

Post-traumatic deformities around the knee

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Abstract— Post-traumatic angular deformities around the knee significantly disrupt lower extremity biomechanics, causing asymmetric stress distribution that often leads to early unicompartmental osteoarthritis. These deformities typically result from physeal arrest or fracture malunions, with pathogenesis heavily dependent on the patient's skeletal maturity at the time of injury. Precise clinical evaluation and preoperative radiographic assessment—utilizing the Center of Rotation of Angulation (CORA) methodology—are essential for quantifying the deformity and planning of surgical intervention. Management strategies are dictated by remaining growth potential and deformity severity. In skeletally immature patients, growth modulation techniques and physeal bar resection offer effective correction. For patients nearing skeletal maturity or those with complex, multiplanar deformities, treatments include high tibial or distal femoral osteotomies, and the application of circular external fixators. The primary surgical objective across all methods is restoring the physiological mechanical axis to preserve joint longevity.

Keywords—physis, growth disturbance, knee deformities, growth modulation, osteotomie, biomechanics

1. Introduction

Angular deformities of the knee represent a major challenge for orthopaedic surgeons, often demanding aggressive treatment. Unlike congenital or developmental deformities, which may present with generalized bone fragility or bilateral symmetry, post-traumatic growth disturbances depend on the initial mechanism of injury and type of fracture and they can lead to unpredictable deformities. The knee, serving as a primary load-bearing joint is highly vulnerable to the biomechanical disturbances caused by angular malalignment¹.

The growth plate (or physis) located at the epiphyseal ends of long bones consists of 5 zones: germinative, proliferative, hypertrophic (or maturation zone), zone of provisional calcification and the ossification zone. The growth plate is further supported by a complex known as the periphysis which consists of two structures - the zone of Ranvier, which is responsible for the latitudinal growth of the physis, and the ring of

Lacroix which provides structural support for the whole structure². Any damage affecting the first two zones of the growth plate leads to replacement of the normal cartilaginous cells with bone tissue via intramembranous ossification which leads to partial or complete growth arrest of the physis. Additionally, conditions associated with increased blood flow to the lower zones of the growth plate can lead to reactive overgrowth (partial or complete).

Malalignment inevitably leads to abnormal force transmission across the articular cartilage. This maldistribution of stress creates a cascade of progressive asymmetric cartilage wear, meniscal pathology, collateral and cruciate ligament laxity, and eventually, severe unicompartmental osteoarthritis.

The objective of this review is to synthesize the current pathophysiological understanding, diagnostic protocols, and surgical management strategies for post-traumatic angular deformities of the knee.

2. Biomechanics of the Normal and Malaligned Knee

The neutral mechanical axis of the lower limb, often referred to as the Mikulicz line, is defined as a line drawn from the center of the femoral head to the center of the ankle plafond. In a normal limb, this line passes either exactly through the center of the knee joint or slightly medial to it, typically traversing the medial tibial spine.

This physiological alignment ensures that the ground reaction forces experienced during the stance phase of the gait cycle are distributed appropriately across the knee. Under normal conditions, approximately 60% to 70% of the axial load is transmitted through the medial compartment, and 30% to 40% through the lateral compartment³.

When an angular deformity occurs, this physiological pattern is disturbed. In a post-traumatic genu varum deformity, the mechanical axis deviates significantly into the medial compartment (Mechanical Axis Deviation, or MAD). According to many authors, as little as 2° of varus angulation can exponentially increase the compressive loads on the medial tibial plateau^{3,4,5,6,7}. Direct clinical evidence of a cause-and-effect relationship between malalignment and arthrosis is not present, but substantial evidence from the orthopaedic literature supports this hypothesis. Hsu et al (1990)⁴ found that 4-6 degrees of varus results in 90% of the knee joint force in single stance is transmitted through the medial compartment. Kettelkamp et al. (1988)⁵ evaluated 14 patients with maligned fractures of either the femur or tibia 32 years after the initial injury and suggested that the unicompartmental degeneration observed during follow-up was a result of the increased mechanical stress arising from the fracture angulation and malalignment.

An important aspect of these types of deformities is the meniscal injury, which represents a key factor for the development of the degenerative process. There is a well-established correlation between medial meniscus tears and a varus alignment of the knee. Lan Z et al⁶. found that each additional degree of varus increased the odds of medial meniscus tear nearly 2-fold, with posterior horn tears being the most common subtype. Conversely, a post-traumatic genu valgum deformity lateralizes the mechani-

cal axis, shifting the weight-bearing burden to the lateral compartment, which is anatomically less equipped to handle excessive loads due to the convexity of the lateral tibial plateau, ultimately leading to lateral unicompartmental arthritis and medial collateral ligament (MCL) attenuation⁸.

3. Etiology and Pathogenesis of Post-Traumatic Deformities

The pathogenesis of post-traumatic deformities around the knee is defined by the patient's skeletal maturity (remaining growth) at the time of the initial trauma, as well as the location and type of fracture.

3.1 Physeal Arrest

In the skeletally immature patient, the physes (growth plates) of the distal femur and proximal tibia are critical for longitudinal bone growth, contributing approximately 65% of the total length of the lower extremity. Trauma to these regions is most commonly classified under the Salter-Harris system and can result in cellular damage to the germinative and proliferative zones of the physis^{2,9}. When this cartilaginous tissue heals by forming a rigid osseous bridge (physeal bar) across the growth plate, asymmetric growth arrest ensues. If the bar forms on the medial aspect of the distal femur or proximal tibia, the lateral aspect continues to grow, progressively driving the knee into a varus alignment and the opposite. The severity and progression of the deformity are directly proportional to the size of the physeal bar and the remaining growth potential of the child¹⁰.

4. Clinical Evaluation

4.1 Physical Examination and Gait Analysis

A thorough history must evaluate the initial mechanism of injury, the precise nature of previous surgical interventions (if present), and the presence of prior infections, which heavily influence the choice of future hardware. Patients primarily present with cosmetic asymmetry, progressive joint pain localized to the overloaded compartment, or mechanical symptoms such as limited range of motion and gait disturbances. The progression of the deformity and the functional demands of the patient must be established in order to plan the urgency and aggressiveness of the proposed intervention¹¹.

The physical examination begins with a comprehensive gait analysis. The physician must observe the patient walking to identify dynamic mechanical deviations, such as a lateral thrust (indicative of dynamic varus instability) or a medial thrust (indicative of dynamic valgus). Rotational profile analysis is mandatory, involving the assessment of the foot progression angle, hip internal/external rotation in extension and flexion, and the thigh-foot axis, as rotational malunions frequently accompany post-traumatic angular deformities^{5,8,12}.

A thorough evaluation of knee range of motion (ROM) is required to document flexion contractures or true recurvatum deformities. Robust ligamentous testing (Lachman,

pivot shift, varus/valgus stress testing) is essential, as performing a bony correction in the presence of unaddressed ligamentous incompetence will inevitably lead to suboptimal outcomes and recurrent deformity¹³.

4.2 Radiographic Assessment

Standardized radiographic imaging is essential for preoperative planning of deformity correction. The minimal requirement is a set of full-length, weight-bearing standing anteroposterior (AP) radiographs of both lower extremities (Figure 1). It is critical that the patient is positioned with the patellae facing strictly forward, rather than aligning the feet, to eliminate rotational artifacts that can falsely exaggerate or mask coronal plane deformities¹⁴.

In addition to full-length views, dedicated weight-bearing AP, lateral, and Merchant views of the knee are necessary to assess joint space narrowing and patellofemoral congruity. Advanced imaging plays a highly complementary role in post-traumatic cases. Computed Tomography (CT) scans with 3D reconstructions are invaluable for defining complex intra-articular malunions, assessing bone stock, and accurately measuring torsional (rotational) deformities of the femur and tibia by comparing the femoral neck axis to the trans-epicondylar axis and the trans-malleolar axis¹⁵. Magnetic Resonance Imaging (MRI) is indicated when there is clinical suspicion of concurrent ligamentous tears, meniscal pathology, or to grade the severity of chondral damage.



Figure 1. M.M, 5-year-old female, who sustained a Salter-Harris IV fracture of the right distal femur. A valgus deformity has developed following the initial treatment.

5. Principles of Correction

The gold standard for preoperative planning of angular deformities was formalized by Paley et al., centered on the Center of Rotation of Angulation (CORA) methodology. This geometric method allows surgeons to objectively quantify the deformity and plan osteotomies that avoid inducing secondary translational deformities¹.

Planning begins with drawing the mechanical axes of the proximal and distal bone segments. The magnitude of the deformity is initially quantified by measuring the MAD (Figure 2 - A).

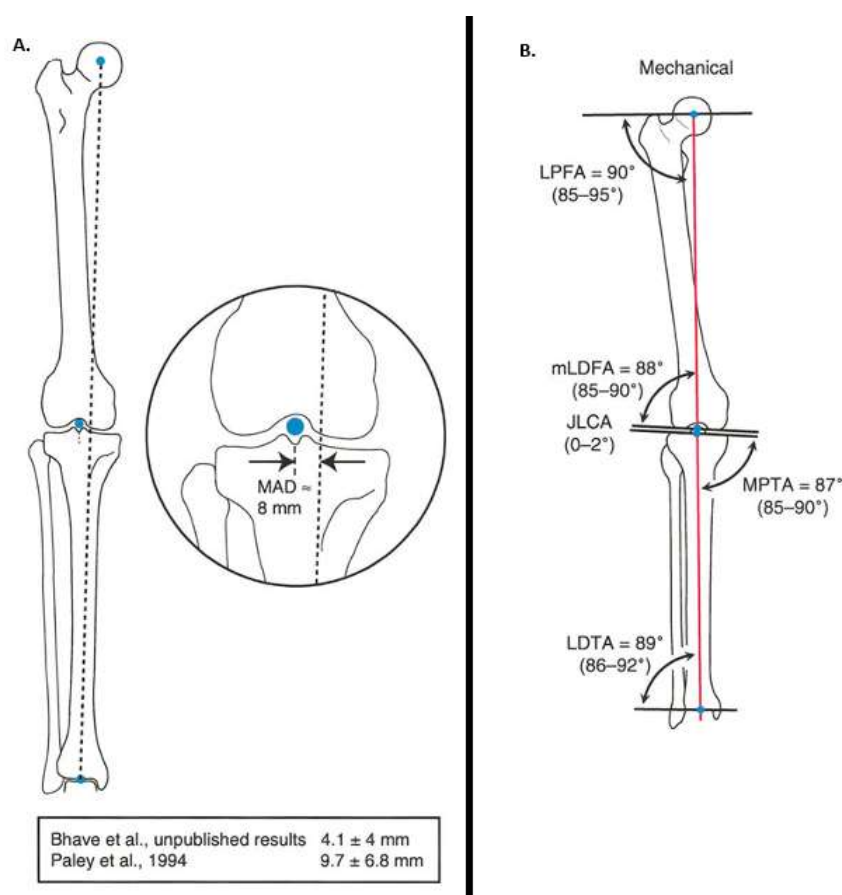


Figure 2. A - MAD normal values as defined by Paley et al. and Bhave et al. B - Joint orientation angles as defined by Paley et al. (16)

Following this, joint orientation angles (Figure 2 - B) must be calculated to pinpoint the source of the deformity. Their normal values of these angles are represented in table 1. By comparing the patient's angles to these normative values, the surgeon determines

whether the angular deformity is localized to the femur, the tibia, or is a combination of both.²⁰ Additionally, the Joint Line Convergence Angle (JLCA) is measured to evaluate for intra-articular deformity or ligamentous laxity contributing to the overall angulation.

Table 1. Normal values of the main joint orientation angles as defined by Paley et al¹⁶.

Angle	Normal Value
mLDFA	85-90°
MPTA	85-90°
JLCA	0-2°

The intersection of the proximal and distal mechanical or anatomical axes defines the CORA. The bisector line passing through the CORA serves as the baseline for correction. Successful surgical execution relies on three fundamental osteotomy rules:

1. When the osteotomy and the hinge of correction both pass through the CORA, perfect angular correction is achieved without translation.
2. When the hinge of correction is at the CORA, but the osteotomy is made at a different level (often dictated by soft tissue constraints or bone quality), angular correction is achieved, but the bone ends will translate relative to one another. This translation is functionally acceptable as long as the mechanical axis is restored
3. When neither the osteotomy nor the hinge passes through the CORA, correction results in an undesirable secondary translation deformity, disrupting the mechanical axis and creating a zig-zag appearance^{1,17}.

6. Surgical Correction Focused on the Growth Plate

6.1 Growth Modulation

The pediatric skeleton and its physes provide a unique ability to safely and reversibly modulate growth by performing a temporary growth arrest (epiphysiodesis) on the contralateral side of the affected physis. This method was pioneered by Walter Blount and his staples. While revolutionary at its core principle, the procedure was and remains moderately effective and with high complication rates¹⁸. The concept of guided growth was further refined by Peter M. Stevens in 2007¹⁹ when he introduced the "eight plate" which utilized the tension band principle -similarly to the Blount staple, the plate mechanically restricts the growth of the physes but unlike the staple, it provides a certain degree of flexibility and thus the frequent complications due to implant failure are avoided. Stevens reported a 97% success rate treating knee (both proximal tibial and distal femoral) deformities, with a correction rate 30% faster than staple epiphysiodesis¹⁹ and 0% of severe complications (IIIA and IIIB based on the classification of Black and al.). The promising results of the tension band principle were further developed by the introduction of the hinge plate (Figure 3) which replaces the tension band plate with a pivot, placed outside the physis, to which the two parts of the plate are connected. By doing so, the hinge plate provides a true fulcrum in the form of a hinge with the intent being to provide an easy way for angular correction to occur and to avoid

the mechanical breakage of screws that plagued the previous tension band devices. A recent study based on 54 patients treated via hinge plate epiphysiodesis for knee deformities also presents very optimistic results with 0% severe complications based on the Black classifications and a 94.5% success rate²⁰.



Figure 3. P.D after a medial hemiepiphysiodesis of the right distal femur with a hinge plate.

Another concept for growth modulation is the compression principle also known as percutaneous epiphysiodesis using transphyseal screws (PETS) (Figure 4). First described by Metizou in 1998²¹, it uses canulated screws whose threads "lock" the metaphysis to the epiphysis thus inhibiting growth. The literature shows this method to be more effective^{18,22} and with fewer or equal complications rate. A recent systematic review of a total of 473 physes confirms this data with every objective correction rate being faster in the PETS group and complications rate being lower in the same group. A noticeable exception is the little bit higher overcorrection rate observed in the PETS group²³.



Figure 4. P.D. 11-year-old male, who underwent bilateral hemiepiphysiodesis of the medial part of the proximal tibial growth plate.

While temporary growth arrest is a very effective and safe procedure, it is not without limitations. First and foremost, a certain amount of remaining bone growth is required so that sufficient correction can occur. Although the proximal tibial physis closes at approximately 16-17y.o. in girls and at 18-19y.o. in boys, its growth after the puberty peak is not sufficient to obtain correction. Ko Kr. et al based on their 2024 research found that sings of epiphyseal fusion of the distal hand phalanges are connected with under correction of varus deformities²⁴ treated with PETS which has even faster and stronger growth arrest potential than the plate methods¹⁸. Based on this data clinicians should reconsider using growth modulation when a patient presents with objective signs of skeletal maturity

Many authors state that the duration of epiphysiodesis should not exceed 2 years as the reversibility of growth arrest becomes unpredictable after this period^{25,26}. The rate of correction in growth modulation varies widely. The systematic review of Sabry AO. and al.²⁷ showed the MPTA correction to be around 0.48° to 0.72°/month in the PETS and 0.46° to 0.55°/month in the tension-band group. A bit faster rates are observed in the LDFA correction rates with 0.81° to 0.92°/month in the PETS group and 0.51° to 0.76°/month in the tension-band group. While the literature does not provide specific

cutt-offs in terms of maximum angulation that can be treated with epiphysiodesis, the above-mentioned data should be kept in mind when planning treatment.

6.2 Physeal Bar Resection

Damage to the lower zones of the growth plate leads to formation of bone bridges through the growth plate. Those bridges tether the bone growth and represent the cause for the deformities occurring after a physeal injury. The removal of such bridges is indicated when no more than 50% of the growth plate is affected, and at least 2 years of growth remain. Access to the bony bridge is achieved through either a direct approach (for peripheral lesions) or an indirect, trans metaphyseal approach (for central lesions). The bar is then excised down to healthy tissue utilizing a curette, osteotome, or bone burr. Although the potential for deformity correction with this technique is modest (rarely exceeding 20%), even partial correction can facilitate a subsequent corrective osteotomy and contribute to a more favorable final outcome²⁸.

7. Surgical Correction via Osteotomies

When the severity of the deformity exceeds the capabilities of guided growth, or when insufficient growth remains, an osteotomy may be performed in order to restore normal biomechanics and prevent osteoarthritic changes.

7.1 High Tibial Osteotomy (HTO)

Although rarely indicated in pediatric patients, HTO could be beneficial for severe deformities in patients nearing skeletal maturity. Either medial or lateral closing wedge osteotomies may be performed.

Medial Opening Wedge HTO: This technique involves creating an incomplete osteotomy from the medial cortex, stopping short of the lateral cortex to preserve a lateral hinge. The osteotomy is gradually opened to the pre-calculated degree and stabilized with a rigid locking plate (e.g., TomoFix). Advantages include highly predictable angular correction and avoidance of the common peroneal nerve. However, it inherently lengthens the limb and can increase the posterior tibial slope if not executed carefully, which may stress the anterior cruciate ligament²⁹.

Lateral Closing Wedge HTO: This historical standard involves resecting a laterally based wedge of bone. While technically demanding and carrying a higher risk of peroneal nerve neuropraxia, it is highly advantageous for patients who already have a leg length discrepancy (where lengthening is undesirable) or require simultaneous correction of a large extension (procurvatum) deformity²⁹.

7.2 Distal Femoral Osteotomy (DFO)

Fractures affecting the distal femoral growth plate carry a risk of growth disturbance in up to 90% of cases. Furthermore, because the distal femoral physis provides the greatest amount of longitudinal growth to the lower extremity, it is highly vulnerable

to clinically significant arrest. This combination of factors creates a high risk for severe angular deformities, resulting in a higher likelihood of requiring corrective osteotomies.

Historically, the medial closing wedge DFO (Figure 4) was the standard for large valgus deformities, utilizing blade plates for fixation. It allows for broad bony apposition and high union rates but requires careful management of the limb length.

With the advent of anatomically contoured locking plates, lateral opening wedge osteotomies have gained popularity. They allow for precise intraoperative adjustments and single-stage correction, although they require structural bone grafting for larger gaps and carry a higher risk of delayed union compared to closing wedge techniques^{16,31}.



Figure 4 - M.H. 4y.o. female who underwent a medial closing wedge DFO

7.3 The Role of External Fixation in Complex Deformities

While single plane osteotomies combined with internal fixation via locking plates are an excellent option for single-plane corrections in a soft tissue status, post-traumatic

deformities frequently present with scarred, compromised soft tissues, active or prior osteomyelitis, or severe multiplanar deformities (e.g., combined varus, internal rotation, and length discrepancy). In these scenarios, circular external fixation is unparalleled¹.

Traditional Ilizarov frames rely on a hinge and motor system to correct deformities gradually through a percutaneous corticotomy and distraction osteogenesis. More recently, hexapod circular fixators (e.g., Taylor Spatial Frame, Ortho-SUV) have revolutionized this approach (Figure 5). Hexapod systems utilize six struts connecting two rings, operating on the mathematical principles of the Stewart-Gough platform. By inputting the patient's exact radiographic parameters and mounting parameters into web-based software, a daily prescription is generated for the patient. The patient adjusts the struts daily, allowing for simultaneous, gradual correction of angulation, translation, rotation, and length down to the millimeter. Gradual correction also minimizes the risk of acute neurovascular traction injuries^{1,32}.

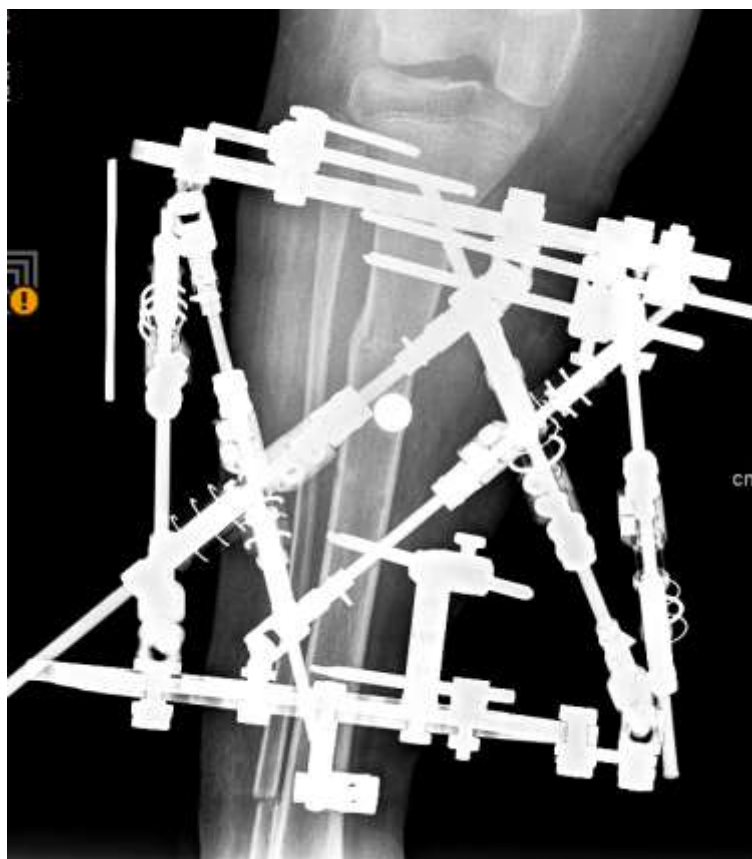


Figure 5 - S.R. 13y.o. male undergoing treatment with a hexapod circular external fixator.

8. Complications and Considerations

The Hueter-Volkmann law states that increased mechanical load on the physis leads to inhibition of growth while decreased load has the opposite effect of increased growth³³. It is important to note that two key variables control growth velocity - the rate of creation of new chondrocytes in the proliferative zone, and the rate of chondrocyte enlargement and matrix synthesis in the hypertrophic zone. Longitudinal growth results from the product of these variables. Mechanical loading of a growth plate was reported as having a small effect on the rate of proliferation, whereas the amount of growth has been found to correlate more with the amount of chondrocyte enlargement occurring in the hypertrophic zone³⁴. This law creates a vicious circle in which the inhibited part of the physis is not only damaged by the trauma but is furthermore inhibited by the increased load, while the unaffected side continues to overgrow and thus increase the deformity. This mechanism is best demonstrated in the pathogenesis of the Blount disease where increased mechanical loading leads to progression of the deformity.

Regarding osteotomies, non-union and delayed union are major concerns, particularly in opening wedge osteotomies or in patients with compromised vascular status. Bone grafting and the use of rigid, fixed-angle constructs mitigate this risk.

Neurologic injury is a devastating potential complication. The common peroneal nerve is particularly vulnerable during lateral closing wedge HTOs and acute corrections of severe valgus deformities due to traction neuropraxia. Peroneal nerve decompression may be indicated in high-risk cases. Pin-tract infections are ubiquitous in external fixation and require meticulous local care and occasional antibiotic therapy, though deep ring-associated osteomyelitis is rare. Overcorrection or undercorrection remains the most severe risk because it requires further surgeries, emphasizing the need for robust preoperative planning and individual approach when selecting the operative technique^{1,16,32}.

9. Conclusions

Post-traumatic angular deformities around the knee represent a complex, heterogeneous group of pathologies that severely disrupt lower extremity biomechanics and predispose to early osteoarthritis. The unique challenges these cases present, including soft tissue scarring, altered bony anatomy, and concurrent ligamentous instability further complicate the treatment. Successful management demands an exhaustive clinical evaluation and precise radiographic analysis utilizing the CORA methodology. By applying rigorous osteotomy principles, orthopaedic surgeons can compile an individual treatment strategy ranging from pediatric guided growth to osteotomies and sophisticated multiplanar external fixators. Restoring the physiological mechanical axis remains the paramount objective, allowing for symptom relief, restoration of function, and the preservation of the knee joint for as long as biologically possible.

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