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Osteotomy around the knee: evolution, principles and results

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Abstract
Purpose This article summarises the history and evolution of osteotomy around the knee, examining the changes in principles, operative technique and results over three distinct periods: Historical (pre 1940), Modern Early Years (1940–2000) and Modern Later Years (2000–Present). We aim to place the technique in historical context and to demonstrate its evolution into a validated procedure with beneficial outcomes whose use can be justified for specific indications.
Materials and methods A thorough literature review was performed to identify the important steps in the development of osteotomy around the knee.
Results The indications and surgical technique for knee osteotomy have never been standardised, and historically, the results were unpredictable and at times poor. These factors, combined with the success of knee arthroplasty from the 1980s onward, led to knee osteotomy being regarded as an irrelevant surgical option by many surgeons. Despite its fluctuating reputation, this article demonstrates the reasons for the enduring practice of osteotomy, not least because achieving the appropriate alignment is now recognised as the foundation step when planning any surgical intervention.
Conclusions With appropriate patient selection, accurate pre-operative planning, modern surgical fixation techniques and rapid rehabilitation, osteotomy around the knee is now an effective biological treatment for degenerative disease, deformity, knee instability and also as an adjunct to other complex joint surface and meniscal cartilage surgery.
Level of evidence V.

Keywords Tibia · Osteotomy · Knee · Evolution · History · Results · Principles

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Introduction

The concept of osteotomy for the treatment of limb deformity has been in existence for more than 2,000 years, and more recently pain has become an additional indication. The basic principle of osteotomy (*osteo* = bone, *tomy* = cut) is to induce a surgical transection of a bone to allow realignment and a consequent transfer of weight bearing from a damaged area to an undamaged area of joint surface.

With the advent and subsequent success of knee arthroplasty surgery, especially in low demand and older patients, there has been a relative neglect of osteotomy as a valid treatment modality in many healthcare services [5, 16, 73, 94]. However, less favourable results have been reported for knee arthroplasty in younger, more active patients [30, 43], causing some clinicians to pause and question this extended indication and search for another solution. The relegation of osteotomy around the knee to 'historic' status, due to a reputation of poor and unpredictable outcomes, has recently been challenged following evidence from several centres, which have both refined and redefined the entire process from patient selection to post-operative rehabilitation [57, 64]. With appropriate indications, planning and a standardised operative technique, we will show that osteotomy around the knee can be a highly effective procedure, resulting in reproducible and enduring functional and symptomatic improvement.

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Materials and methods

A PubMed search conducted during November 2011 using the search terms 'osteotomy' and 'tibial' or 'femoral' produced 3,312 results in the English language. After the evaluation of each abstract, 352 full text articles were retrieved, based upon their relevance to the history, evolution, principles and results of osteotomy around the knee. The authors' critical analysis of each paper was required to select the most pertinent articles for inclusion in the final review based upon three main historical periods: Historical (pre 1940), Modern Early Years (1940–2000) and Modern Later Years (2000–Present).

Fig. 1 The Hippocratic Scamnum was a traction device used for deformity correction over two millennia ago. Reproduced with permission and copyright© of the British Editorial Society of Bone and Joint Surgery [36]

Fig. 2 A gimlet, such as the one pictured was used during the 'subcutaneous' osteotomy technique by Prof. Pancoast to create multiple femoral perforations at the osteotomy site (image from Wikipedia)

History and evolution

Historical osteotomy (pre 1940)

The concept of deformity correction has been established since the time of Hippocrates (460–370 BC) with the Hippocratic Scamnum, a traction device used to set bones [36] (Fig. 1). The prequel to osteotomy in the sixteenth century was *osteoclasia*, where malalignment was treated by breaking a deformed bone, before immobilising it in the correctly aligned position as it healed. Bosch and Lorenz separately developed apparatus derived from a bookmaker's press, which were used for the correction of static deformities including varus, valgus, recurvatum and flexion contractures, to improve function [4].

Advances were slow during the subsequent three centuries—poor antisepsis, limited understanding of the underlying biological principles, little dissemination of new techniques and rudimentary operating equipment were significant obstacles.

The first successful surgical osteotomy about the knee is attributed to John Rhea Barton from Pennsylvania, USA (1794–1871), who performed a supracondylar wedge femoral osteotomy for an ankylosed knee in 1835 [57, 59]. He reported success in 12 of 14 procedures, noting of the remaining two that they 'perished…of hectic irritation and exhaustion' post-operatively.

Langenbeck, using techniques adapted from his experiences in the Schleswig–Holstein war in Germany, performed several osteotomies about the knee for rachitic deformity and ankylosis in the 1850s [1]. He drilled an aperture and inserted a small saw to almost complete the osteotomy before applying lateral force. Unfortunately, infection rates were high, attributed initially to a 'foreign body reaction' to the created bone sawdust. Other surgeons in Germany, including Billroth, Mayer, Wernher and Volkmann, pioneered the use of modified instruments, which made 'subcutaneous' osteotomy possible, improving aseptic practice [87]. In 1859, Professor Pancoast in the USA reported using a 'stout gimlet' to create multiple perforations at a femoral osteotomy site through a single small incision before applying a corrective force [1] (Fig. 2). Despite these measures, infection still ensued, although a good eventual recovery is recorded in this patient.

The technique was adapted by Professor Gross of Philadelphia, USA, who used a custom-made chisel to complete the drill holes with good results in four cases [1]. At around this time, Louis Little, a surgeon in London, UK, used a carpenter's chisel to correct a post-infective (*strumous*) knee ankylosis in a 14-year-old girl [56].

Several further osteotomy procedures were reported in Europe by Volkmann, Ogsten, Barwell and Lister, although

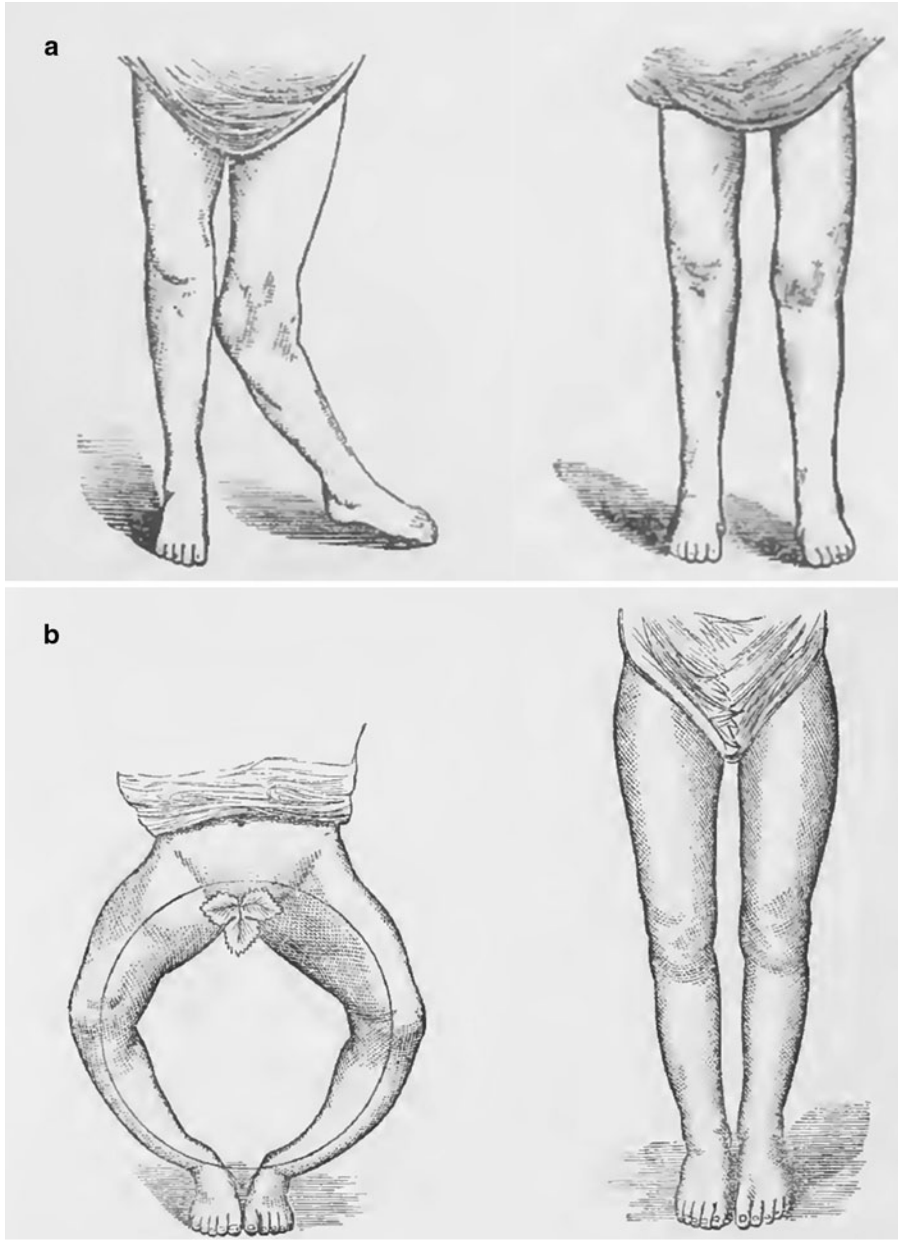

Fig. 3 Pre- and post-operative images of a patient with **a** genu valgum and **b** genu varum, treated by William Macewen [59] at the end of the nineteenth century

William Macewen from Glasgow Royal Infirmary in the UK was probably most prolific at this time. In 1879, he reported on a transverse femoral osteotomy technique to correct genu valgum and 'anterior tibial curves', which he used in 50 cases [58] (Fig. 3). He described a medial femoral approach that avoids significant vascular complication and warned against correcting with 'a quick jerk', rather advising 'the bending ought to be performed gradually'.

In 1880, Macewen [59] published the first book devoted to osteotomy, in which he presented his series of 1,800 cases without major complications. With good antisepsis and improved operative techniques, osteotomy gained rapid acceptance throughout Europe [87]. For the next 75 years, osteotomies were performed regularly for wide-ranging indications, although techniques still varied dramatically. Some surgeons advocated the creation of the osteotomy by means of driving a chisel straight in through the skin, as described to one of the senior authors (NPT) by Karl Nissen (*personal communication*). Results remained mixed, particularly as there was no internal fixation or radiographic analysis of correction, and only rudimentary post-operative immobilisation was practiced.

In 1934, Brett performed the first osteotomy immediately distal to the tibial plateau in a case of genu recurvatum [15]. Following an incomplete anteroposterior osteotomy, he elevated the anterior tibia as an opening wedge, filling it with bone chips and adding screws for support (Fig. 4). One year post-operatively, the patient was pain free, had returned to work and no longer suffered hyperextension (Table 1).

Historical osteotomy (pre 1940)
Early osteotomies had highly variable outcomes
Techniques varied greatly and used rudimentary equipment
Complications included loss of correction, infection, stiffness

Modern early years (1940–2000)

The transfer of osteotomy techniques to the treatment of arthritis

Until the mid-twentieth century, traditional approaches for the treatment of degenerative and inflammatory knee arthroses were limited, with arthrodesis as the mainstay for severe cases. Although the application of osteotomy to such patients for the treatment of unicompartmental osteoarthritis (OA) became recognised at this time, it required significant time and iteration before the start of appropriate patient selection, consistent surgical techniques and good patient follow-up. Initial attempts were made in the UK by Brittain and Wardle, who transferred the techniques from the treatment of genu valgum and childhood rickets, respectively. In 1948, Brittain first described distal femoral osteotomy for two groups of patients with genu valgum: in children, resistant to conservative corrective measures; and in adults with lateral compartment knee OA as a consequence of unbalanced loading [17]. He described an opening-wedge distal femoral osteotomy and argued against High Tibial Osteotomy (HTO) following his experience of a high rate of vascular complications after traumatic fractures to this area. Wardle reported on his series of 35 patients commencing in 1941, of HTO for the treatment of knee OA. He performed his osteotomies distal to the tibial tubercle, at the junction of the upper and middle thirds of the tibia. The same procedure had been used in Liverpool since the time of Sir Robert Jones in 1928, originally for the correction of knee deformity as a consequence of childhood rickets [114, 115]. Of the 38 knees (in 35 patients) reported on, he noted “complete relief of pain in all his patients”, with many gaining increased range of movement following osteotomy. Complications were few and results persisted even beyond 5 years. Despite correcting the lateral deformities, he attributed the relief of pain to the reduction in intramedullary venous pressure due to the osteotomy itself. He demonstrated with intra-osseous venography the presence of a ‘medullary block’ at the healed osteotomy site, isolating the proximal tibia from the venous outflow from the tibial shaft, and preventing a build-up of peri-articular pressure. Interestingly, in a more recent limited evaluation of six incomplete non-displaced HTOs, where femorotibial alignment was not altered, prompt improvements in rest pain and bone scans that returned to normal following the procedure appear to add weight to the premise that raised intra-osseous pressure may be a factor in the development of peri-articular pain [27].

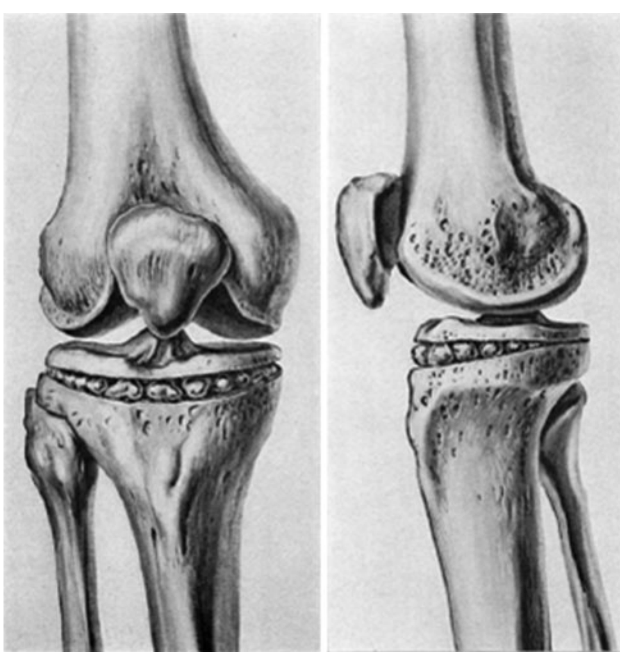

Fig. 4 Brett’s HTO for recurvatum deformity. Reprinted with permission from J Bone Joint Surg Am [15] http://jbjs.org

In 1958, Jackson reported on his series of six femoral supracondylar and eight HTOs for the treatment of disabling pain in patients with OA associated with a lateral deformity [47]. Neither procedure resulted in neurovascular complications and only one of the patients undergoing femoral osteotomy, and two in the HTO group, subsequently complained of pain. HTO was his favoured option, as it resulted in reduced post-operative loss of movement. In 1961, Jackson and Waugh published their series of 11 HTOs for knee OA with valgus or varus deformity and disabling pain [48] (Fig. 5). For the first time, they published radiographic evidence of realignment and union and quantified the correction of deformity obtained following osteotomy around the knee at a mean follow-up of 31 months.

By 1964, the concept of delaying joint degeneration by realignment with HTO was established. Gariépy from Montreal, Canada, described a transfibular lateral closing-wedge HTO proximal to the tibial tubercle [34]. He reported on 22 cases in 13 patients, in whom good results were obtained at 1–7 years, although there were two cases

Table 1 Osteotomy timeline, detailing the key players responsible for the evolution of modern osteotomy around the knee

Dates	Name	Role
400 BC	Hipprocrates (460-370)	Documented scamnum for deformity correction
1500s	Bosch, Lorenz	Developed osteoclasia techniques
1835	John Rhea Barton (1794–1871)	Supracondylar wedge femoral osteotomy
1850s	Bernhard von Langenbeck (1810–1887)	Osteotomies for rachitic deformity and ankylosis
1859	Joseph Pancoast (1805–1882)	Subcutaneous femoral osteotomy using multiple perforations through a small skin incision
1868	Theodor Billroth (1829–1894)	First subcutaneous tibial osteotomy using a chisel
1869	Louis Stromeyer Little (1840–1911)	First reported osteotomy about the knee in England
1875	Sir William Macewen (1848–1924)	First antiseptic osteotomy in UK, presented 1,800 cases
1880	Sir William Macewen (1848–1924)	First book published exclusively on osteotomy about the knee, concentrating on opening- and closing-wedge procedures of the distal femur
1928	Sir Robert Jones (1857–1933)	Performed tibial osteotomy at the junction of middle and proximal thirds, for rachitic deformity
1934	AL Brett	First HTO proximal to tibial tubercle (for genu recurvatum)
1948	HA Brittain	Described lateral opening DFO for children with genu valgum and in adults with secondary valgus OA
1960s	JP Jackson and W Waugh	HTO performed just distal to the tibial tuberosity, first to publish radiographic evidence of realignment and union
1964	EN Wardle	Used intra-osseous venography to demonstrate normalisation of tibial venous flow following corrective osteotomy
1964	R Gariépy	Transfibular lateral CW HTO, just proximal to tibial tubercle, for unicompartmental OA with genu varum. First to report on an internal compression clamp to stabilise the osteotomy site
1965	Mark B Coventry	HTO secured with staples, proximal to tibial tubercle
1969	Mark B Coventry	Introduction of the stepped staple to prevent loosening of hardware at the osteotomy site
1970	WR Harris	First to demonstrate correction related to mechanical and anatomical axis on long-leg alignment views
1971	Werner Muller	First report of AO T-plating for osteotomy fixation
1979	Yoshiyuki Fujisawa	Seminal arthroscopic study on the effects of HTO on articular cartilage degeneration, recommending the ideal correction when the mechanical axis passed through a point 30–40 % lateral to the midpoint of the tibial plateau
1984	Kosuke Ogata	Introduced the step-cut 'interlocking wedge' osteotomy to improve stability
1985	Mark B Coventry	Preoperative planning method published using anatomical axis to calculate appropriate correction required in HTO
1988	William L Healy	First report of 90-degree AO distal femoral blade plate
1992	TW Dugdale	Preoperative planning method published using weight-bearing line to calculate appropriate correction required in HTO
1998	Goran Magyar	Reported on hemicallotasis (angular callus distraction) for OW osteotomy
1999	RE Ellis	Computer-assisted surgical planning and guidance system developed
2002	Giancarlo Puddu	Developed first generation 'tooth' plate to stabilise osteotomy
2000–2003	Alex E Staubli, Philipp Lobenhoffer	Development and confirmation of efficacy of fixed angular stable plates
2003	Philipp Lobenhoffer	Development of refined surgical technique and early rehabilitation protocol
2005	Dominique Saragaglia	Navigation of osteotomies around the knee to improve accuracy of correction
2008	René Marti	Published seminal instructional book on post-traumatic deformity correction

HTO High tibial osteotomy, *DFO* distal femoral osteotomy, *OA* osteoarthritis, *CW* closing wedge, *AO* Arbeitsgemeinschaft für Osteosynthesefragen

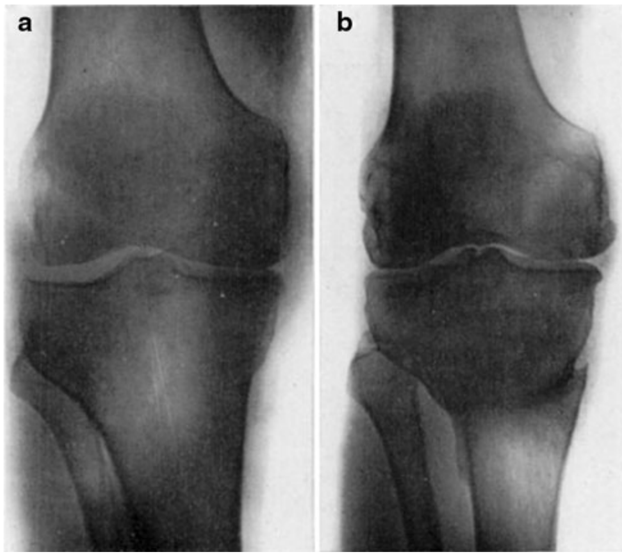

Fig. 5 Anteroposterior radiographs of a degenerate knee associated with a varus deformity **a** prior to and **b** following HTO by Jackson. Reproduced with permission and copyright© of the British Editorial Society of Bone and Joint Surgery [48]

of delayed union. Coventry from the Mayo Clinic, Rochester, USA, adopted Gariépy's osteotomy, securing it with one or two staples to allow early weight bearing and range of motion [20] (Fig. 6). His rationale was that this would be near the site of deformity, involve primarily cancellous bone that would unite more quickly and would allow the action of quadriceps to pull on the site of osteotomy, presumably to encourage union. Preliminary results were reasonable, with 18 of the 30 knees achieving pain relief, good stable range of motion and full active extension, beyond a year post-operatively. However, despite internal fixation and post-operative casting for 4–6 weeks, he reported loosening of the staple in several cases. Over the subsequent decades, many other groups published their experience of osteotomy around the knee and this led to the introduction of several improvements such as the assessment of alignment and mechanical axis using a long-leg anteroposterior radiograph [38].

However, complications were often high, particularly in patients with rheumatoid arthritis. Additionally, results were difficult to correlate across studies as techniques differed widely even within cohorts, and patient numbers and follow-up varied considerably (Table 2). Although the pioneering development of osteotomy around the knee up to the mid-1970s resulted in broadly good outcomes in certain hands and in selected patient groups, there is evidence that the procedure was performed for a wide range of indications, using varying techniques with poor fixation and with delayed rehabilitation protocols. Consequently, the results in the early years were mixed and poorly reproducible. Furthermore, widespread complications were reported, including failure of fixation, displacement, non-union, infection and peroneal nerve palsy [4, 10, 11, 38, 101].

Thus, the advent of knee arthroplasty, with its superior initial results, led to a dwindling popularity of osteotomy, even when used in non-controversial indications. Fortunately, during the intervening years, there remained a relatively small core of proponents, who continued to refine its indications, develop the operative techniques and hardware, improve rehabilitation and develop robust tools to analyse post-operative results. Coventry's publication of his 87 patient series in 1973, with up to 9-year follow-up, led to many useful conclusions and recommendations: He found corrective osteotomy relieved pain and restored movement in the majority of patients with degenerative or quiescent rheumatoid arthritis [22]. Furthermore, his conclusions contained the prophetic statement that 'recently developed total knee replacements can be expected to change the indications for osteotomy', although he restates the view that 'the patient with early, symptomatic unicompartmental OA will remain an ideal candidate for osteotomy', and broadly this remains true to this day.

Development of secure fixation

Although many surgeons continued to rely on plaster casting alone to maintain correction [6, 44, 49, 52], up until the late 1980s, the most popular technique for fixation of the osteotomy was staples, usually augmented with casting or using Charnley's compression device [70]. Hardware failure was a considerable burden: staples frequently loosened because they sometimes did not fully engage into the distal tibia and this was addressed by the introduction of the stepped staple in 1969 [21] (Fig. 7).

Few studies explicitly noted a loss of correction using such fixation; however, the recurrence of varus deformity over longer periods implies that early stability was suboptimal, and certainly range of motion had to be limited for the initial post-operative period [29, 31, 40, 72, 110]. Although indications were becoming better defined, and most surgeons employed closing-wedge osteotomies of the proximal tibia, results remained mixed [10, 103]. Worse results were noted in pre-operative valgus deformities, leading to an acceptance that alternative procedures were most suited to the treatment of valgus OA [108].

An increasing awareness of the need to ensure accurate fixation led to the hardware and principles developed by the AO foundation (initially for fracture treatment) being advocated as potential concepts for osteotomy fixation. As early as 1969 Werner Muller et al., from Basle, Switzerland, used AO T-plates as their method of choice, and although they reported a high rate of insufficient correction and some cases of metalwork fatigue and fixation failure

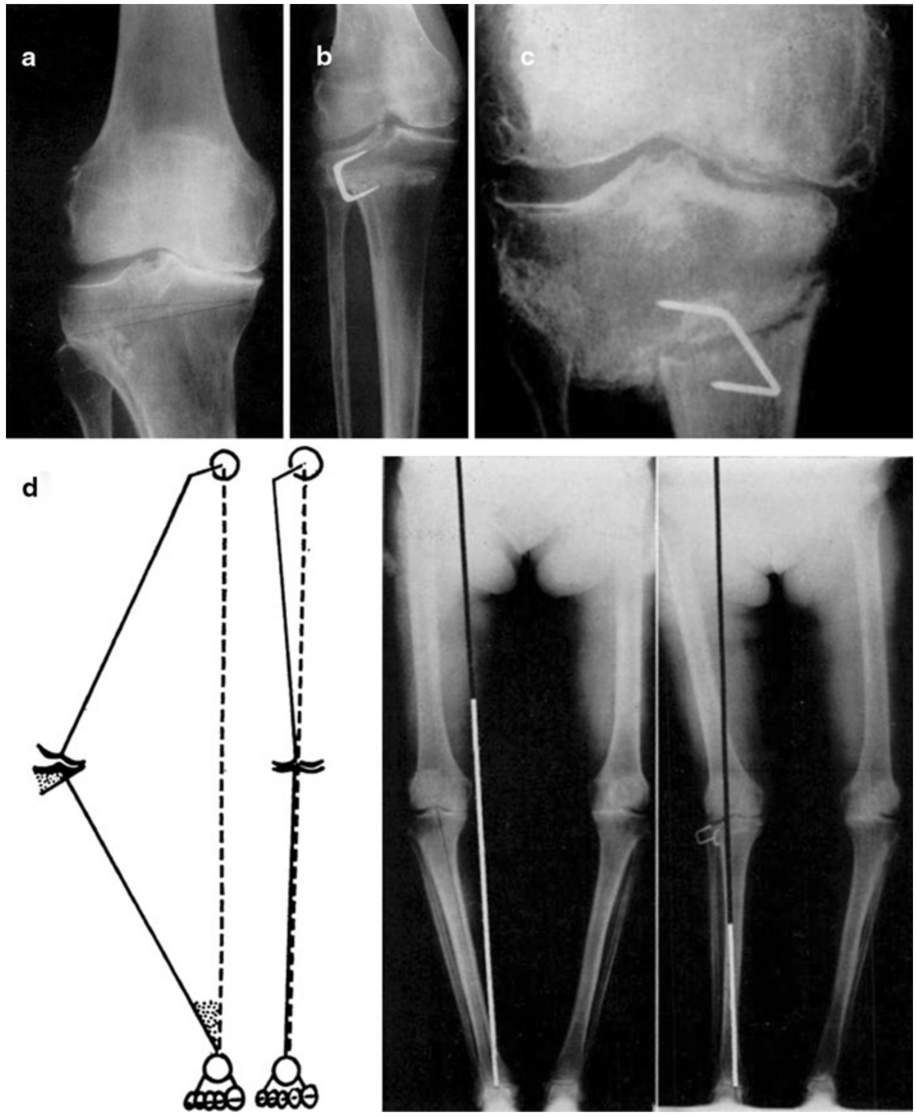

Fig. 6 Anteroposterior radiographs of a degenerate knee **a** prior to and **b** following HTO by Coventry. Note the pre-operative templating for the proposed osteotomy and the post-operative joint line obliquity created in this case. Reprinted with permission from J Bone Joint Surg Am [20]. **c** A post-operative radiograph following HTO by Bauer. Note the rather distal osteotomy site. Reprinted with permission from J Bone Joint Surg Am [10]. **d** Harris was one of the first to use long-leg radiographs to template and demonstrate correction with respect to the mechanical axis of the limb following HTO. Reprinted with permission from J Bone Joint Surg Am [38] http://jbjs.org

during their early experience (which initially included different fixation methods), overall 83 % of patients had a good or excellent outcome after 1–6 years (mean 2.1 years) [71]. The potential for an earlier stable range of movement was realised; however, the longer-term benefits of these fixation systems were not appreciated from initial series as they also contained other inferior fixation methods, and sub-group analysis was seldom performed [6]. The first group to report exclusively on distal femoral osteotomies performed with a 90-degree AO distal femoral blade plate produced good or excellent outcomes in 93 % of procedures [39]. An alternative internal fixation method consisted of a bent five-hole one-half tubular plate with two screws [70] (Fig. 8). The initial report of 41 HTOs performed using this technique was encouraging, with early stability allowing immediate range of motion, although precision of correction was still challenging with this device.

Other approaches to increase initial stability included the interlocking wedge osteotomy, as a modification to the standard lateral closing-wedge (LCW) [83]. The rationale for this approach was to increase the bone contact surface area and stability by making a step-cut in the osteotomy, thereby interlocking the anterior and posterior cortices of the tibia. In a series of 36 interlocking wedge HTOs followed for 1–3 years, early union occurred in all cases and subjective evaluation of the patients' pain and function revealed good results in 77.8 % of cases, with no poor outcomes.

The search for the ideal corrective angle

The initial concept of osteotomy, to relieve pain by altering angular alignment, evolved during this period from restoration of the anatomical axis to correction of the mechanical axis, using radiographic analysis. In 1979, Fujisawa

Table 2 Outcome studies of HTO for knee arthrosis between 1968 and 1977

Years	Author	Procedure	Fixation	Follow-up (years)	Results/conclusions	Complications
1968	Ahlberg et al. [4]	MOW or LCW DFO or HTO	Varied	4.5	Improvement in 44 %. Poor results in RA. Preferred CW HTO proximal to patellar insertion and secured with staple	11 % subluxation, 11 % pseudarthrosis, 3.7 % revised
1969	Bauer et al. [10]	LCW HTO	POP	1.4 mean	Clinical improvement in over half of patients	9.5 % fracture, 12.7 % displacement, 1.6 % vascular injury, 6.3 % VTE, 1.6 % non-union, 3.2 % infection
1969	Benjamin et al. [11]	Combined dome HTO and DFO	POP	ns	Successful in 83 % of OA and 81 % of RA group	5.3 % fracture, 1.8 % VTE
1970	Harris et al. [38]	CW HTO	2 staples	Over 1 year	72 % good, 14 % fair, 14 % poor	5 % nerve palsy, 3 % delayed union, 3 % fracture
1971	Muller et al. [71]	CW HTO	AO T-plate	2.1 mean	50.7 % excellent, 32.5 % good, 11.4 % moderate, 5.6 % poor	3 % infection, 3 % nerve palsy, 1 % PE, 3 % non-union, 3 % fracture
1973	Coventry et al. [22]	CW HTO or DFO	Blade plate/staples + POP	1–9	OA group—good in 88 %, fair in 10 %, poor in 3 % RA group—good in 55 %, fair in 30 %, poor in 3 %	4 % VTE, 1 % arterial thrombosis, 3 % delayed union, 1 % ligament avulsion, 1 % infection, 1 % recurrent deformity
1973	Appel et al. [6]	MOW HTO	Varied	5 mean	77.1 % improved	11.4 % failed, 8.6 % revised to arthrodesis
1973	Levy et al. [55]	LCW or inverted V HTO	POP ± staples	ns	32 % very satisfactory, 47 % satisfactory, 16 % no improvement, 5 % worse	44 % loss of correction
1973	Shoji et al. [103]	MCW HTO	POP	2.6 mean	Pain improved in 53 %. Optimal correction to 5 degrees valgus, overcorrection was detrimental	6 % fracture 6 %, 4 % thrombophlebitis, 2 % nerve palsy, 20 % loss of correction
1974	Insall et al. [44]	CW HTO	POP	5 mean	65 % satisfactory, 35 % unsatisfactory, 59 % total pain relief, 18 % partial pain relief	10 % fracture, 2 % arterial injury, 4 % thrombophlebitis, 2 % delayed union, 4 % infection, 12 % displacement, 23 % loss of correction
1974	Jackson et al. [49]	Dome and LCW HTO	Staples + POP or ex-fix	Over 0.5	16 % failure of correction, 1 % revision/ arthrodesis	1 % death, 4 % VTE, 3 % deep infection, 2 % non-union, 12 % nerve palsy, 15 % fracture
1975	Seal et al. [101]	Dome and LCW HTO	4 % internal fixation, 96 % POP alone	7.6 mean	67 % complete pain relief, 2 % no relief. 2 % revision to arthrodesis. Subjectively, 60 % excellent, 18 % good, 22 % poor All poor results were corrected to outside the range 163–180 degrees	16 % DVT, 2 % nerve palsy, 9 % loss of correction, 7 % displacement, 7 % delayed union

Table 2 continued

Years	Author	Procedure	Fixation	Follow-up (years)	Results/conclusions	Complications
1975	Surin et al. [108]	CW HTO	POP	3.2 mean	Subjectively, 42 % satisfied, 33 % improved, 25 % poor. Objectively, 45 % excellent, 25 % good, 30 % poor Poor results in initial valgus deformities	5 % revision—2 % delayed union, 3 % poor correction
1976	Kettelkamp et al. [52]	LCW HTO	ns	5.2 mean	67 % good or acceptable at 5 years. Best results if corrected beyond 5 degrees valgus	ns
1977	Ranieri et al. [90]	HTO	ns	5–15	85 % excellent, 9 % good, 6 % poor. 87.8 % had no pain at 10 yrs. Results achieved at 6 months tended to endure	2.6 % nerve palsy, 1.6 % infection, 27.8 % chronic cellulitis

Note the variation in technique, follow-up and outcome measures. *MOW* Medial opening wedge, *LCW* lateral closing wedge, *DFO* distal femoral osteotomy, *HTO* high tibial osteotomy, *VTE* venous thromboembolism, *DVT* deep vein thrombosis, *RA* Rheumatoid arthritis, *POP* plaster of paris, *ns* not stated

Fig. 7 Coventry's stepped staple used to secure the osteotomy site. Reprinted with permission from J Bone Joint Surg Am [21] http://jbjs.org

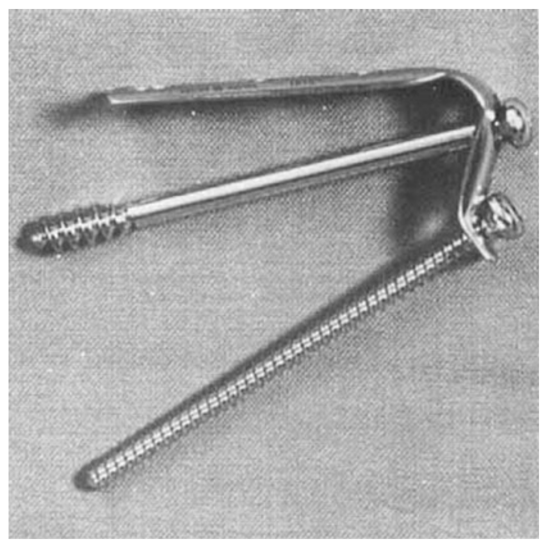

Fig. 8 The bent 5-hole one-half tubular fixation plate utilised for HTO fixation by Miniaci. Reprinted with permission from Wolters Kluwer publishers [70]

et al. [31] published a seminal paper examining the mechanical axis and arthroscopic grade of degeneration before and after HTO in 54 cases (Fig. 9).

The authors found arthroscopic evidence of articular cartilage regeneration with fibrocartilage and meniscal repair in those knees that were corrected so that the mechanical axis passed through a point 30–60 % lateral to the midpoint of the tibial plateau, a finding that was supported by histological analysis in a subset of 20 patients.

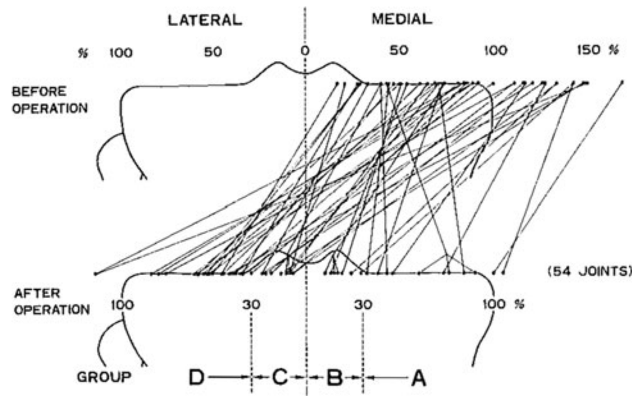

Fig. 9 Pre- and post-operative corrections with respect to the intersection of the mechanical axis with the tibial plateau. Reprinted with permission, copyright Elsevier [31]

Consequently, they defined an ideal correction to be achieved when the mechanical axis passed through a point 30–40 % lateral to the midpoint of the tibial plateau. The recommendations of this study have since been applied strictly with the 'Fujisawa point' (with the mechanical axis passing at 62 % of the way across the knee measured from the medial side) deemed the gold standard level of correction [16, 28], but only recently have the limitations of this study been recognised and more rigorous analysis of dynamic correction angles and outcomes been undertaken. In 1985, the concept of reducing the adductor moment around the knee was reported [89]: A group in Chicago, USA, studied knee joint loading during gait in 21 patients following HTO and compared outcomes to age-matched controls. They found that those patients with a high-adduction moment, tending towards a dynamic varus, performed significantly worse in the long-term following HTO than patients in the low-adduction moment group. In addition, the former patients tended to have a recurrence of their initial varus knee deformity. The authors conclude that a high-adduction moment may be a compensatory mechanism secondary to the underlying deformity that may worsen outcomes if this persists following HTO. It appears, therefore, that dynamic loading, in addition to static alignment, should be taken into account for accurate prediction of outcome following HTO.

Acceptable post-operative tibiofemoral angles for longevity of correction and adequate function were the subject of significant debate. Hernigou et al. [40], from Creteil, France, performed a retrospective study on 93 knees operated upon in the same hospital over a 3-year period. They noted a dramatic deterioration in results beyond the first 7 years post-operatively; however, further analysis revealed that those patients corrected to a hip–knee–ankle angle of 183–186 degrees (valgus) had fewer symptoms at longer-term follow-up. Several other studies confirm the requirement to 'overcorrect' the knee beyond neutral alignment for longevity (Table 3).

Many authors recommended overcorrection, with a valgus position between five and 16 degrees [50, 51, 92, 95, 111, 119], although other authors showed no relationship between post-operative valgus and clinical outcome [13, 107], and further studies showed progression of lateral tibiofemoral compartment degenerative changes following mild overcorrection [40, 45]. Most authors agreed the ideal post-operative alignment to be a valgus overcorrection of

Table 3 Studies showing improved outcomes following overcorrection of HTO

Years	Author	Final cases	Follow-up (years)	Results
1979	Fujisawa et al. [31]	54	0.3–6.3	Arthroscopic improvements in articular cartilage in 87 % of patients when MA corrected to 30–60 % lateral to midline, and only 33 % of patients corrected medial to midline
1980	Myrnerts et al. [72]	78	2	Significantly better starting pain, walking ability and overall satisfaction at 2 years in overcorrected group (5 degrees valgus MA) versus patients corrected to neutral MA
1987	Pachelli et al. [84]	38	4.4	Good or excellent results in 66 % overall at 4.4 years, but only 27 % if <6 degrees valgus AA alignment obtained, and 91 % in those cases aligned ≥6 degrees valgus AA
1987	Hernigou et al. [40]	93	10–13	Dramatic deterioration after 7 years, but patients corrected to a HKA of 183–186 degrees (i.e. valgus) had fewer long-term symptoms
1988	Cass et al. [19]	86	2–17	Better long-term outcomes if AA corrected to 10–12 degrees valgus
1990	Odenbring et al. [81]	314	10–19	Overall revision rate 19.7 %, increasing to 31.8 % if undercorrected and reducing to 5.6 % if overcorrected or normalised with respect to hip–knee–ankle angle
1991	Odenbring et al. [80]	38	10	Overcorrected knees (HKA <180 degrees) at 1 year post-operative had better outcomes (78 % good result at 10 years). Radiographic OA progression occurred in 75 % of normo- or under-corrected knees, but just 17.6 % of overcorrected group
1999	Naudie et al. [75]	106	10–22	Survivorship reduced from 73 % at 5 years to 30 % at 20 years Early failure if valgus alignment not maintained at 1 year

MA Mechanical axis, *AA* anatomical axis, *HKA* hip–knee–ankle angle between three and eight degrees [25, 45, 46, 92, 119], although some advocated significant overcorrection to eight to 10 degrees valgus as the deformity tends to decrease over time, resulting in the recurrence of pain and worsening medial arthritis [63].

A major contributor to the literature at this time is Coventry, who reported on 213 HTOs with an average 16-year follow-up [23]. He demonstrated the ability of articular cartilage in the newly non-loaded compartment to regenerate following realignment and found 61.8 % of patients were improved beyond 10 years. He advocated an overcorrection to 10 degrees of anatomic valgus stating that if adequate overcorrection was not achieved, gradual deterioration of radiological and clinical results occurred over time.

A group from China performed a prospective study of 93 HTOs to define the most important predictors of conversion to arthroplasty, and whether pre- and post-operative angles influenced this [42]. They investigated multiple factors including age, gender, body mass index (BMI) and radiographic degeneration, but found only the pre-operative tibiofemoral angle to be a significant predictor of conversion to arthroplasty and of patient dissatisfaction. They found an ideal prognostic tibiofemoral angle to be nine degrees varus or less, which led to a probability of HTO survival for 10 years of over 90 %, but reduced to 57 % for greater pre-operative deformities. Post-operative alignment was not found to be a factor in this study, in line with several other studies, that revealed the passage of time along with pre-operative deformity were stronger prognostic factors [13, 41, 45, 91, 107]. Huang et al. [42] concluded that patients with pre-operative tibiofemoral varus of greater than nine degrees may be more suitable for total knee arthroplasty. Majima et al. [62] evaluated radiographic changes in both the medial and the lateral compartments at 10-15 years following HTO. They found that HTO did not protect against progression of medial arthrosis for more than 10 years, and reported a correlation between the post-operative tibiofemoral angle and the progression of medial joint arthrosis with inferior function.

In summary, there is significant variation in the literature in both indications for surgery and the method of recording angular correction, thus reducing clarity of interpretation. The consensus opinion is that correction in the presence of degeneration should be to beyond neutral. A more modern approach is to consider the intersection point of the line of Mikulicz (weight-bearing line) with the tibial plateau, recording the correction achieved in terms of mechanical axis, rather than the change in tibiofemoral axis. Correction to less than neutral is now universally deemed unacceptable and is associated with earlier failures.

Improving osteotomy survivorship

Longer-term results of HTO were not reported until the late 1970s. In 1977, Ranieri et al. [90] published a retrospective study of 187 knees at 5–15 years following HTO at the Rizzoli Institute, Italy. Patient age and the exact operative technique were not stated as they wished the results to be 'objective and instructive', and only 41 patients were examined 10-12 years following surgery. However, at this point, 36 (87.8 %) had no pain and the authors concluded 'the results achieved at 6 months following surgery are usually permanent'. Worryingly, some 27.8 % of patients developed chronic subcutaneous cellulitis following surgery. In 2003, Aglietti et al. [2] reported on a 10–21 year single-surgeon, retrospective study of 91 cases of HTO for medial gonarthrosis. At review, 33 % had been revised to Total Knee Replacement (TKR) after 11 years on average. More recently good 10- to 16-year survival data in LCW HTO were published for patients with specific indications [112]. This retrospective analysis of 100 cases performed during the 1990s confirmed 25 % were revised by 10 years, although this was just 15 % in men and 41 % in women. The study concluded that gender and radiographic stage of OA were the most important predictors of survival, stating that men with medial compartment OA of Ahlback grade 1 had almost a tenfold lower failure rate at 10 years when compared to women with higher pre-operative grades of OA.

Ritter et al. [93] performed survivorship analysis of their LCW HTOs using the Hospital for Special Surgery Knee Evaluation. Overall osteotomy survival was 58 % at 10–13 years, although they performed little sub-group analysis to define which patient groups were more prone to failure. They concluded that a reliable lifetime for HTO was approximately 6 years. Rudan et al. [96] published a retrospective analysis of 128 LCW HTOs performed according to Jackson's technique between 1970 and 1984. At a mean follow-up of 7.5 years, they demonstrated a total revision rate 10.9 % with good or excellent Hospital for Special Surgery (HSS) scores in 70 % at 10–15 years. Interestingly, they found no significant differences in results between patients aged under or over 60 years at operation, nor did they find a difference in prognosis between genders.

Few other series extended beyond a 10-year follow-up, and in a technique that evolves rapidly, long-term follow-up studies necessarily tend to analyse the results of already outdated procedures (Fig. 10).

Open versus closing technique

By 1974, Jackson and colleagues [49] had collected sufficient data to review the outcomes of 226 HTOs performed using six different techniques since the 1950s (Fig. 11). Although they had by that time refined their indications to

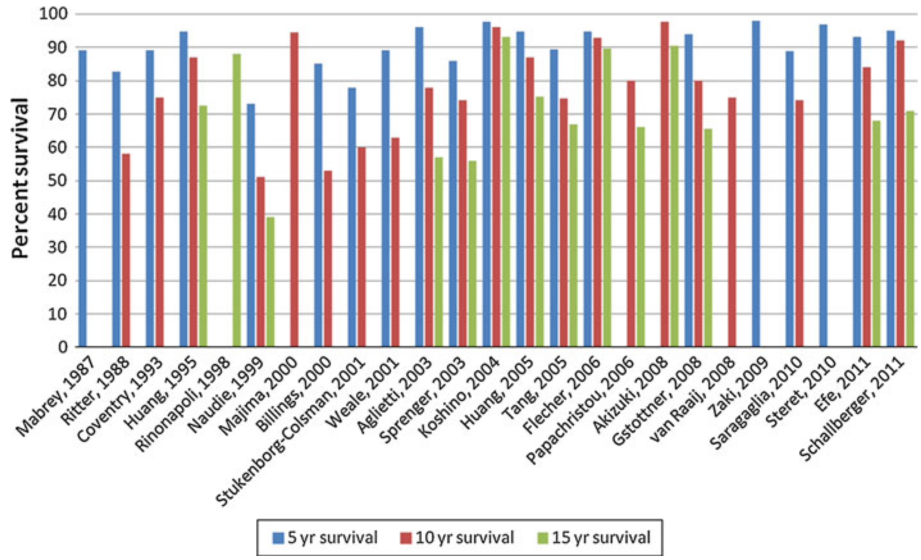

Fig. 10 Survival rates of HTOs at 5, 10 and 15 years since 1987 (usually stated in the original papers as Kaplan–Meier survival). Mean (and standard deviation) survival are as follows: 90.2 % (6.7) at 5 years, 77.5 % (14.1) at 10 years and 71.3 % (15.3) at 15 years

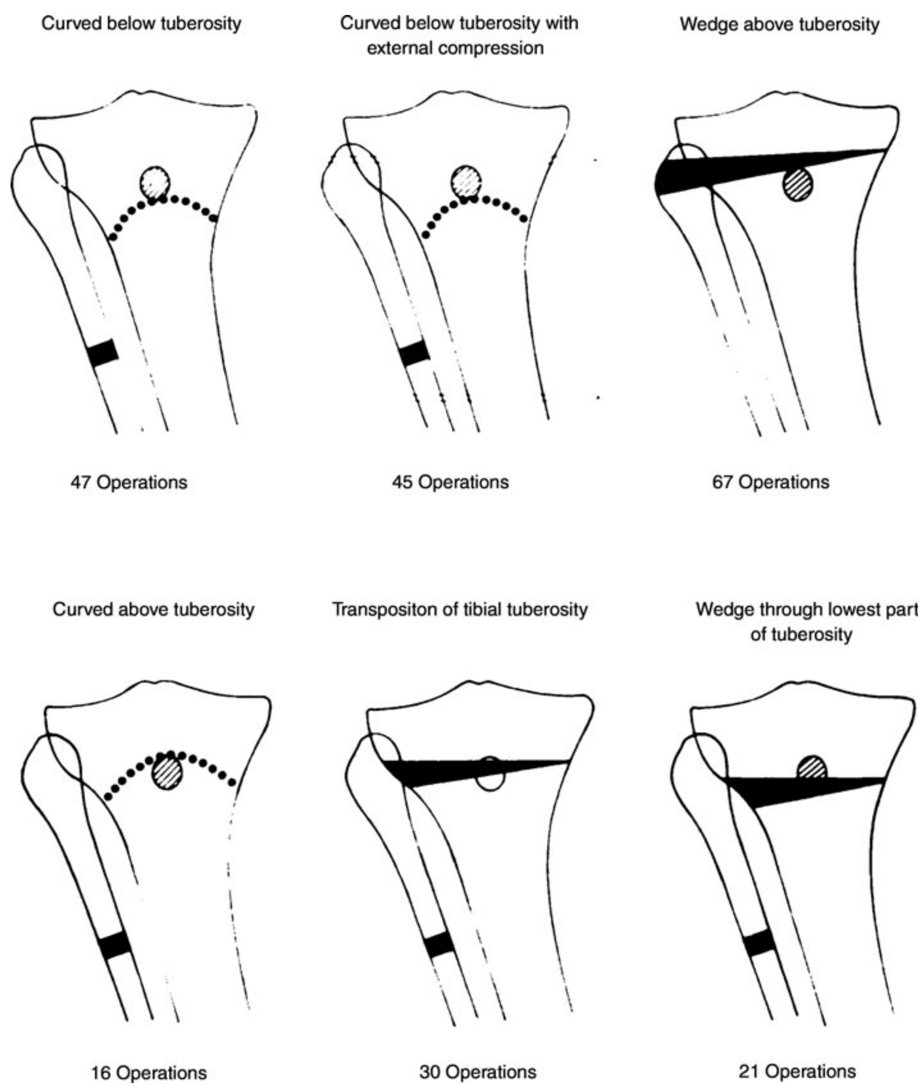

Fig. 11 Six different HTO techniques used by Jackson. Reproduced with permission and copyright© of the British Editorial Society of Bone and Joint Surgery [49]

painful OA of the knee, with varus or valgus deformity secondary to either medial or lateral degeneration, respectively, there was little consensus on the most appropriate type of osteotomy.

Disadvantages of the closing-wedge osteotomy technique include difficulty in achieving a predictable degree of correction [40, 53, 65]. Furthermore, it often requires a concomitant fibular osteotomy with the attendant risks of compartment syndrome and potential injury to the common peroneal nerve [98]. Possible shortening of the patellar tendon, and the change in tibial condylar offset, can make subsequent conversion to TKR demanding [74]. Therefore, the use of a dynamic external fixator to progressively open a medial wedge using hemicallotasis or angular callus distraction gained popularity during the late 1990s [61]. Advantages of the procedure included simpler surgery, less soft-tissue scarring and tibial distortion, an earlier discharge time at 1–2 days post-operatively and shorter overall rehabilitation. In addition, there is a reduced incidence of patellar baja [74], and a virtual absence of peroneal nerve palsy, which is quoted at up to 9.2 % in laterally exposed closing-wedge procedures [105, 119]. The distraction process is commenced at 7–10 days post-operatively and can be performed by the patients themselves. In addition, no device remains at the osteotomy site following union. However, this process is time-consuming, requires high patient concordance and carries a considerable risk of pin tract infection. A Swedish group reported significant improvements in relevant scoring markers and good maintenance of correction at 143 months in 36 patients [61]. Their median fixation time was 88 days, with only minor complications; however, superficial pin-site infections occurred in 21 % of patients. A randomised study of 50 operations comparing conventional LCW osteotomy to this new hemicallotasis medial opening-wedge (MOW) technique at 2 years revealed improvements in all scores, but no clinical differences between the groups [60]. The authors found the hemicallotasis technique to give more precise and predictable correction, with fewer patients losing correction over the first post-operative year. They concluded that this was due to a reduction in the influence of ligamentous laxity in progressive distraction, whereas in LCW osteotomy, only osseous deformity can be accounted for in planning the correction. This utility of this technique has recently been confirmed at a follow-up of 4.6 years [63].

The evolution of pre-operative planning

In pursuit of the ideal corrective angle to ensure longevity of native knee function, it is now clear that accurate and appropriate pre-operative planning is critical to the osteotomy procedure itself [85, 86]. Initially, before radiography facilities existed, corrections were judged ‘by eye’, and even though there was an appreciation that the exact site of deformity needed to be identified and corrected, this was difficult to achieve without modern imaging modalities [59]. Even with the advent of radiography, imaging was often restricted to short knee films without regard to the overall axis of the limb or location of the deformity [4, 17, 47]. The use of long-leg radiographic films revolutionised the assessment of pre-operative deformity and post-operative correction [38]. Miniaci et al. [70] published their method of pre-operative planning using long-leg weight-bearing films in addition to varus and valgus stress tests. By plotting the planned medial corticoperiosteal hinge position of the tibial osteotomy along with the desired correction of the mechanical axis at the knee, as defined by Fujisawa et al. [31], they were able to define the corrective angle required (Fig. 12). Using trigonometric data produced by Hernigou et al. [40], this angle could be converted into the required osteotomy gap, in mm at the lateral cortex.

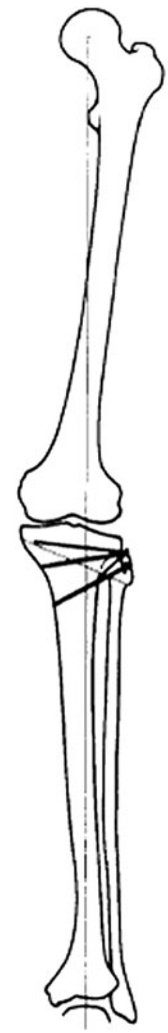

Fig. 12 The Miniaci technique of determination of angular correction using long-leg films. Reprinted with permission from Elsevier [70]

This led to further work by Dugdale et al. [28] who produced an algorithm to evaluate the tibial wedge size required

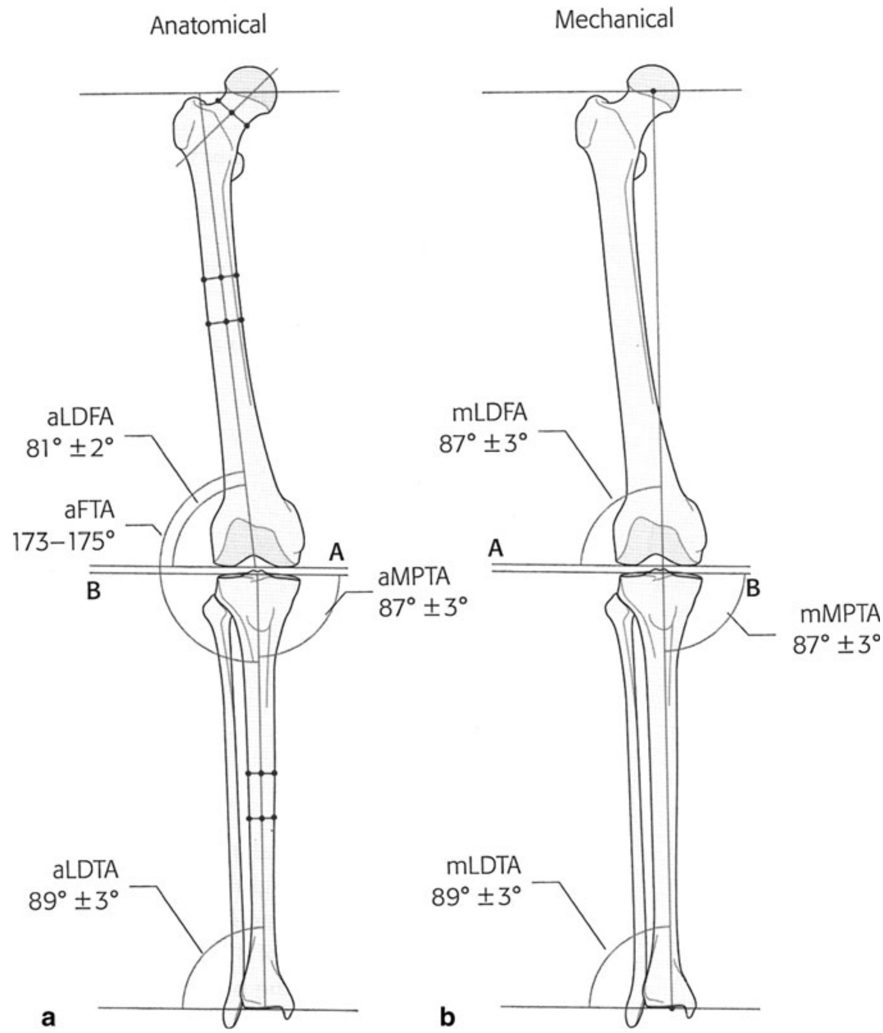

Fig. 13 Physiological axes of the leg. Reprinted with permission from AO Foundation[57]. *A* tangent to the femoral condyles, *B* Tangent to the tibial plateau, *a/mFTA* anatomical/mechanical femorotibial angle, *a/mLDFA* anatomical/mechanical lateral distal femoral angle, *a/mMPTA* anatomical/mechanical medial proximal tibial angle, *a/mLDTA* anatomical/mechanical lateral distal tibial angle

for optimal angular restoration, based on calculations from standing long-leg radiographs and incorporating the corrective angles utilised by other studies. Noyes et al. [79] defined the 3-triangle method to correct the axial alignment and tibial slope in opening-wedge HTO, allowing the calculation of the size of the gap required from the angles measured.

Considerable progress was made by the work of Dror Paley in Baltimore, USA, who defined the Centre of Rotation of Angulation (CORA) which when applied with respect to the mechanical axis of the limb, allows accurate identification of the site, magnitude and direction of correction required [85] (Fig. 13). Doctrine has dictated that a varus deformity was corrected in the proximal tibia and a valgus deformity corrected in the distal femur without any reference to the true site of deformity. Although application of Paley's concept of CORA to identify the source of the deformity sometimes contradicts this, failure to follow these principles can lead to correction of the wrong bone, resulting in the creation of a new deformity in the form of joint line obliquity, which is associated with early failure.

Table 4 Results of HTO deteriorate with reducing metaphyseal tibia vara

Tibial bone metaphyseal axis (degrees)	Clinical success rate of HTO (%)
<0	36
0–2	56
2–5	71
>5	83

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By applying Paley's principles, Babis et al. [7] performed corrective double-osteotomy in both the tibia and the femur for complex deformities with some excellent outcomes. The recognition of metaphyseal tibia vara is accepted as key to the successful outcome of HTO, as highlighted by Bonnin et al. [14] and has a direct effect on outcome and longevity (Table 4).

By considering these principles and applying them to long-leg films in combination with digital radiography and computer software, digital planning is now straightforward and highly reproducible. There is considerable overlap in the planning techniques used for correcting post-traumatic deformities, and progress in this field has owed much to the work of Prof René Marti [64], from the Netherlands. More recent techniques of computer-aided navigation with CT-based pre-operative planning and guidance systems are proving successful in increasing accuracy and precision of correction, although the superiority of these techniques over the longer term has yet to be assessed [9, 35].

The role of distal femoral osteotomy

Valgus knee deformity, as a consequence of developmental, traumatic or degenerative cause, is much rarer than varus [66]. Although initial reports suggested HTO was successful at relieving pain associated with varus gonarthrosis, subsequent data suggest HTO should be limited only to the painful arthritic valgus knee [24]. The inherent valgus femorotibial articulation limits the correction of a tibial varus osteotomy to approximately 12 degrees—any greater and joint line obliquity leads to increased shear forces, resulting in medial femoral subluxation upon the tibia during gait [103]. A major valgus knee deformity is often associated with a joint line that slopes superolaterally, which cannot be corrected unless the osteotomy is performed proximal to the knee joint. Furthermore, the anatomical alignment of the femur limits the ability of a varus HTO to transfer load medially on the knee, and varus HTO in the valgus knee shifts weight bearing not just medially, but also to the lateral portion of the intercondylar region, thus preventing complete correction [3]. Consequently, in a knee with valgus deformity (greater than 10–12 degrees of valgus) and lateral degeneration, a distal femoral osteotomy is usually indicated [22, 24, 103]. Because the vast majority of osteotomies about the knee are now HTOs, this review concentrates on the principles and outcomes of the latter.

Modern early years (1940–2000)

Significant advances included

- Transfer of techniques to the treatment of osteoarthritis
- Development of secure fixation to maintain correction, even in opening-wedge techniques
- Identification of ideal corrective angle for longevity of function
- Appreciation of requirement to consider whole leg axis for accurate correction
- Development of pre-operative planning

Overall, successful HTO survival during this period is

- 90.2 % at 5 years
- 77.5 % at 10 years
- 71.3 % at 15 years

Modern later years (2000–present)

Within the last decade, the benefits of open-wedge HTO have been further exploited by an evolution of internal fixation devices, which have also allowed concomitant soft-tissue reconstructive procedures [8]. This technique dispensed with the requirement for fibular osteotomy, tibial shortening and displacement of extensor musculature and had a further advantage of a near-midline incision that could easily be converted to a TKR in future (although modern techniques use a small oblique incision along with a separate distal incision) [33, 68, 69, 106, 113]. The popularity of MOW osteotomy was limited for a long time by the need to fill the osteotomy site with bone graft to prevent non-union or progressive collapse and hardware failure. Autologous iliac crest bone graft could be harvested, but this carried significant donor-site morbidity. Bone graft substitutes were proposed to fill the osteotomy, but initial attempts using wedges of bone cement gained little support [98]. By the 1990s, the Puddu plate was developed which incorporated a small spacer 'tooth' to provide additional stability within the osteotomy gap (Fig. 14). A recent study comparing the Puddu plate with external fixation in MOW HTO found an equivalent improvement in post-operative function and satisfaction scores at a mean of 3 years [69]. However, a further retrospective study examining failures in 49 MOW HTOs secured with the Puddu I osteotomy plate showed concerning outcomes, with only 63 % achieving radiological union at 1 year [76]. The authors record a 45.8 %

Fig. 14 The Puddu plate incorporates a small spacer tooth to enhance stability in opening-wedge HTO. Reprinted with permission of SAGE publications [26]

complication rate, including hardware failure, fracture and one infection in their series, and they conclude that the OW HTO is a technically demanding procedure with some pitfalls, particularly in large opening wedges. Similar results were described for MOW HTOs secured with the 'position' HTO plate, which lost correction in 6 %, with an overall complication rate of 34 % in one recent study [100]. The authors conclude that despite improvements in functional, subjective and objective outcome scores, this plate was not successful without additional augmentation.

In response to these reports, several authors have augmented fixation in MOW osteotomies using allograft or biomaterials to enhance osteogenesis without causing donor-site morbidity due to autogenous bone harvest. Yacobucci et al. [118] reported an average time to union of 12.1 weeks, with a non-union rate of 4 %, using a corticocancellous proximal tibial allograft to augment Puddu plate fixation in MOW HTOs. Saragaglia et al. [98] reported on outcomes of MOW HTOs performed in 124 patients using an AO T-plate augmented with a Biosorb beta-tricalcium phosphate (β-TCP) wedge at a mean follow-up of 10.4 years. Overall osteotomy survival at 10 years was 74 %; however, there were seven cases (5.6 %) of delayed union. A study comparing the accuracy of correction 1 year following LCW osteotomy or MOW osteotomy using the Puddu plate with ipsilateral iliac crest bone graft showed the former group achieved more accurate correction with less deviation from a 4 degree valgus overcorrection than the medial opening-wedge technique [18]. Despite this, there was no difference in pain or functional scores between the groups.

In order to improve fixation in MOW techniques, specific locking compression plates (such as the TomoFix device) have also been developed, borne from AO principles of trauma osteosynthesis surgery, and these give greater success than earlier MOW devices, without the need for bone substitution [88, 120]. The TomoFix plate was evaluated in MOW HTOs after 2 and 3 years, without additional bone substitution, and two-thirds of patients had good or excellent outcomes [77, 78]. Of 43 cases, just one resulted in non-union, and although patients had not functionally improved by 6 months following the osteotomy, this improved dramatically subsequently and by the 3-year clinical outcome was not significantly compromised, even in partial-thickness lateral cartilage defects. Local discomfort associated with the implant was a disadvantage in 40.6 % [78]. A further study to evaluate early full weight bearing at 2 weeks following MOW HTO using the TomoFix plate augmented with β-TCP bone wedges found no cases of non-union or implant failure in 57 cases [109]. The authors found enduring correction at a mean follow-up of 3.3 years. In addition, mean American Knee Society scores improved significantly from 50.9 to 91.7, with mean function scores improving from 59.3 to 94.1. Zaki et al. reported on their series of 50 MOW HTOs secured with TomoFix device, using no augmentation material [120]. Patients were allowed to weight bear as tolerated immediately following surgery, and at a mean of 5 years, the mean Oxford, KSS and Functional scores had all significantly improved (from 48 to 22, from 38 to 82 and from 35 to 75, respectively). Only one patient required revision to TKR during this period, resulting in a survival of 98 % at 5 years. These reports show that these fixation methods can achieve immediate stability, enduring deformity correction and good outcomes without the need for supplementary bone graft or its substitutes, at least into the medium term.

A multicentre questionnaire study of 182 OW HTOs, performed with various fixation devices and augmentation methods, found an overall non-union rate of just 1.6 %, with delayed union in 6.6 % [113]. These rates compare favourably with respective rates of delayed or non-union of 8.5 and 0.5–5.7 % observed with traditional CW HTOs [75].

Concerns over the potential for increased non-union in non-augmented opening-wedge osteotomy prompted a recent retrospective study to investigate the risk factors with an influence on the rate of healing in MOW HTO with TomoFix fixation [67]. A comparison with LCW techniques revealed these to have non-union rates between 0 and 5.7 % [67, 75, 105], compared to the study's finding of non-union in 5.4 % of MOW HTOs. Of the 10 non-unions, half were current smokers and a further two were former smokers, compared to 23.3 % smokers in the population with an unproblematic consolidation. Furthermore, five of the non-unions occurred in obese patients. A further complication that may lead to non-union is fracture of the lateral cortex, which was encountered in 60 % of patients who went on to develop a non-union, compared to just 26.3 % of those that healed without complication. In the authors' experience, though, this can usually be avoided with prudent technique. Several studies have failed to identify a significant difference in overall outcomes and survivorship following opening- or closing-wedge osteotomy, although few are prospective in design [12, 18, 32, 99]. Some authors obtain good union by placing the osteotomy distal to the tibial tubercle to mitigate the risk of patella baja [102]. In their study, Shim et al. recorded a 97 % union at 3 months, with universal improvements of scores at a mean of 3 years following MOW HTO secured by a calibrated plate.

A recent meta-analysis of clinical and radiological outcomes of opening- or closing-wedged HTO in the treatment of isolated medial compartment OA found no difference in the incidence of infection, thromboembolism, peroneal nerve palsy, non-union or revision to knee arthroplasty [104]. There was a significantly greater posterior tibial slope and mean angle of correction, reduced patellar height and hip–knee–ankle angle following OW HTO, although no significant difference was found for any clinical outcome.

Modern later years (2000–present)
Resurgence in opening-wedge HTO
Development of fixed angular stable plates
Development of early rehabilitation protocols to reduce stiffness
Introduction of CT and computer-based navigation techniques
Osteotomy on its own or with concomitant soft tissue and/or articular cartilage procedures for ligament as well as degenerative problems

Conclusions

The principles of orthopaedic surgery when applied to the knee allow replacement, fusion or realignment. The practice of osteotomy has been in existence for over two millennia and allows a return of function whilst conserving the native joint. This article summarises the evolution of the practice of osteotomy around the knee, highlighting the important changes and contributions made by surgeons throughout the world. Up until the mid-twentieth century and prior to arthroplasty, osteotomy was the favoured choice for the treatment of deformity and degenerative disease. In this paper, we have identified three distinct periods (historical, modern early and modern later years) and we have tracked the evolution not only of the surgical procedure, but also outcomes and their variability. There are several limitations to our study: Despite a large number of trials and outcome analyses for HTO and DFO, techniques, indications, methods of patient evaluation and their expectations have all evolved over the years, making accurate comparison of results challenging. Furthermore, there exist many anecdotal reports and case series giving rise to techniques which have become enshrined in surgical practice with little further development, in essence bypassing the rigours of modern scientific scrutiny. Early outcome data seldom included validated scoring tools, consistent operative technique or a standardised post-operative programme. However, there is much to learn from a review of these papers.

With accurate planning, modern surgical technique and rigid fixation, we now have a reproducible operative protocol which provides rapid rehabilitation. Longer-term outcomes can now be studied, and both indications and prognosis further refined. More recent studies have shown similar results in opening- and closing-wedge HTOs when performed skilfully with modern fixation techniques and adequate angular correction. It is accepted that the key to successful knee function following osteotomy is the selection of osteotomy site, position and size, giving an appropriate alignment which avoids joint line obliquity or the creation of a new deformity. Once this is established, further reconstructive procedures can be utilised for augmentation.

Although no consensus exists regarding optimal angle of correction, there is a school of thought that the alignment should be tailored to the individual and the particular disease process, so that for the unstable knee, a neutral alignment may be more appropriate than overcorrecting, which would be required in a degenerate knee (Werner Müller, *personal communication*). Whether "neutral" alignment should be based on notional anatomical perfection or the patient's own anatomy still has to be decided though historically the former has been favoured.

In our experience, many patients present with knee pain late in the process of osteoarthritic change. Although osteotomy would ideally be carried out as a prophylactic measure to prevent progression of deformity and pathology in young active individuals at an early stage in the disease process, patients with more advanced disease still do well following osteotomy. This allows for the avoidance of knee arthroplasty which should be postponed until the patient is older and less active.

Due to the technical demands of both planning and executing the procedure and surgeons' familiarity with the technique of knee arthroplasty, the frequency of tibial osteotomy for the treatment of OA has decreased internationally over the last three decades in line with the increase in knee replacement surgery [37, 54, 116, 117]. However, recent studies have shown that even demanding sporting activities can be maintained following HTO [82, 97]. We therefore conclude from our extensive literature review, coupled with considerable first-hand clinical experience, that by addressing the risk factors for early deterioration of osteoarthritis of the knee—including age, gender and the mechanical axis—sound long-term results can be obtained by osteotomy, and the continued reluctance to consider arthroplasty in the younger, active patient with unicompartmental arthritis can be justified.

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