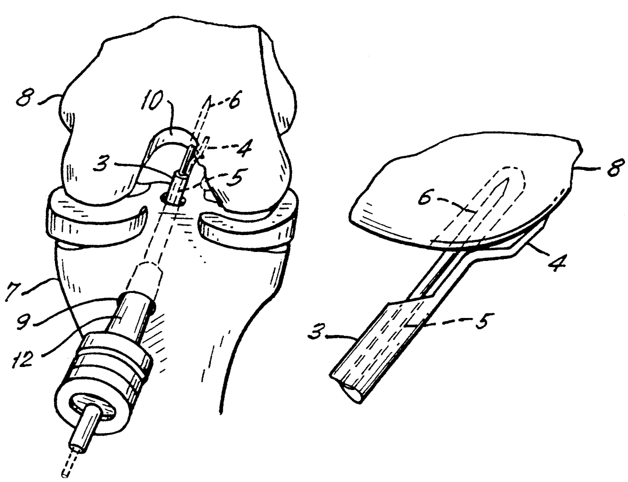


Fig. 41 Illustration of patent application for an endoscopic femoral off-set drill guide designed by Schmiedling in 1991 (US patent No. 5.320.626) [256]

most isometric fibres are the first to become taut, the remaining non-isometric fibres are strategically arranged to allow for their progressive recruitment as increased biomechanical demands arise during extension. Müller tried to solve this conundrum by suggesting a compromise between isometric and anatomic graft placement and conceived the notion of "anatometry" in the early 1980s [213, 214]. Instead of working with a fixed point of isometry, Müller described the so called 'transition line', which he believed should represent the anterior border for ACL graft placement, as any fibres positioned anterior to it would be exposed to un-physiological elongation during knee flexion [214, personal communication] (Fig. 42).

Over time it became apparent that any non-anatomical single-bundle technique was unable to fully restore normal knee kinematics or reproduce normal ligament function and was hence thought to be responsible for the relatively disappointing clinical results and the high prevalence of arthritis long term [147, 180, 306]. The beginning of the twenty-first century saw a movement away from the concept of isometry towards ACL reconstruction focussing more on physiological and anatomical principles, led by Kazunori Yasuda of Sapporo and Freddie Fu of Pittsburgh [307, 312]. Thus it was realised that any reconstructive effort must restore any injured anatomic structure to its normal functional position and tension. This philosophy, however, was not new as Hey Groves, Palmer, Wirth and Hughston had already recommended anatomic reconstruction in the treatment of these injuries previously.

In 1997 the group of Freddie Fu of Pittsburgh examined the in situ force distribution between the anteromedial (AM) and posterolateral (PL) bundles of the ligament in response to applied anterior tibial loads and revealed that the magnitude of forces in the PL bundle was significantly affected by the flexion angle whilst forces in the AM bundle remained relatively constant [89, 254]. This study was the first to suggest that in order for an ACL graft to reproduce in situ forces of the native ACL, reconstruction technique would have to focus on the role of both bundles. This prompted Fu to explore possible merits of anatomic ACL reconstruction [312]. He has since developed the 'anatomic double bundle concept' which aims to more closely replicate the native ACL anatomy, in its dimensions, insertion and fibre arrangement [88, 210, 308] (Fig. 43). The 'anatomic double bundle concept' can be achieved through single or double-bundle reconstruction. The reconstructive procedure is customised, based on the patient's individual anatomy and the precise mapping of the ACL bundle insertion sites, which are known to show significant variability [87, 160, 288]. Despite the enthusiasm for this new technology, Jon Karlsson and associates have emphasised the importance of differentiating between anatomic and double-bundle reconstruction, as the latter "is merely a step closer to reproducing the native anatomy … [and] can still be done non-anatomically" [148].

Double-bundle ACL reconstruction

Karl Ludloff, aware of the tension pattern displayed by the antero-medial and postero-lateral bundles of the ACL,

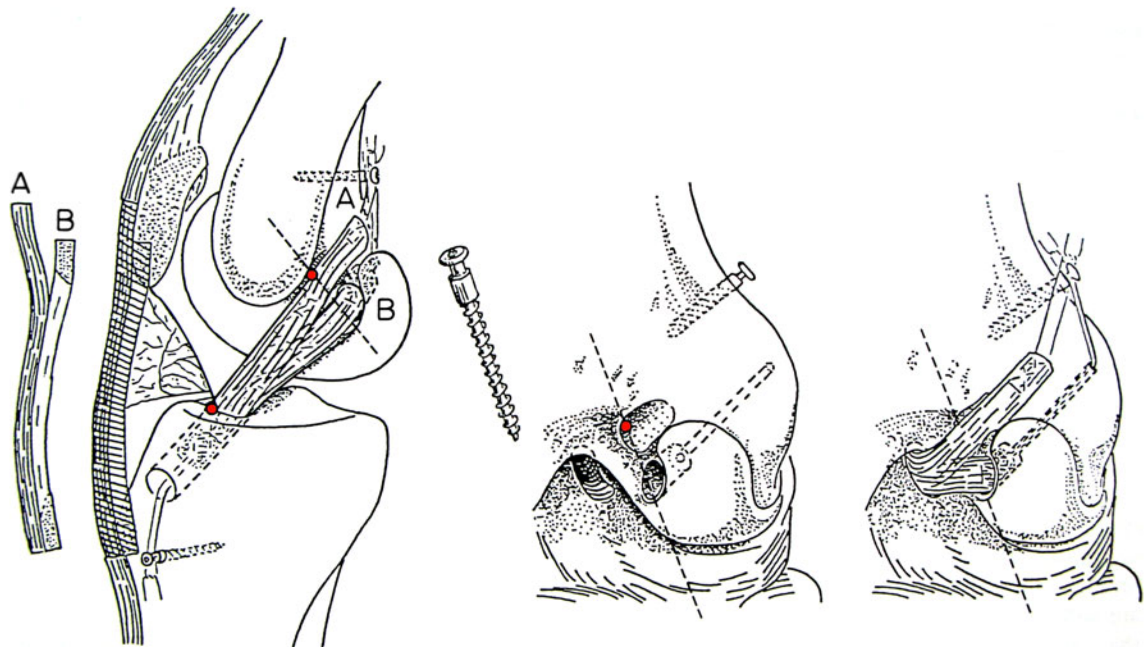


Fig. 42 "Anatometric" double-bundle reconstruction according to Müller. The AM bundle is placed in a 4 mm trough at the isometric point (*open circle*) and none of the remaining fibres attach anterior to the transition line (*line*) (with kind permission of Springer Science, Berlin) [214]

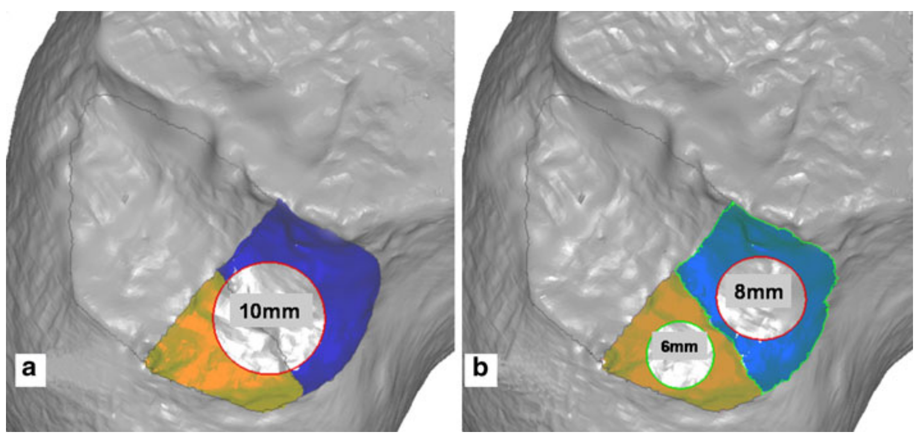


Fig. 43 'Anatomic double-bundle concept' according to Fu and associates. Three dimensional laser scan image highlighting the femoral insertion sites of AM (*blue*) and PL (*yellow*) ACL bundles. *Circles* indicate best graft placement in anatomic single-bundle (**a**) or double-bundle (**b**) reconstruction (with kind permission of Elsevier, Philadelphia; images courtesy of Freddie Fu and Carola van Eck, Pittsburgh) [288]

recognised that "reconstitution of relatively normal function would require the new cruciate ligament to consist of two separate bundles" [182]. Palmer had already performed double-bundle ACL repairs in the 1930s claiming good results, but his technique failed to find wider acceptance [232].

Karl Viernstein and Werner Keyl of Munich pioneered double-bundle ACL reconstruction with a proximally detached semidendinosus and gracilis graft in 1973 [289]. In the description of their technique, the tendons were routed through a single tibial tunnel into two separate femoral tunnels and sutured against each other at the exit (Fig. 44). Viernstein and Keyl noted that by placing the femoral tunnels close to the anatomic foot prints of the native ACL bundles, they were able to emulate the natural twisting between the two graft bundles during flexion. In 1990 Müller introduced his "anatometric" double-bundle reconstruction with split patellar tendon [214]. The free tendon graft emerged from a single tibial tunnel, with one leg being placed intra-osseously, whilst the other was positioned over-the-top of the femoral condyle (see Fig. 42). Up to this point, traditional single-bundle reconstruction techniques had aimed to replace the antero-medial bundle, thereby predominately restoring antero-posterior laxity. The addition of a postero-lateral bundle was hoped to address any remaining elements of rotational laxity.

The first publication on a double-bundle ACL reconstruction in the English literature was provided by William Mott of Jackson, Wyoming in 1983. He created double tunnels in both tibia and femur through which he placed a free semitendinosus graft, a technique he called the "semitendinosus anatomic reconstruction" or STAR procedure [211]. He was followed by Walter Blauth of Kiel,

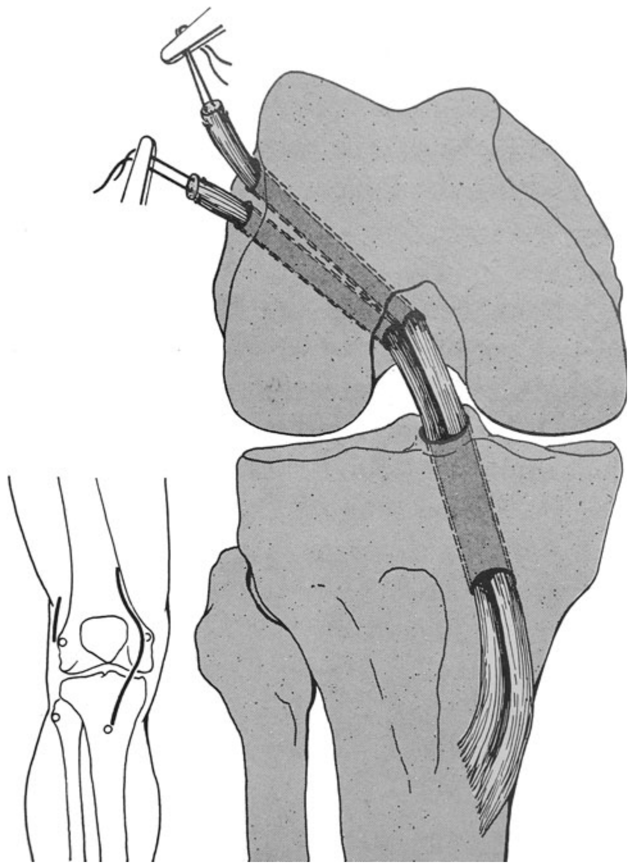


Fig. 44 Inaugural double-bundle ACL reconstruction method devised by Viernstein & Keyl of the Staatlich Orthopädische Klinik in Munich-Harlaching in the early 1970s (with kind permission of Urban & Fischer, Munich) [289]

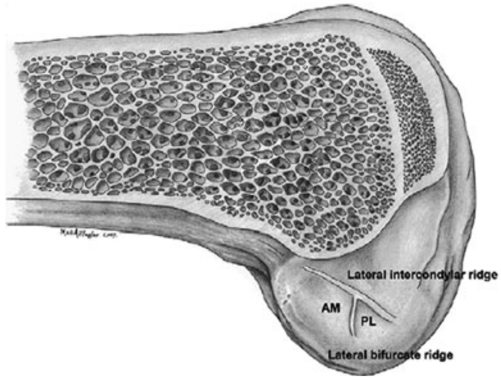
who had started using a free quadriceps tendon graft to reconstruct both the anteromedial and posterolateral bundle in 1981 and was able to publish promising results 3 years later [21] (see Fig. 24). In 1990 Jean-Louis Meystre of Lausanne reported 77% good to excellent results with his technique of semitendinosus double tibial and single femoral tunnel reconstruction [205]. An arthroscopically assisted technique for double-bundle ACL reconstruction was first introduced by Tom Rosenberg in 1994, who used single tibial and double femoral tunnels [248] (Fig. 45). More recently, selective bundle augmentation in cases of partial ACL ruptures has apparently been performed with considerable success [31, 223, 272]. In 1999 Bradley Edwards and associates of New Orleans presented the results of an in vitro study comparing single bundle with 3 different double-bundle techniques (dual tibial/dual femoral, dual tibial/single femoral, single tibial/dual femoral) [67]. With the exception of the dual tibial and dual femoral tunnel reconstruction, "all of the [other] procedures placed greater strain on the reconstructive tissues than was observed on the native ACL, after approximately 30 degrees of flexion".

Fig. 45 Antero-posterior radiograph of a double-bundle ACL reconstruction according to Rosenberg's original technique utilising Endobuttons for proximal graft fixation (author's case)

Modern double-bundle reconstruction aims to re-establish positioning of the ACL bundles at their respective anatomical foot prints and according to clinical and biomechanical studies more closely resembles physiological knee kinematics with respect to translation and rotation [8, 157, 187, 210, 282, 306] (Fig. 46). It is hoped that improvements in kinematics might translate into a reduction in the prevalence of osteoarthritis in the long term. Eije Kondo and associates of Saporro and Paolo Aglietti and associates of Florence were able to show improved outcome results in terms of stability and function with double-bundle compared to single-bundle reconstruction [4, 156]. So far however, it has remained unclear whether the increased surgical complexity and trauma associated with this technique might outweigh proposed long-term benefits [101].

ACL graft fixation methods

Over the best part of the twentieth century, fixation of the ACL graft consisted by and large of simple suturing of the protruding parts of the graft to the periosteum at the tunnel exits. Fred Albee of New York (1876–1945) believed that the principle reason for failures following ACL reconstruction was the inappropriateness of graft fixation which he thought would allow for "laxity to increase with the



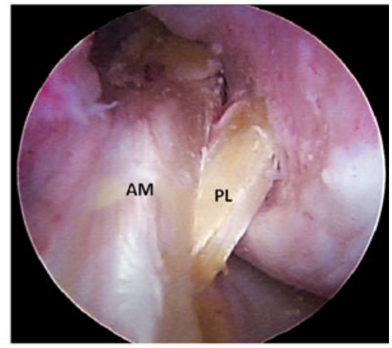
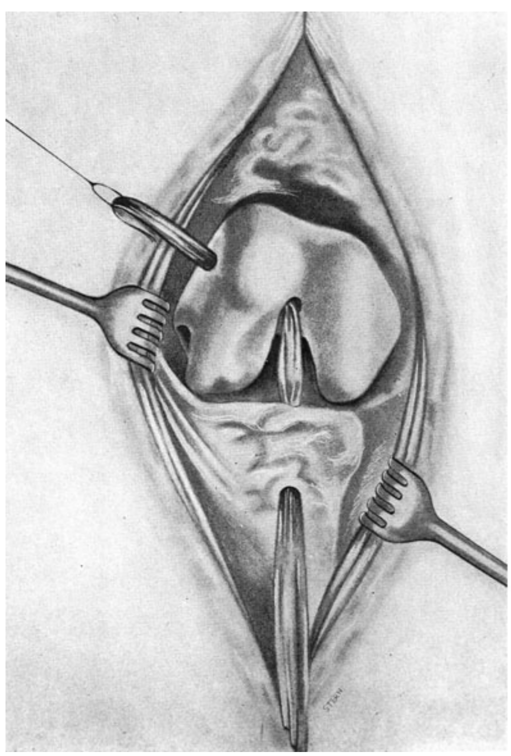


Fig. 46 Anatomic landmarks used in modern double-bundle ACL reconstructions, to position AM and PL graft bundles at their respective, native insertion sites (with kind permission of Elsevier, Philadelphia; intra-operative image courtesy of Freddie Fu, Pittsburg) [78]

passage of time" [5]. In 1943 he suggested securing free fascia graft with small bone wedges harvested from the anterior tibia and driven alongside the tendon into the tunnel. Although his technique was flawed through positioning tunnels centrally within the joint, his idea of graft fixation anticipated the principles behind interference screws by many decades (Fig. 47). Broader awareness that the "mechanically weak link of the reconstructed graft is located at the fixation site", as suggested by Masahiro Kurosaka of Kobe, Japan however did not emerge until the 1980s and gave rise to the development of a plethora of ligament fixation devices [161, 194] (Fig. 48).

Brückner, whilst still using the then traditional suture fixation on the femoral side, left a slightly oversized triangular bone block attached to the inferior part of a free patellar tendon graft which he press-fitted into the tibial tunnel thereby stopping the tendon from slipping through [30, 239] (Fig. 49). Hans Pässler of Heidelberg did much to introduce press fit graft fixation to a wider audience. He adopted Brückner's original idea and converted it for the use of soft-tissue grafts by knotting hamstring grafts at the end [231].

In 1927 Arnold Wittek introduced, what is believed to be the first intra-articular screw fixation of an ACL ligament graft when he utilised a torn medial meniscus to replace the ACL [302] (Fig. 50). In 1970, Kenneth Jones, who was using distally attached patellar tendon, described a method for fixation of the femoral bone block by means of a 2.4 mm Kirschner wire "drilled across the femoral tunnel and into the opposite femoral condyle" [142]. He was aiming to traverse the base of the femoral tunnel and thereby stopping the graft from being dislodged. In his



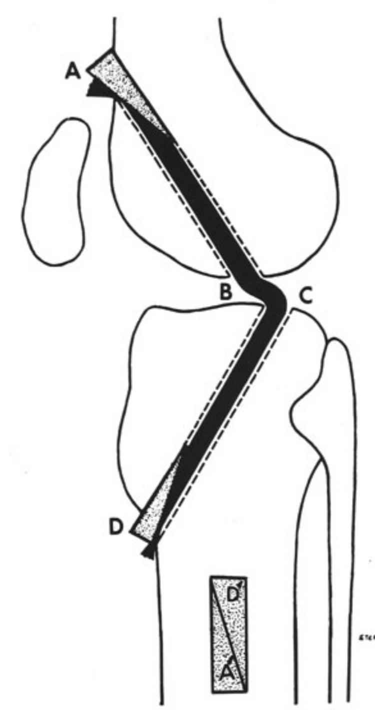


Fig. 47 ACL reconstruction according to Albee in 1943: Bone wedges taken from the proximal tibia were driven alongside the tendon graft to facilitate interference fixation (with kind permission of Elsevier, Philadelphia) [5]

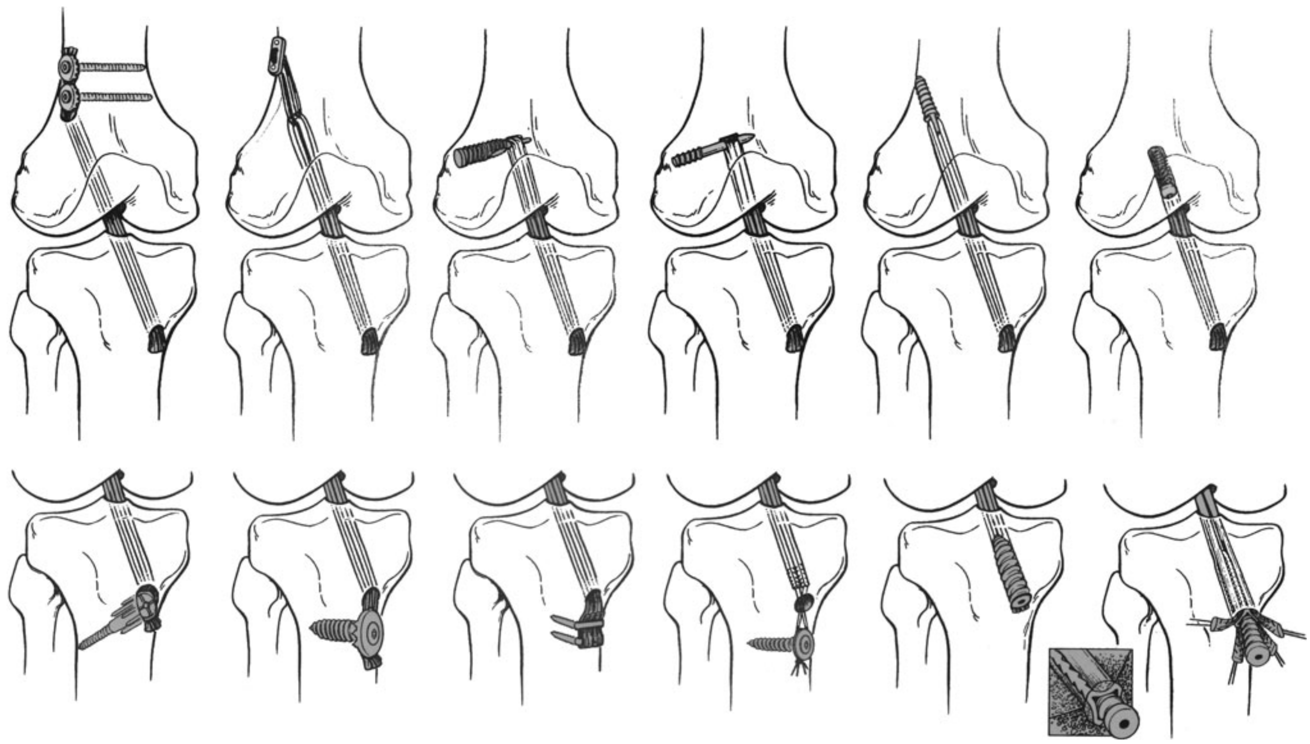


Fig. 48 Drawing depicting various methods of graft fixation at tibia and femur (with kind permission of Elsevier, Philadelphia) [194]

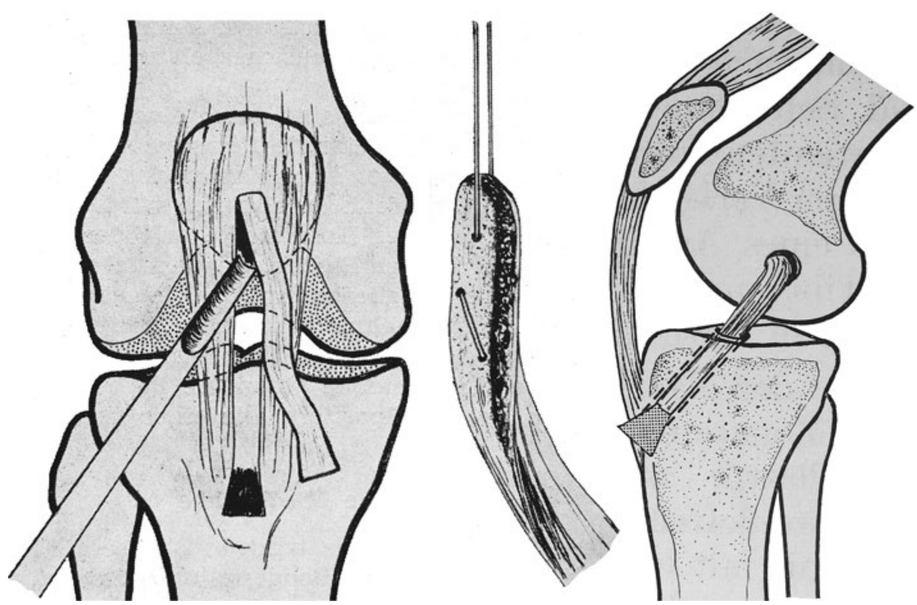


Fig. 49 Brückner's tibial 'press-fit' technique of free bone-patellar tendon-bone graft ACL reconstruction (with kind permission of Springer Science, Berlin) [239]

opinion, it was not essential that the wire went directly through the bone plug itself. This technique received wider attention with the introduction of the Transfix® device for the suspension of hamstring grafts designed by Eugene Wolf of San Francisco and Donald Grafton of Naples in 1998 [39, 105].

Aperture fixation with interference screws was originally described by Kenneth Lambert of Jackson, Wyoming in 1983, who utilised standard 6.5 mm AO cancellous screws of 30 mm in length which he passed from outside-in alongside the bone blocks of B-PT-B grafts [164] (Fig. 51). The screw produced an "interference fit, whereby it actually engages both the side of the bone block and the screw hole in a more or less cogwheel fashion". Interference screws gained wider attention through Kurosaka's work on the fixation strength of various fixation methods, which he

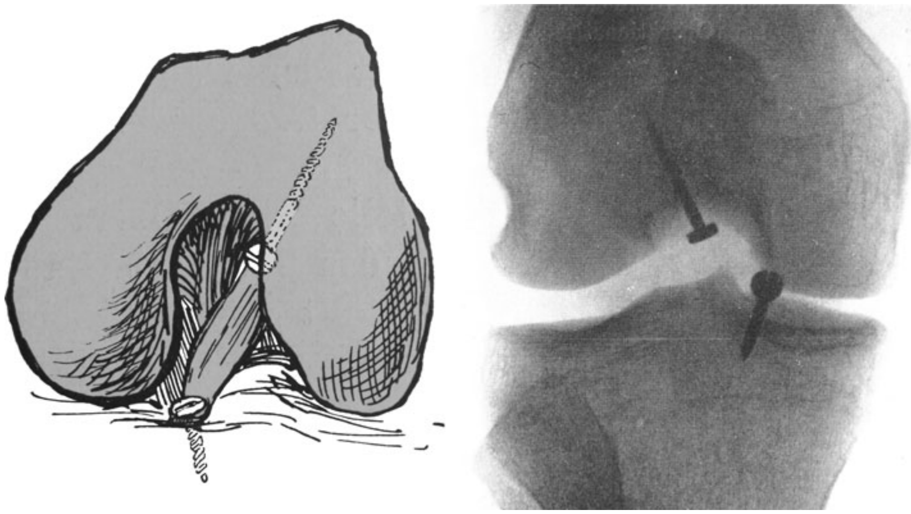


Fig. 50 Screw fixation of a meniscal ACL graft performed by Wittek of Graz in 1927 (with kind permission of Springer Science, Berlin) [302]

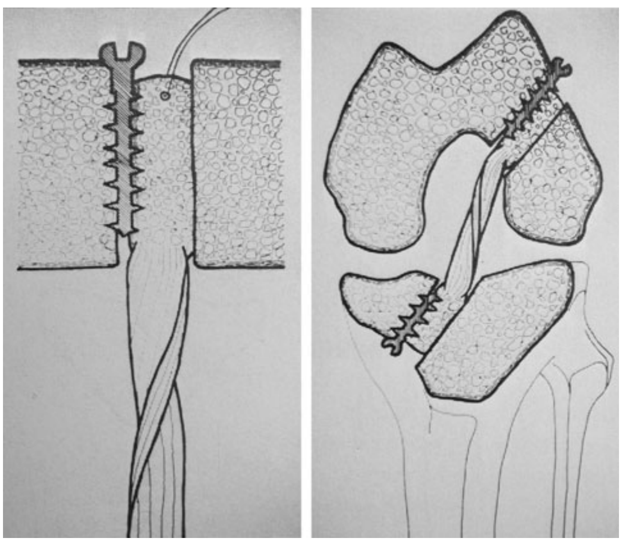


Fig. 51 Interference screw fixation of patellar tendon graft with AO screws according to Kenneth Lambert. The cancellous screw engages both the wall of the drill hole and the bone plug of the graft (with kind permission of Lippincott Williams & Wilkins, Philadelphia) [164]

published in 1987 whilst working at the Cleveland Clinic in Ohio [161]. The study compared staples with "tying sutures over buttons" and interference screws and revealed that specially designed large diameter cancellous screws provided the strongest fixation. This commenced a period of relative popularity of metal interference screws, which became the fixation method of choice for patellar tendon grafts. Within a few years, interference screws made of biodegradable materials such as PLA (polylactic acid), PGA (polyglycolic acid) and TCP (tri-calcium phosphate) or any combination thereof also became available [273].

In 1992 Leo Pinzcewski & Gregory Roger of Sydney invented the RCI screw, a cannulated interference screw, which, due to its relatively 'smooth' thread and spherical head safeguarded against tendon damage and was hence universally suitable for B-PT-B and soft tissue graft fixation [240]. In 1994 Ben Graf, Joseph Sklar, Tom Rosenberg and Michael Ferragamo introduced the Endobutton®, a ligament suspensory device that works as a tissue anchor by locking itself against the cortex of the femoral condyle [35, 104, 248] (Fig. 52). The Endobutton® was primarily designed for the femoral fixation of hamstring grafts, but was later re-adapted to accommodate other graft materials

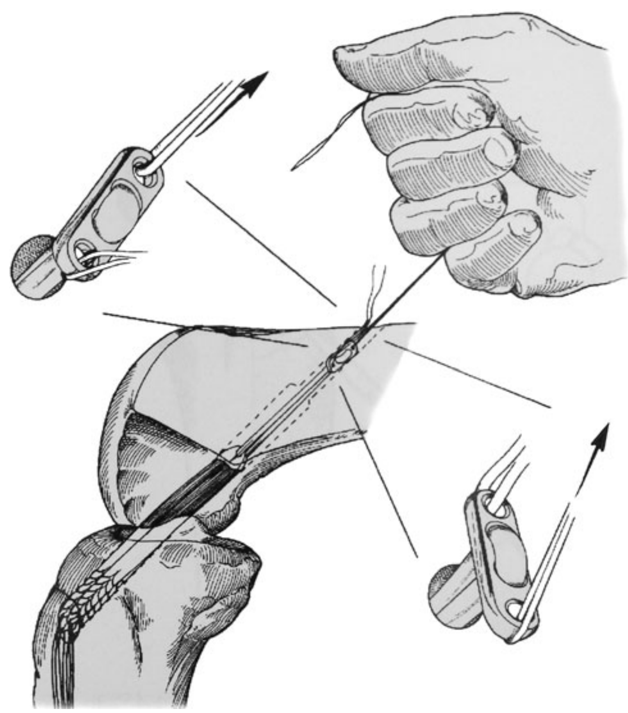


Fig. 52 The Endobutton®, a ligament suspensory device designed by Graf, Sklar, Rosenberg and Ferragamo, was first introduced in 1994 (with kind permission of Elsevier, Philadelphia) [35]

including BPTB, and has become one of the most popular fixation methods in ligament surgery altogether. Although critics have highlighted theoretical biomechanical disadvantages of suspensory fixation compared to aperture fixation including windscreen wiper and bungee effect, clinical results between the various fixation methods however have not highlighted significant differences [117].

Arthroscopic ACL reconstruction: 1980—today

In the early parts of the twentieth century, ACL surgery was still considered by most surgeons a formidable procedure. This is reflected in the treatise on 'Internal Derangements of the Knee-Joint' by Timbrell Fisher, who in 1933 appealed for prudence when considering ACL reconstruction as "we must bear in mind that an operation, which may appear easy, when performed by a master of technical methods, may present extreme difficulty to the average surgeon" [80]. In the 1950s, prior to the advent of operative arthroscopy, Willy König of Hannover and Li from Russia had already performed trans-articular reconstruction of the ACL without opening of the joint, by either relying on anatomical land marks or on radiographic control and guidance for positioning of femoral and tibial tunnels [158, 175] (Fig. 53). The increasing familiarity with knee arthroscopy popularised by Robert Jackson of Toronto, Canada (1932–2010) and David Dandy of Cambridge, England in the 1970s together with improvements in arthroscopic instrumentation allowed surgeons to consider more and more intricate operative procedures to be performed via keyhole [47, 132]. David Dandy performed the first arthroscopically assisted ACL reconstruction at Newmarket General Hospital on the 24th April 1980 [48, 49] (Fig. 54). He reported the use of a carbon fibre prosthesis supplemented with a MacIntosh lateral extra-articular substitution in 8 patients with good results at 1 year. Dandy later admitted that the good results might have been due to the extra-articular reconstruction rather than the carbon fibre ACL replacement, which often disintegrated with time [49].

Arthroscopic ACL reconstruction in those days was a complex and challenging procedure as neither sophisticated instrumentation nor camera and monitor units providing for appropriate magnification were available. In addition, the close proximity between the surgeon's eye and the rod lens system created a constant danger of de-sterilisation, nota bene accurate placement depended on hand-eye coordination monitored by arthroscopic visualisation of the tunnel entry points [49]. Studies comparing open with arthroscopic techniques finally confirmed the benefits associated with arthroscopically performed ACL reconstruction in terms of lessened post-operative morbidity, improved cosmesis, increased speed of recovery and enhanced range of motion [29]. Initially, the procedure required a two-incision technique [57]. One incision was needed to facilitate graft harvest and tibial tunnel preparation, whilst a second incision placed over the outside of the femur was required to position a 'rear-entry-guide' around the posterior aspect of the lateral condyle for outside-in drilling of the femoral tunnel. The introduction of arthroscopic drill and off-set guides allowed for femoral tunnel preparation either through the tibial tunnel (transtibial) or through the medial portal, making a second incision unnecessary.

By the end of the 1990s, most surgeons had adopted the single-incision technique for arthroscopic ACL reconstruction [106]. However, criticism emerged about

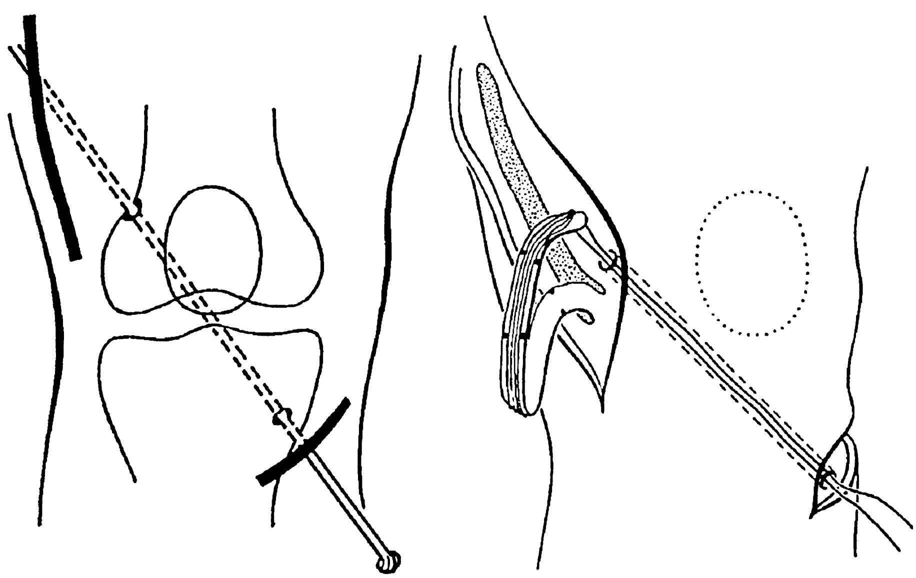


Fig. 53 Trans-articular ACL reconstruction as devised by Willy König in 1955, using anatomical land-marks without formal joint arthrotomy (with kind permission of Springer Science, Berlin) [158]

Fig. 54 Arthroscopic ACL reconstruction using a composite carbon fibre graft performed by David Dandy in 1980 (photographs courtesy of David Dandy, Cambridge)

potential disadvantages of femoral tunnel placement using single-incision, trans-tibial techniques, especially in cases of single-bundle reconstruction [15, 88, 229]. In a study published in 2001, Markus Arnold and associates of Nijmegen in Holland found it impossible to position the femoral tunnel at the anatomical foot print when using a single-incision technique due to restrictions in drill-guide placement [11]. In 1993 Stephen Howell of Davis, California developed a specific drill guide (Howell® 65° tibial guide) used in conjunction with radiographic control to overcome such problems believing that the tibial tunnel holds the key in correctly positioning the femoral tunnel [121, 122]. Although refinements in surgical technique might safeguard against notch impingement, single-incision ACL reconstruction remains more likely to result in a vertically orientated, non-anatomic graft, unable to effectively control rotation [15, 159]. Thus prompting some researchers to re-consider the benefits of a revised two-incision technique [95, 98].

Conclusion

The number of injuries to the ACL has risen exponentially, since the days when only a fall from a horse could send the cavalry officer into early retirement due to an unstable knee. High-speed travel and an ever increasing enthusiasm for sports are to be blamed for this development. From a healthy scepticism towards surgery in the nineteenth century to an ever increasing plethora of operative solutions, simplified by a myriad of surgical aids and implements, we have come a long way, and many of us may not even remember the challenging days when ACL surgery required opening of the joint. The treatment of the ACL-deficient knee has seen many changes since Adams described the first a clinical case of ACL rupture 175 years ago. Arthroscopic ACL reconstruction has since become a standard procedure for almost every knee surgeon, but we are in danger of becoming complacent. It is essential that we all continually review our own results and carefully assess the values and merits of new techniques and technologies in order to offer our patients the best treatments available. We should however not forget Jack Hughston's advice that there is no knee injury which could not be made worse by inappropriate surgical management.

It is intriguing to review the pioneering work of Hey-Groves and Smith as it anticipated many of the modern ideas on graft obliquity and anatomic reconstruction, and in many respects, the surgical philosophy of ACL reconstruction has come full circle. Many advancing ideas were dismissed, or forgotten only to be re-discovered, often without giving credit to the original inventors. We should hence not lose sight of the achievements of our surgical forefathers and be encouraged to become familiarised with the historical developments as it may assist us in the pursuit of, what Ivar Palmer called, the restoration of the physiological joint.

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