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Current Concepts in Double-Level Osteotomies around the Knee

Conceptos actuales en osteotomías en doble nivel alrededor de la rodilla

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Abstract

With single-level osteotomy, correction of the limb axis in patients with combined femoral and tibial deformities can be achieved. This correction, however, will generate a pathological alteration in the joint line oblicuity, leading to ligament elongation, instability, joint degeneration and, ultimately, it will compromise the longevity and functional results of the correction. By analyzing the most recent literature, we can conclude that there is a significant number of patients who require a combined procedure to achieve an optimal biomechanical goal. The purpose of a double-level osteotomy around the knee is to restore normal anatomy, unload the affected compartment, normalize the mechanical angles and the orientation of the joint line. Physiological axes can be reestablished by means of a thorough preoperative analysis, observing the biomechanical principles and stable fixation with locked plates. It is a demanding procedure with increasing indications, which has progressively been established in clinical and biomechanical studies as a justified treatment alternative for the management of severe deformities around the knee.

Keywords
► Mikulicz line
► joint line obliquity
► double-level osteotomy
► distal femoral osteotomy
► high tibial osteotomy
► osteotomy around the knee

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Resumen

Con la osteotomía en un solo nivel, se puede lograr la corrección del eje de la extremidad en pacientes con deformidades combinadas femoral y tibial, pero de forma simultánea generará una alteración patológica en la oblicuidad de la interlínea articular, lo que conducirá a elongación ligamentaria, inestabilidad, degeneración articular y, en última instancia, comprometerá su sobrevida y los resultados funcionales. En virtud del análisis de la literatura más reciente, podemos concluir que existe un número significativo de pacientes que requieren de un procedimiento combinado para lograr un objetivo biomecánico óptimo. La finalidad de una osteotomía en doble nivel alrededor de la rodilla consiste en restablecer la anatomía normal, descargar el compartimiento afectado, normalizar los ángulos mecánicos y la orientación de la interlínea articular. Los ejes fisiológicos pueden restablecerse a través de un análisis preoperatorio exhaustivo, respetando principios biomecánicos y fijación estable con placas bloqueadas. Es un procedimiento demandante y con indicaciones en evolución, que progresivamente se ha instaurado como una alternativa de tratamiento justificada en estudios clínicos y biomecánicos para el manejo de deformidades severas alrededor de la rodilla.

Palabras Clave

- ► línea de Mikulicz
- ► oblicuidad de la interlínea articular
- ► osteotomía en doble nivel
- ► osteotomía femoral distal
- ► osteotomía tibial proximal
- ► osteotomía alrededor de la rodilla

Introduction

Alignment is the most critical hierarchical factor in the evaluation of ligamentous, meniscal, and cartilage injuries for joint preservation surgery.[1] Unicompartmental overload results in progressive pain and several grades of chondral damage; it is an independent risk factor for the development and progression of osteoarthritis.[2] An osteotomy around the knee may correct the joint biomechanics and have powerful effects over the local biology.[3–10] This explains why an isolated procedure may be sufficient to relieve the symptoms from chondral injuries, meniscal insufficiency, and chronic ligamentous injuries. The progressive dissemination of the mechanobiological concept[1,11] (which makes the biological outcomes of a joint intervention contingent on the adequate correction of biomechanical factors) and the technological improvements in fixation devices and techniques led to a boom in its indication. A double-level osteotomy (DLO) has increasing relevance in such a context because of its clinical and biomechanical justification. A DLO is a one-time osteotomy to correct deformities in the distal femur and proximal tibia. Its application is based on the need to preserve a physiological joint line obliquity (JLO) without generating new deformities. The present study provides a detailed description of the highlights of the procedure in the tibiofemoral joint and the coronal plane.

Biomechanical Principles in the Planning for Coronal Deformity

The systematic analysis of the deformity according to Paley's criteria[12,13] enables the identification of the affected bone segment (►**Table 1**).

An osteotomy study group[14] has recently proposed a simple formula to determine the value to subtract from the planned coronal axis correction and avoid an excess resulting from the variations in the joint line convergence angle (JLCA): [planned corrected angle] – [(JLCA – 2)/2]. On the other hand, if the preoperative JLCA is $\leq 6°$, a conventional osteotomy can correct an intra-articular deformity to acceptable values (JLCA $\leq 5°$).[15] If a satisfactory extra-articular correction of a combined (intra- and extra-articular) deformity is not feasible, we suggest evaluating the option of an intra-articular osteotomy as described by Chiba[16–19] on a case-by-case basis. This is especially true in cases of osteoarthritis with a Kellgren-Lawrence (KL) classification ≤ 3 as a consequence of tibial pagoda deformities (in which there is an excessive change in the coronal inclination of the articular surface of the tibial plateau), such as in Blount disease, posttraumatic defects and vicious consolidations. However, we recommend unicompartmental prosthetic surgery for severe monocompartmental osteoarthritis (bone on bone contact). This procedure may be accompanied by an osteotomy to correct the axis in cases of residual metaphyseal misalignment,[20] because the overloads will ultimately affect the survival of the implant.[21]

There are several proposals to correct the Mikulicz line and normalize the mechanical tibiofemoral axis.[3,22–24] Nonetheless, a consensual approach remains a controversial issue. In varus alignment, Feucht et al.[25] proposed a personalized approach to translate the Mikulicz line from 50% to 65% of the proximal tibial joint surface depending on the reason for axis correction (increasing osteoarthritis severity and treatment of chondral, meniscal or chronic ligamentous injuries) (►**Figure 1**). Hohloch et al.[26] confirmed this proposal in a clinical setting, and concluded that patients with KL-1 and -2 osteoarthritis benefit from a correction of 55% of the tibial joint width, whereas KL-3 subjects require a 60% correction. No clinical cases could confirm the proposed 65% correction for KL 4,[25] in which an indication for osteotomy is more questionable. Bonnin and Chambat[27] described the tibial bone varus angle (TBVA), defining values $> 5°$ as abnormal and implying a metaphyseal deformity. An osteotomy is

Table 1 Systematic analysis of a long leg standing radiograph according to Paley's criteria[12,13]

Angles and axes	Definitions	Normal values	Meaning of the altered values
Mechanical tibiofemoral angle	Angle between the femoral mechanical axis (a line drawn from the center of the femoral head to the center of the femoral groove) and the tibial mechanical axis (a line drawn from the center of the tibial spines to the center of the ankle)	$0° \pm 3°$	Coronal deformity in varum or valgum
Weight-bearing axis or Mikulicz line	Line drawn from the center of the femoral head to the center of the ankle	It must intersect the tibia on a surface between both tibial spines	Varum: the line is > 15 mm medial to the center of the knee; valgum: The line is > 10 mm lateral to the center of the knee
Mechanical lateral distal femoral angle	Lateral angle formed by a line tangent to the femoral condyles and the femoral mechanical axis	85°–90° (average: 87°)	Distal femoral metaphyseal deformity
Mechanical medial proximal tibial angle	Medial angle formed by a line tangent to the joint surface of the tibial plateaux and the tibial mechanical axis	85°–90° (average: 87°)	Proximal tibial metaphyseal deformity
Joint line convergence angle	Angle connecting lines tangent to femoral and tibial joint surfaces	$0° \pm 2°$	Intra-articular deformity or chronic ligament injury

curative (deformity correction and joint line obliquity normalization) in cases with abnormal TBVA alone, with a success rate > 90% at a 10-year follow-up.[27,28] Since this value has reportedly low interobserver correlation,[29,30] an abnormal TBVA must be equivalent to a mechanical medial proximal tibial angle (mMPTA) < 85°.

In contrast, the literature is scarce on the goal of a valgus alignment correction. According to expert recommendation,[31] the desired correction of the Mikulicz line is neutral in KL-1 and -2 osteoarthritides (traversing 50% of the tibial articular surface) and just medially to the medial tibial spine in the most severe cases of KL-3 and -4 (equivalent to 45% of the tibial articular surface) (►**Figure 1**). The best evidence comes from Shivji et al.,[32] who clinically confirmed a survival rate of 89% at a 10-year follow-up after varus femoral osteotomy for KL-2 to -4 osteoarthritis. Their goal was to correct the Mikulicz line in 45% of the tibial joint surface and customize it to maintain a mechanical lateral distal femoral angle (mLDFA) ± 3° within the normal range.

Biomechanical Justification of the Double-Level Concept

The JLO is the angle between a line parallel to the ground and a line tangent to the proximal tibial articular surface. Its normal value has been calculated in clinical[33–36] and biomechanical[37,38] studies as $0° \pm 4°$. Its lateral tilt (valgum) generates a positive value, and a medial tilt (varum) results in a negative value. The distance between the centers of both hips is greater than the space between the centers of both knees and ankles. Therefore, the Mikulicz line runs slightly obliquely from proximal to distal and lateral to medial at approximately 3° from the midline, leading to a JLO with a 3° varus. During the stance phase of walking, the joint line is parallel to the ground, resulting in a physiological neutralization of the varus deformity and optimal load distribution.[13] Any frontal plane correction must consider this biomechanical pattern. The pathological inclination of the joint line generates shearing forces that increase the stress over collateral ligament structures and cause progressive joint cartilage damage.[37] Park et al.[39] developed a predictive model for postosteotomy joint line orientation, and concluded that the obliquity increases approximately 1° for every 2° increase in the correction angle. At the same time, it may be possible to predict the postoperative JLO as the sum of the preoperative JLO and the adduction angle of the affected lower extremity; this angle is formed by the native Mikulicz line and the one planned for the resolution of the case.[40] The adverse effects of an oblique joint line warrant a DLO.

Advances in knowledge improved the understanding of joint geometry and led to a paradigm shift when planning osteotomies. Eberbach et al.[41] analyzed 420 long leg standing radiographs of patients with valgus alignment (mechanical tibiofemoral angle [mTFA] ≥ 4°), and their study revealed that axis and JLO correction with a tolerance of $0° \pm 4°$ required a tibial osteotomy in 55.2% of cases, a DLO in 25.2%, and a femoral osteotomy in 19.5% of the subjects. In contrast, Feucht et al.[42] assessed 303 long leg standing radiographs of patients with varus alignment (mTFA ≥ 3°), and the maximum corrected axis tolerance had a mMPTA ≤ 95° and mLDFA ≥ 85°. These values were based on previous studies,[37,43–45] and were established to avoid JLO alterations and tibiofemoral subluxation.[37,43–45] The article[42] revealed that, in simulated osteotomies, the correction site was tibial in 57%, double-level in 33%, and femoral alone in 8% of the cases. In addition, it confirmed that DLOs are significantly more frequent in knees with severe varus (mTFA ≥ 9°), which is consistent with previous studies.[33,34,46,47]

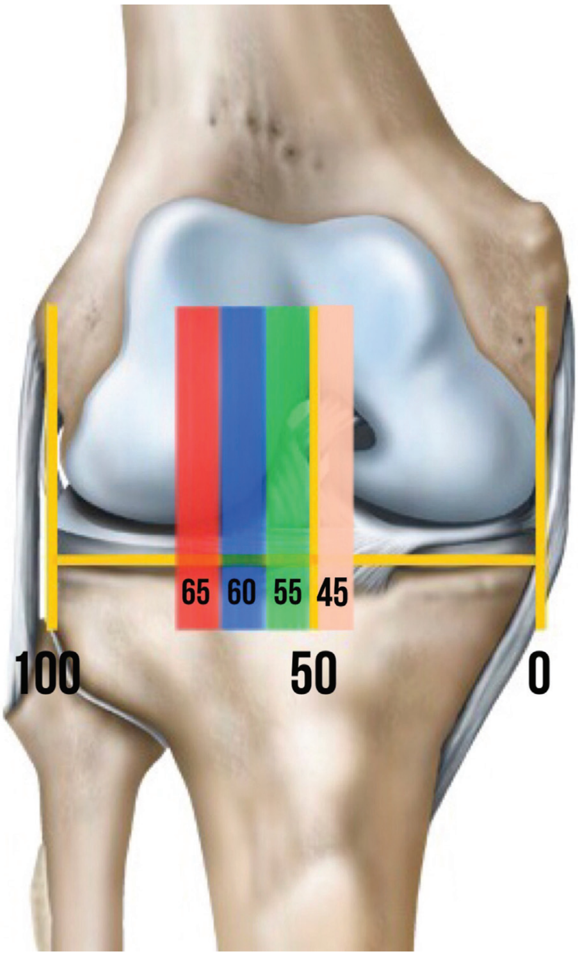

Fig. 1 Weight-bearing axis distribution across the tibial joint surface. Conventionally, this is performed from the medial (0%) to the lateral (100%) ends of the tibial joint surface. When planning an osteotomy, move the Mikulicz line (ML) to one of the colored areas depending on the type of coronal correction and the Kellgren-Lawrence (KL) grade of unicompartmental osteoarthritis. In varus, we recommend moving the ML to the green area (55%) in KL type-1 and -2 lesions, to the blue area (60%) in KL type-3 injuries, and to red area (65%) in KL type-4 lesions. In valgus, the recommendation is to move the ML to the center of the knee (50%) in KL type-1 and -2 injuries, and to the pink area (45%) in KL type-3 and -4 lesions.

Clinical Assessment

The history may reveal symptoms of chronic posterolateral or posteromedial corner instability. Patients with severe deformities usually present a latent history of malalignment and progressive ligamentous laxity generating a varus or valgus thrust[48,49] (►**Figure 2**).

Patient-specific variables (age, body mass index, workload, expectations, and motivations) are relevant prognostic indicators and influence selection. In addition, it is critical to know potential contraindications, such as smoking and the ability to adhere to a postoperative treatment.

The evaluation continues with the patient in recumbent position to document an acceptable joint range for the procedure (loss of extension < 15° and at least 90° of flexion) and analyze ligament stability. The examination must also consistently determine the presence of unicompartmental pain, which will be the main indication to proceed with the preoperative study in a DLO.

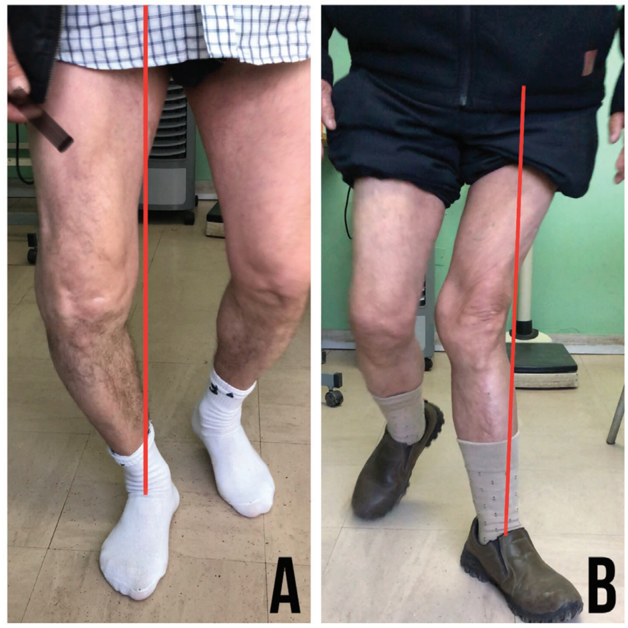

Fig. 2 Dynamic change of the mechanical axis (*red line*) during gait. (**A**) **Varus thrust.** The adductor moment increases during the stance phase of walking, which results in progressive elongation of the posterolateral corner and the central pivot, deteriorating the medial tibiofemoral cartilage. (**B**) **Valgus thrust.** The abductor moment increases during the stance phase of walking, which leads to progressive elongation of the posteromedial corner and the central pivot, deteriorating the lateral tibiofemoral cartilage.

Imaging Assessment

Comparative anteroposterior (AP) knee radiographs with weight-bearing assess the symmetry of the deformity. The Rosenberg projection (a posteroanterior radiograph with load and the knee flexed at 45°) is essential to determine the severity of joint impingement. In addition, it has a powerful predictive value in identifying the early stages of degenerative disease, influencing postoperative clinical outcomes.[50] Lateral and axial radiographs of the patella allow the evaluation of the patellofemoral joint in order to modulate the patellar height by means of the type of osteotomy. A long leg standing radiograph is a crucial imaging study because it enables a systematic analysis of the deformity. Magnetic resonance imaging (MRI) allows the evaluation of associated lesions and reveals areas of subchondral bone edema as a sign of overload, facilitating the surgical decision.[51]

Traditionally, a proper analysis requires long leg standing radiograph standardization (with the patellas centered on the femoral condyles regardless of the patient's natural posture, one-third overlap of the fibular head on the tibia, and pelvis leveling with enhancement in case of length discrepancies). The most relevant and comparable methods[53] for freehand preoperative planning of a femoral or tibial osteotomy have been reported by Miniaci et al.[52] and Dugdale et al.[22]

Today, special software does the preoperative planning for these injuries. They enable the modification of the desired correction parameters and simulate different osteotomy types on the screen. In addition, it is possible to test the effects of variations on biomechanical parameters before surgery with high precision.[54,55] As such, we can understand the reorientation of the mechanical tibiofemoral axis and its correlation with a JLO change. The foot positioning must remain plantigrade after the osteotomy simulation, so the measurements adjust to the real weight-bearing scenario.[56]

Indications

As a preoperative functional requirement, the pain level must enable the patient to have an active lifestyle.[57] We recommend DLO for patients younger than 60 years of age because there is no significant correlation between JLO and an objective functional evaluation of the knee after osteotomy in older subjects.[58] Any axis alteration in which the Mikulicz line does not contact the knee is highly suggestive of a DLO since it indicates a severe deformity (mTFA $\geq$ 9°). Optimal outcomes require that unicompartmental wear is lower than KL 3.[34,46,47,59] Subjects must present altered mLDFA and mMPTA or a JLO higher than 4° at the simulated one-level osteotomy.[33] This usually happens in cases with a planned opening or closing wedge $\geq$ 15 mm[37,57] (►**Figure 3**). Recently, Sohn et al.[60] postulated a predictive algorithm for DLO based solely on preoperative parameters to avoid the need for software simulation. In this algorithm, a JLO $\geq$ 3° and a JLCA $\geq$ 5° are a highly suggestive recommendation for a double-level correction.

Although there are different DLO combinations, we believe the best options for the correction of varus deformity are the lateral closing wedge distal femoral osteotomy and the medial open wedge high tibial osteotomy (►**Figure 4**). For valgus deformity, the best option is a medial closing wedge osteotomy at a femoral and tibial level. If possible, the opening wedge graft must come from the closing wedge of the adjacent segment. A medial closing wedge high tibial osteotomy for valgus management requires special consideration. We recommend repairing or tightening the superficial medial collateral ligament if any intraoperative clinical evidence indicates pathological medial laxity. The lack of a specific intervention results in medial instability in 25% of the subjects when starting to walk with full weight-bearing; 70% of these patients remained with instability at a 4.5-year follow-up.[61]

Surgical technique

Advances in surgical techniques with biplanar osteotomies and the development of compressive locking plates as an essential design concept improved early stability. In addition, since rotational control and consolidation increased, these are currently seen as fundamental improvements in osteotomy to manage such injuries.[31,62] Regardless of the patient selection criteria, the fundamental goal of a successful osteotomy around the knee is proper correction planning.

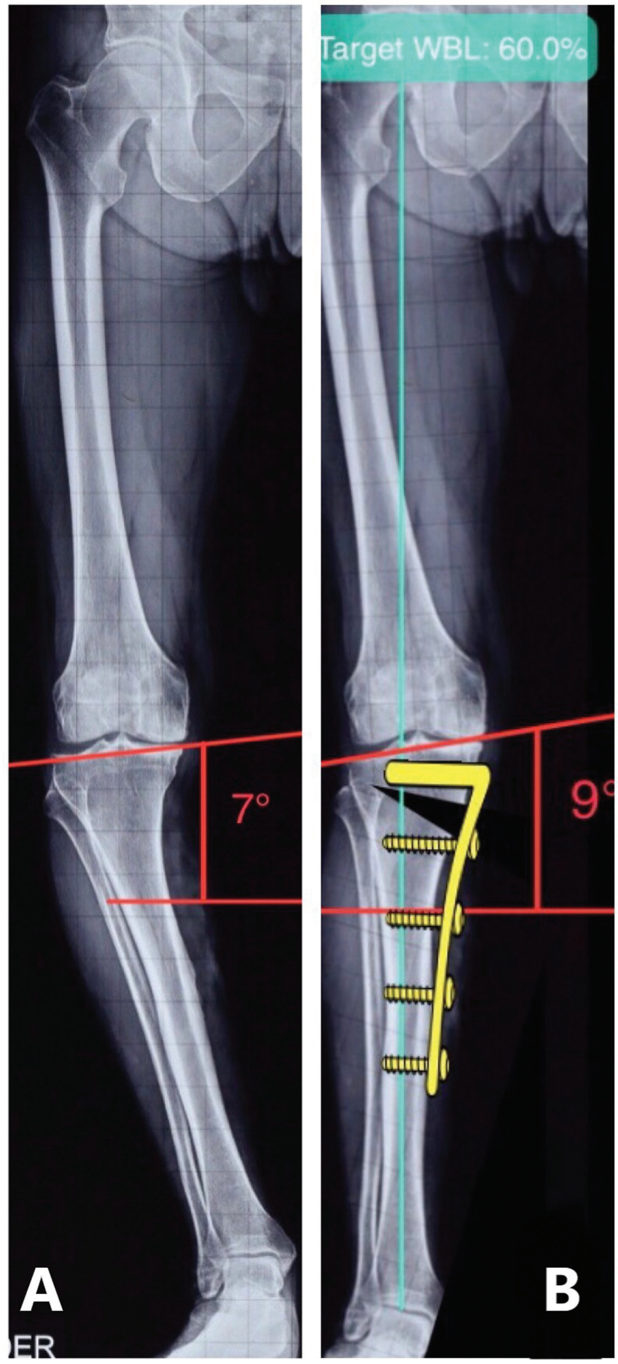

Fig. 3 Severe genu varum and implications of the traditional one-level correction. (**A**) A genu varum deformity with the following features: mechanical tibiofemoral angle: 16°; mechanical lateral distal femoral angle: 91°; mechanical medial proximal tibial angle (mMPTA): 80°; joint line convergence angle: 6°; and joint line obliquity (JLO): 7° (*red*). These features confirm a severe genu varum resulting from distal femoral, proximal tibial, and intra-articular components with a markedly pathological joint line. This case is an ideal indication for a double-level osteotomy. (**B**) Simulation of a traditional (one-level) osteotomy. A medial open wedge high tibial osteotomy of 20° aims to correct the Mikulicz line at 60% of the tibial joint surface due to the severity of the medial tibiofemoral osteoarthritis (Kellgren-Lawrence type 3). However, limb axis correction creates a severe secondary proximal tibial metaphyseal deformity (mMPTA = 100°) and increases the JLO to 9° (*red*). These changes compromise survival because of the shearing forces over the cartilage, the risk of hinge injury, and osteotomy consolidation.

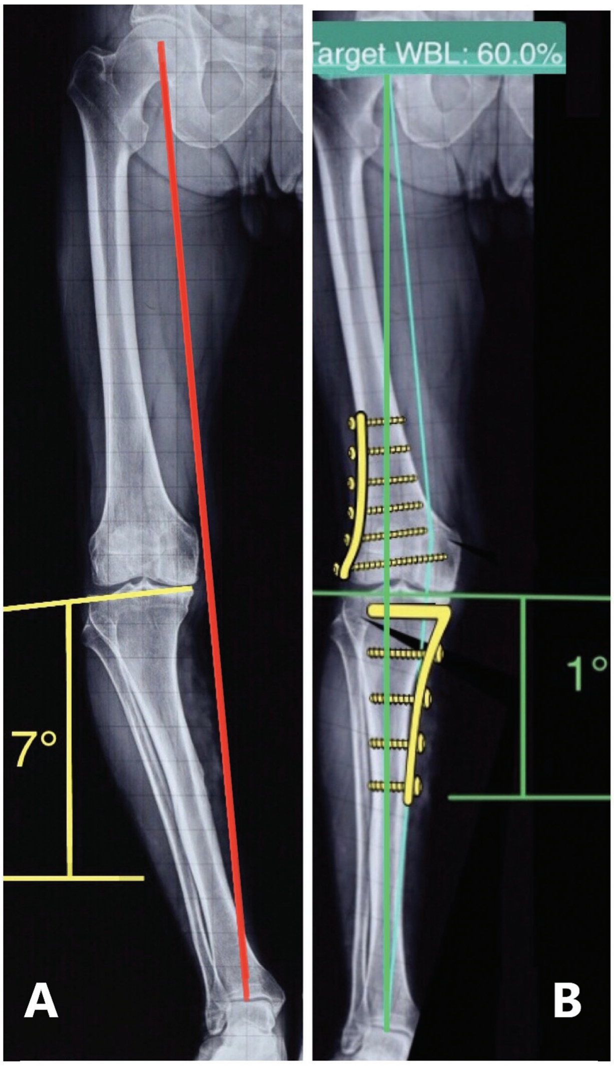

Fig. 4 Severe genu varum and double-level osteotomy. (**A**) This case is the same presented in ►**Figure 3**. Note that the Mikulicz line (*red*) does not contact the knee, which is a significant indication of a double-level procedure. In addition, the pathological joint line obliquity (JLO) of 7° (*yellow*) is critical for the indication. (**B**) Resolution with a double-level osteotomy with a 10° lateral closing wedge distal femoral osteotomy and a 10° medial open wedge high tibial osteotomy. The following are fundamental concepts for an optimal functional outcome: preoperative planning, simulation of the final JLO, locking plates, and biplanar osteotomy at both levels. Axis correction is proper, with a Mikulicz line crossing the joint surface in 60% (*green line*) and a physiological JLO of 1°.

Fig. 5 Patient positioning on the operating table for a double-level osteotomy. Patient in supine position. (**A**) The lateral thight support and the distal heel support fixate the knee in flexion for an adequate intra-articular inspection through arthroscopy. These supports reduce the risk of neurovascular injury during the procedure and enable a proper assessment of the lateral plane with an image intensifier. (**B**) The contralateral lower extremity requires a leg holder to move it away from the operative area, enabling proper access to the medial osteotomy and the image intensifier positioning in the anteroposterior and lateral planes. Based on our experience, we do not recommend the use of tourniquet because the procedure may take more than two hours.

Both undercorrection and overcorrection decrease procedural survival and result in poor functional outcomes. The systematic analysis of the deformity helps to recognize its magnitude, level, plane, and direction.

The patient is placed on a radiolucent operating table (►**Figure 5**). The use of a tourniquet should be avoided with meticulous hemostasis and the preoperative administration of tranexamic acid. The procedure can begin with arthroscopy to assess the tricompartmental cartilage and treat the intra-articular injury.

We recommend starting the DLO in the femur and performing a closing osteotomy at this level. This decision lowers the possibility of intraoperative correction after bone section. As such, if correction is required, an open wedge high tibial osteotomy enables a fine adjustment at that level. However, planning is based on a long leg standing radiograph of the patient and in particular conditions of ligamentous laxity (revealed by the JLCA). So, we agree with several authors[63-67] that adapting the planning during surgery can lead to errors only subject to objective assessment in a follow-up long leg standing radiograph performed under similar conditions. This is why we trust in adequate preoperative planning and software simulation regarding alignment and joint line during the procedure.

From a trigonometric point of view, the only required intraoperative analysis is the confirmation of the wedge size based on the length of the osteotomy, which is variable in each case depending on the bone dimensions of the patient (►**Figure 6**). This analysis can occur after positioning the wires that determine the wedge (►**Figures 7A** and **7B**). Next, we cross-reference this value on the trigonometric table of

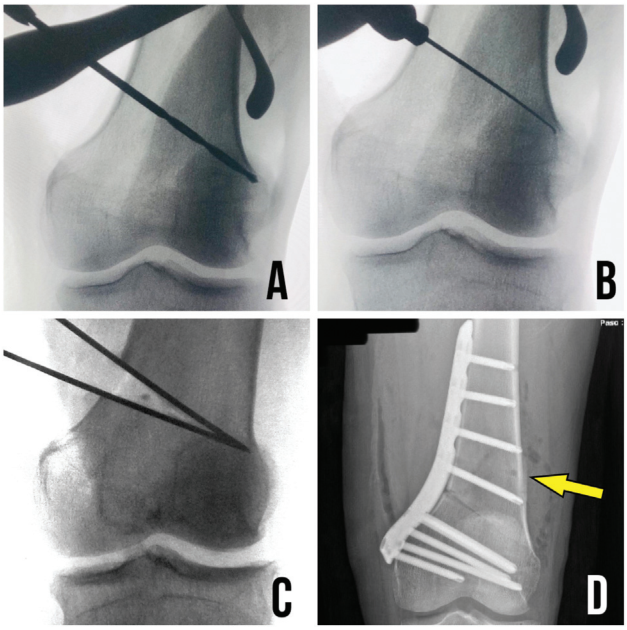

Fig. 6 Intraoperative tips for the proper management of an osteotomy (OTT). (**A**,**B**) The only trigonometric correction required during a femoral or tibial OTT is a refined measurement of OTT length and the transfer of this value (in millimeters) to the Hernigou[68,69] table (**table 2**). Thus, we avoid the simplication that indicates that 1 mm in the height of (an opening or closing) wedge is equivalent to 1°, which can lead to errors and undermine the degree of correction. (**C**) A closing wedge forming an isosceles triangle enables the coaptation of the osteotomized fragments. These fragments fit the cortices perfectly, preventing subsidence and an insufficient correction. The femoral hinge (in both lateral and medial OTTs) must be in the safety zone provided by the origin of the gastrocnemius muscle, at the shadow generated by the proximal end of the femoral condyle. (**D**) The definitive fixation construct for a locking plate must present locking screws alone. In addition, it must have a bicortical transition screw with a compressive effect on the metaphyseal fixation segment to ensure hinge stability. See the path of the *golden screw* (already removed) demarcated with a yellow arrow.

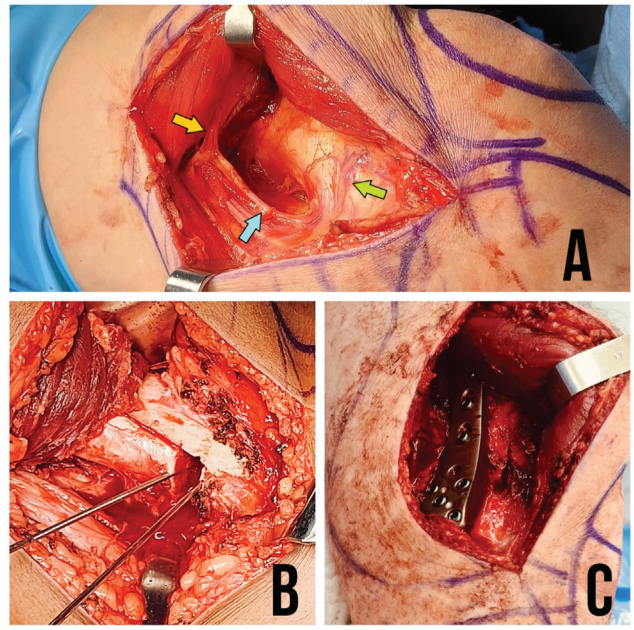

Fig. 7 Closing wedge distal femoral osteotomy. (**A**) The three sisters (*green arrow*) are a consistent vascular group composed of a transverse artery and two veins located at the lateral and medial distal femur, which enable the definition of the starting point of a transverse osteotomy. The image shows a subvastus medial approach and the local vascularization determined by the descending genicular artery (*light blue arrow*). This artery is a subsidiary of the superficial femoral artery, which sends a direct anterior muscular branch to the vastus medialis (*orange arrow*) and the terminal branches forming the three sisters (*green arrow*). Laterally, terminal anastomosis is generated through the lateral longitudinal artery, a subsidiary of the superior lateral genicular artery. (**B**) A biplanar femoral osteotomy. The approach is determined by two transverse sections generating the closing wedge and guided by the path of Kirchner wires, forming an isosceles triangle. In addition, an ascending cut in the anterior third of the femur enables rotational stability, increases the metaphyseal surface to improve consolidation, and reduces the bone volume removed. Moreover, it protects the patellofemoral joint by preventing an iatrogenic section through the femoral trochlea. (**C**) Definitive configuration of a locking plate at the distal femur.

the studies by Hernigou[68,69] to confirm the wedge size (in millimeters) based on our preoperative angular planning (►**Table 2**). This cross-reference prevents the consideration of 1° as 1 mm, which would decrease the precision, a key factor to a successful outcome.

The preferred technique for a distal femur osteotomy is the biplanar closing wedge,[31,70] which enables a wide angular correction, with more predictable consolidation[71] and increased rotation stability. In the sagittal plane, identify a consistent vascular group composed of a transverse artery and two accompanying veins, collectively known as the *three sisters* (►**Figure 7A**). These vessels occur on the medial and lateral aspects of the distal femur. Their disruption does not cause a loss of vascular supply due to supplementary collateral branches.[72] At this level, perform two incomplete transverse sections in the shape of an isosceles triangle in the posterior 3/4 of the femur to obtain a closing wedge with endogenous stability[73] and directed towards the hinge, which must be immediately proximal to the upper edge of the femoral condyle, 5 mm to 10 mm from the opposite cortex[31] (►**Figure 6C**). This prevents unstable hinge fractures because the origin of the gastrocnemius muscle provides coverage and the local bone density is good.[74,75] Next, perform a third ascending section in the coronal plane of the anterior 1/4 of the femur, covering a distance of 2 cm to 3 cm at an approximate proximal angle of 95°, parallel to the posterior cortical bone of the femur and with at least 10 mm in thickness (►**Figure 7B**). Biomechanical tests showed that a biplanar osteotomy is superior to the uniplanar section and distal femoral opening techniques.[76,77] The potential of consolidation increases because the wedge is smaller.[71] In addition, these procedures have a lower risk of damaging the joint surface of the trochlea. Finally, close the osteotomy gradually with plastic deformation of the cortical bone containing the hinge. Upon completion of the closing, the cortices of both bone segments must be in exact apposition to prevent subsidence and unwanted axis deviations.[73] Begin osteotomy fixation in the distal segment with locking screws. Next, place a bicortical *gold screw* due to its compressive effect over the hinge in the proximal portion of the

Table 2 Hernigou[68,69] table

Correction angle	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°
Osteotomy length												
50 mm	3	4	5	6	7	8	9	10	10	11	12	13
55 mm	4	5	6	7	8	9	10	10	11	12	13	14
60 mm	4	5	6	7	8	9	10	11	12	14	15	16
65 mm	5	6	7	8	9	10	11	12	14	15	16	17
70 mm	5	6	7	8	10	11	12	13	15	16	17	18
75 mm	5	6	8	9	10	12	13	14	16	17	18	20
80 mm	6	7	8	10	11	13	14	15	17	18	19	21

Note: The trigonometric conversion table determines the height of a wedge (either opening and closing, femoral or tibial) in millimeters according to the length of the transverse osteotomy measured intraoperatively and the correction angle planned for that level before surgery. It customizes the correction and results in the imaging outcomes planned before surgery. For instance, if an 8° medial open wedge high tibial osteotomy is planned for varus correction and the intraoperative length of the osteotomy is of 70 mm, a 10-mm opening wedge is required.

osteotomy. This screw must be in a divergent position to the trait and in the cortical combined hole to increase coaptation. In case of a hinge fracture, this screw increases the contact between bone surfaces by reducing the displacement. After completing the proximal osteotomy fixation with locking screws, replace the gold screw with an additional bicortical locking screw (►**Figures 6D** and **7C**). Finally, depending on the stability achieved, place a reduction cannulated screw at the hinge level, perpendicular to it.

Since the early 2000s, the medial open wedge high tibial osteotomy (MOWHTO) has become more popular than its lateral closing counterpart due to the introduction of locking plate systems and benefits such as a lower risk of peroneal nerve injury, lower levels of soft-tissue aggression, and the possibility of correction modulation (fine tuning of the opening).[78] From a technical point of view, we recommend a biplanar section to improve rotational stability[62] and consolidation[79] compared with a uniplanar osteotomy. The ascending component of the osteotomy must form a 110° angle with the horizontal section; in addition, it must be located posterior to the tibial tubercle and have 10 mm to 15 mm in thickness (►**Figure 8A**). The release of the superficial medial collateral ligament is mandatory to avoid a paradoxical increase in medial unicompartmental pressure.[80] This technique produces a proximal metaphyseal bone fragment with good size and excellent healing potential (the osteotomy is performed immediately above the pes anserinus insertion,[81] and it must go towards the hinge in a safety area extending from the proximal end [styloid process] to the circumferential line of the fibular head. This is known as "hit the hat", and it provides stability due to the attachment of capsuloligamentary structures[82] and the 10-mm distance from the lateral cortex) (►**Figure 8B**). If you want to maintain a native tibial slope, create a trapezoidal opening wedge (the anterior gap must be half of the posterior one due to the triangular shape of the tibia).[83] The plate must be as posterior as possible because the natural tendency is an anteromedial location, which increases the slope. Biomechanical studies[84,85] support the use of a 2-mm Kirschner wire at the hinge level to prevent fracture and improve stability during the opening process. In most MOWHTOs, the tibial tubercle remains attached to the distal fragment, lowering the patella. This also occurs in DLOs.[86]

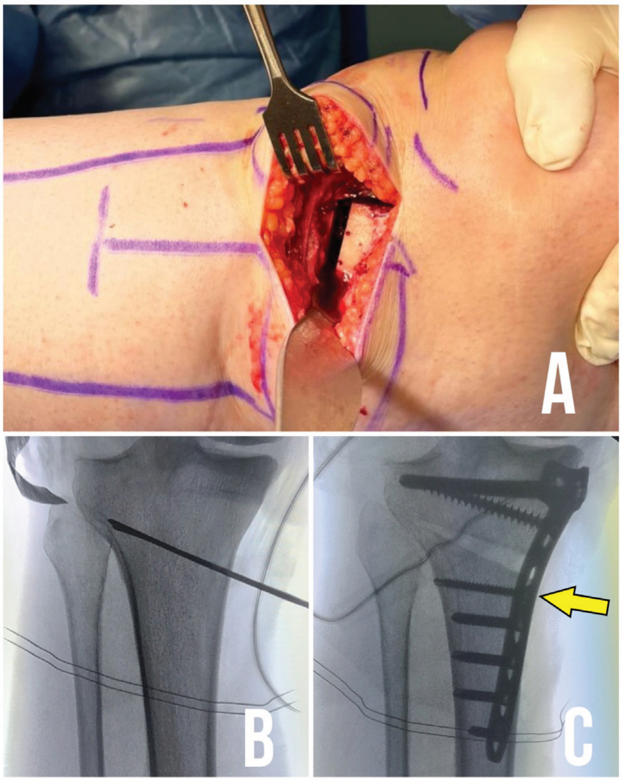

Fig. 8 Medial open wedge high tibial osteotomy. (**A**) Biplanar tibial osteotomy, which consists of a guided transverse cut through two parallel Kirchner wires and an ascending (as shown here) or descending retrotuberosity cut. Biplanar osteotomy enables the modulation of patellar height, provide rotational stability, and increase the metaphyseal surface, optimizing osteotomy consolidation. (**B**) The osteotomy hinge must be in the safety zone between the proximal end of the fibula and its proximal circumferential metaphyseal contour; this is known as "hitting the hat" of the fibula. (**C**) Configuration of a locking plate in the proximal tibia. See the *golden screw* for bicortical transition (*yellow arrow*), which compresses the hinge and ensures its stability during the procedure.

Therefore, in patients requiring openings greater than 10° and presenting patella baja (Caton Deschamps index < 0.8), a modification in the biplanar technique is needed, and the osteotomy in the coronal plane must be distal.[87–90] Descending retrotuberosity osteotomies require additional fixation with one or two 3.5-mm compressive screws in the AP direction to avoid a change in the proximal segment slope (before plate fixation) or tuberosity avulsion fractures due to the traction exerted by the patellar tendon over this segment. Osteotomy fixation follows the same principles as in the femur. Here, initially fix the proximal segment with locking screws and then place a *gold screw*. Complete the osteosynthesis using distal locking screws and replace the gold screw with a bicortical locking screw in the combined hole (►**Figure 8C**). Finally, depending on the outcome, place a small-fragment cannulated screw at the hinge level (intersecting the section plane) to increase its stability.[91] There is good evidence[92,93] that adding bone grafts or synthetic substitutes does not provide functional advantages or improve patient-reported outcomes. When using locking plates, we only recommend bone grafts in openings > 10 mm[92] or in special cases with combined risk factors for nonunion or loss of correction, such as smoking and obesity.[94]

Complications

Hinge fractures are less frequent than in traditional one-level osteotomies due to the distribution of the angular correction between the femur and tibia. These injuries usually result from improper techniques or excessive segment correction (> 12 mm).[95] They can compromise the axial and rotational rigidity of the construct and increase micromotion at the osteotomy level, disturbing the correction of the axis and consolidation. These fractures can be classified according to Takeuchi et al.[97] depending on their direction:[96,97] in line with the osteotomy (type 1), with metaphyseal extension (type 2), or with joint extension (type 3). Most cases are type-1 fractures, which do not require additional treatment. In type-2 and -3 lesions (especially those with > 2 mm coronal displacement),[98] we recommend protecting the hinge with a 3.5-mm locking plate.

The main constitutional risk factors affecting the consolidation of an osteotomy are smoking and obesity.[94,99] The nonunion rate is of 3.8% in femoral osteotomies,[100] and it ranges from 2.5%[95] to 3.2%[101] in tibial procedures.

Vascular injuries are infrequent (0.7%)[102] but devastating for the functional outcome. Bisicchia et al.[103] mapped the vascular structures at risk at both levels using computed tomography (CT) scans and cadaveric dissection. They concluded that the popliteal artery is at moderate risk of vascular injury in the femur and tibia when its average distance from the posterior cortex is of 11.6 mm and 9.6 mm respectively. Direct the saw at an angle lower than 30° in the axial plane to keep the section away from the fibular head, reducing the risk of injury at the tibial level.[104,105] Keeping the knee at 90° of flexion during osteotomy distances the artery from the posterior cortex.[104] The genicular arteries on the contralateral side are at risk of injury because it is impossible to view or protect them during the procedure, particularly in cases with hinge compromise. Klecker et al.[106] recommend an MRI scan of the anterior tibial artery because its aberrant trajectory is relatively common; instead of running behind the popliteus muscle, the artery is in close contact with the posterior cortical bone of the proximal tibia. This variant has a 2% prevalence, and it is a relative contraindication for the procedure. During an MOWHTO, Kley et al.[107] advocate the creation of a secondary viewing window located posterior to the medial collateral ligament to protect the posterior neurovascular structures.

Other complications[102] include superficial (1.6%) and deep (0.7%) wound infections, compartmental syndrome (0.7%), and deep vein thrombosis (0.3%).

Appropriate counseling is crucial; warn patients undergoing osteotomy that the need for plate removal after bone consolidation is frequent because of soft-tissue irritation (with rates > 50%), which affects the iliotibial band in the lateral distal femur, whereas the close contact with the subcutaneous cellular tissue accounts for the irritation at the medial and proximal tibia.[95]

Postoperative Care

Locking plates enable a safe and functional rehabilitation, including immediate mobilization and early partial weight-bearing of 15 kg to 20 kg (protected with 2 crutches) starting in the third week. In general, there is no need for mobility restriction and bracing. Pharmacological thromboprophylaxis is performed for 3 weeks. If the clinical and radiological findings are favorable, we allow full weight-bearing in the seventh week.[31,108] Recently, Hai et al.[109] described an accelerated protocol for early loading (from the third postoperative day) using parallel bars and visual feedback. This protocol would enable full loads in 1 month provided that the hinges are intact and a CT scan rules out fractures. Consolidation often occurs 3 to 6 months after surgery, when sports activities can be resumed.

Outcomes

The most critical prognostic factors to define the successful outcome of a DLO include the adequate treatment of the bone deformity both in terms of location and correction accuracy, as well as the postoperative joint line orientation (►**Figure 4**). Preserving the JLO within narrow margins (0° ± 4°) ensures an osteotomy survival of 96% at an average follow-up of 8 years.[33] Contemporary level-based studies estimate that the 5- and 10-year survival rates range from 87% to 99% and 66% to 84% for the proximal tibia and from 74% to 90% and 64% to 82% for the distal femur respectively.[110]

A recent study[111] has demonstrated the mechanobiological effect of a DLO. The rate of chondral repair was higher than 95% in the unloaded compartment (with no need for additional procedures) in an average follow-up period at the time of an arthroscopic second look of 17 ± 5 months. Moreover, the clinical evaluation scores improved significantly.[111]

From an activity point of view,[110–114] 85% of the patients undergoing an osteotomy around the knee resume their sports activity, usually those of low impact. A similar percentage resume work, often performing activities with similar or lower joint demand. The most significant prognostic factor to resume sports is continuous participation in them within the year before surgery; for work, the most important is being the breadwinner. Therefore, one of the most relevant factors for good outcomes is the patient's motivation. Most subjects can perform physical activities and work six months after surgery. If the patient cannot work, consider a potential progressive functional deterioration; in this case, ensure an intervention as early as possible.[113] A specific recent study[115] about this topic in DLO confirmed most of the aforementioned assertions.

Patient expectations regarding osteotomies are high in terms of work capacity, pain relief, and restoration of joint function. The natural course of osteoarthritis and the potential need for conversion to a knee prosthesis are underestimated. Therefore, discuss realistic expectations with the patient to improve satisfaction.[116]

Our Experience

Our team's experience is based on the concepts described in the present review. It corresponds to the period from 2019 to 2022, when we performed 52 osteotomies due to coronal deformity (70% in varus). The average age of the patients was 48 years, and 75% of the subjects were male. We performed a DLO in 27% of the total varus cases and in 13% of the total valgus cases. Twelve cases had a mean follow-up period shorter than 2 years (►**Figure 9**). Our short-term functional outcomes are promising and consistent with those published in the literature.[57]

Conclusions

A single-level osteotomy can correct the limb axis in patients with combined femoral and tibial deformities. However, it also causes a pathological alteration of the joint line, leading to ligamentous elongation, instability, and joint degeneration. Ultimately, these changes compromise survival and functional outcomes. The most recent literature states that a significant number of patients require a combined procedure to achieve an optimal biomechanical outcome.

A DLO around the knee restores the normal anatomy, unloads the affected compartment, normalizes the mechanical angles and the joint line orientation. Moreover, it restores the physiological axes through careful preoperative analysis, respecting biomechanical principles, and stable fixation with locking plates (►**Figure 10**). It is a demanding procedure with evolving indications. It has been established

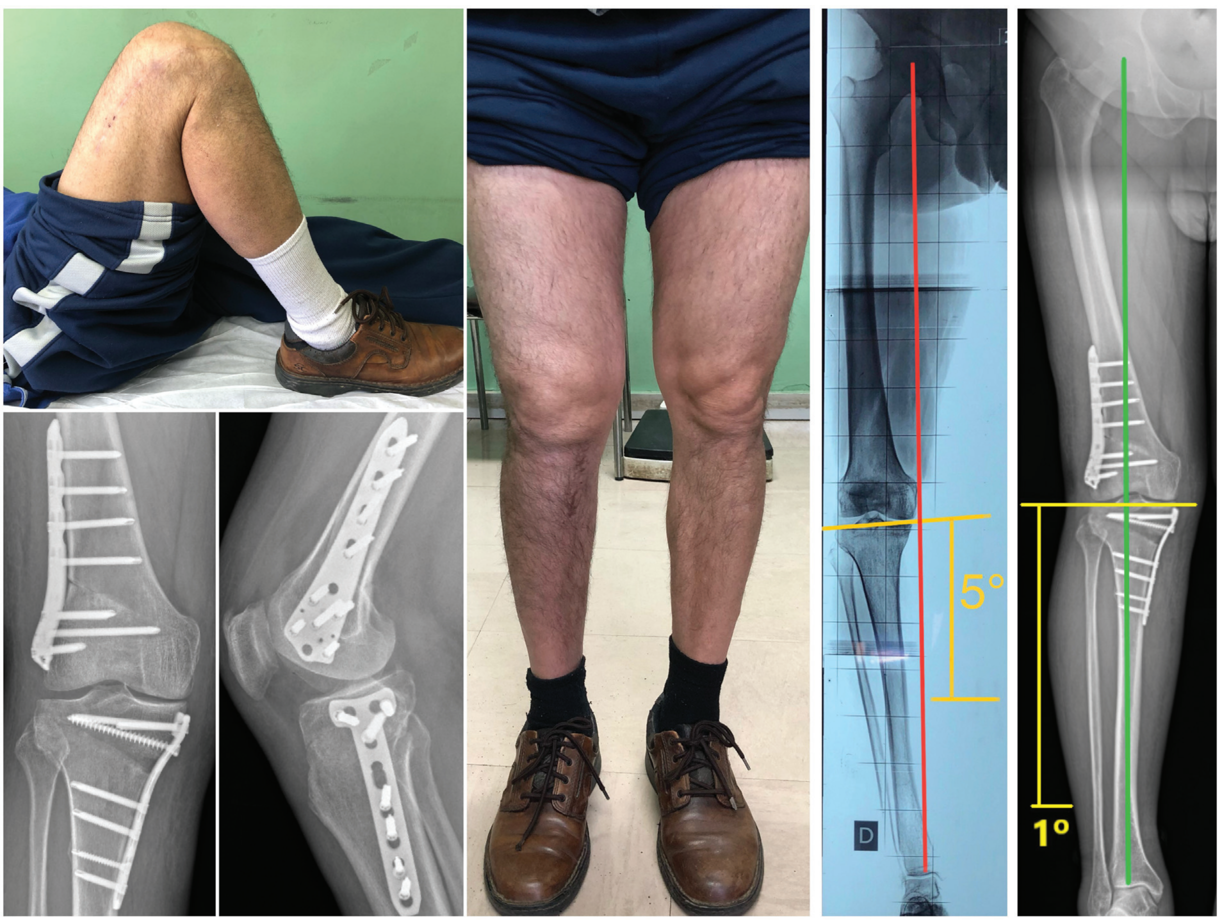

Fig. 9 Imaging and functional outcomes of a double-level osteotomy around the knee. This patient with a severe right genu varum was followed up for 12 months after surgery. The patient walks with no claudication or residual pain, presents a full range of joint motion, and resumed their work in agriculture. From an imaging point of view, it is essential to assess hinge integrity and confirm the normalization of the Mikulicz line and joint line obliquity (*yellow*).

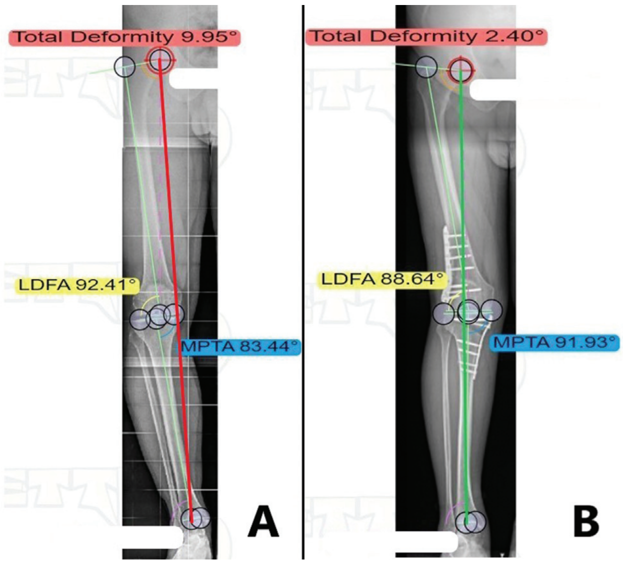

Fig. 10 Planning and outcomes of a double-level osteotomy around the knee. (**A**) The Bonesetter (Bonesetter Solutions, LLC. Michigan) open-access software was used to perform a systematic analysis of the coronal deformity. The mechanical tibiofemoral angle had 10° (severe varus), and the Mikulicz line (*red*) barely contacted the knee. The mechanical lateral distal femoral angle (mLDFA) was of 92° (*yellow*), and the mechanical medial proximal tibial angle (mMPTA) was of 83° (*blue*), reflecting the double-level metaphyseal deformity around the knee. (**B**) The outcome of a double-level osteotomy around the knee, with the desired Mikulicz line (green) correction based on the severity of the medial tibiofemoral osteoarthritis (Kellgren-Lawrence grade: 3; 60% of the tibial surface). We corrected the mechanical tibiofemoral angle (mTFA) to 2°, a physiological value. Both mLDFA ($\geq$ 85°) and mMPTA ($\leq$ 95°) are within the optimal simulated ranges, preventing a pathological joint line obliquity and a tibiofemoral subluxation.

as a justified treatment alternative in clinical and biomechanical studies to manage severe deformities around the knee.

Conflict of interests
The authors have no conflict of interests to declare.

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