Diaphyseal osteotomy after post-traumatic malalignment

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Abstract Tibia and femur shaft fractures can sometimes lead to post-traumatic deformities. Correction by means of circular external frames is a valuable option. The aim of this article is to give an overview of the problem and to focus on some important technical issues of the preoperative planning, the surgical procedures, and the postsurgical management of circular external fixators.

Keywords Post-traumatic deformity · Circular external frame · Bone correction · Tibia · Femur

Introduction

Fractures of the long bones of the lower limb (tibia and femur) occasionally result in post-traumatic malalignment as a result of malunion or nonunion of the bone. Diaphyseal malalignment can lead to secondary complications including difficulty walking, cosmetic abnormality, and chronic pain. In addition, abnormal peri-articular joint loading because of malalignment, muscle, or ligament strain may lead to early arthritis of adjacent joints [1].

The incidence of femur fracture tends to have a bimodal age-distribution. The reported incidence of diaphyseal femur fracture is 10/100,000 persons per year [2]. With present

surgical techniques in advanced nations, the incidence of malunion is decreasing, however, in general, malunions and nonunions remain problematic. The majority of femoral shaft nonunions are the result of a combination of angular and rotational deformity, as well as shortening. Currently accepted definitions of unacceptable femoral alignment include angulation or malrotation $>10^\circ$ or shortening >2 cm [3].

Diaphyseal fracture of the tibia is the most commonly occurring fracture of a long bone. The incidence of diaphyseal tibia shaft fractures is approximately 26/100,000 fractures per year [4]. According to Milner et al as many as 8 % of tibial shaft fractures heal with levels of deformity outside of the acceptable range [5]. While the definition for unacceptable, tibial alignment remains elusive and is variably described in the literature, generally accepted recommendations of unacceptable alignment include varus/valgus angulation of $>5^\circ$, $>10^\circ$ of anterior/posterior angulation, internal rotation $>5^\circ$, external rotation $>10^\circ$, or shortening of >1 cm [6].

As previously mentioned values for acceptable long bone alignment remain ill-defined. Alterations in gait, including limp have been reported with leg length discrepancy of 2 cm or more [7]. Alterations in gait, however, are less clearly reported for rotational or angular deformity. Additionally the amount of deformity acceptable may vary on an individual basis and may have to do with pre-existing deformity or variability in mechanical axes. For example, a patient with increased native varus alignment who sustains an injury with resulting worsening varus malalignment and deformity may be more adversely affected than an individual with less native varus alignment [8].

In current practice, there are 3 generally accepted indications for corrective osteotomy of post-traumatic diaphyseal (tibia and femur) malalignment. These include malalignment, which leads to: (1) a painful functional deficit, (2) an unacceptable cosmetic appearance, and (3) a high risk for degenerative osteoarthritis due to abnormal load distribution of

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adjacent joints. The treatments for post-traumatic malalignment are variable. Given the variability in the etiology, deformity, and treatment options available, making evidence based recommendations on the basis of current literature is difficult. However, the treatment principles of post-traumatic malalignment of both the tibia and femur are similar. When malalignment (nonunion) is diagnosed early, the treatment will be correction of malalignment and bony stabilization in acceptable alignment with adherence to accepted bone healing principles. When malalignment is diagnosed late (malunion) and the bone is healed, corrective osteotomy will be required. Corrective osteotomies require thoughtful preoperative planning for both the correction of deformity as well as subsequent fixation. This article will review classic and more recently published studies on the principles behind and the techniques for diaphyseal osteotomy for post-traumatic malalignment.

Preoperative planning

Preoperative planning is perhaps the most important step to successful treatment of post-traumatic malalignment. The most powerful site of osteotomy is that which is closest to the deformity allowing a surgeon to obtain maximal correction without creating distortion of the treated limb. The basic method for preoperative planning is drafting to simulate the location of osteotomy, fixation implant, and bone graft needs.

There are many options for osteotomy in current practice. A transverse osteotomy is the best way to treat malunion with malrotation alone. The closing and opening wedge osteotomies are a variation of transverse osteotomy. The closing wedge osteotomy can provide good stability and often does not require a bone graft [8]. The disadvantages relate to soft tissue balance, particularly if performed close to a joint and involving shortening of the limb. The opening wedge is technically easier as surgeons can adjust the degree of correction after osteotomy. Another advantage of the opening wedge osteotomy is the treated limb will invariably gain length. The main disadvantage of opening wedge osteotomies, are that they require a bone graft to fill the wedge. This may lead to a longer healing time and longer time to fully heal the osteotomy site. For wedge osteotomy, the most important step is accurate pre-operative planning and accurate intraoperative osteotomy. Knight et al reported the precision guide pin technique for wedge and rotational deformity in long bones of the lower limbs [9]. They compared the accuracy of the technique by comparing pre-operative templating with postoperative results in 57 patients and found that 85 % of cases were within $\pm 3^\circ$ of the preoperative templating. Pullisetti et al presented a mathematical formula that can convert the malrotation angle in pre-operative CT scan to millimeter of bone to be removed intra-operatively [10].

The oblique osteotomy can provide multidimensional correction of deformity in 1 cut. It provides good apposition of bone surfaces, which can be compressed with lag screw and has good bending and rotational deformity. However, the planning and execution of such oblique osteotomies can be difficult [11]. In an attempt to improve the precision of osteotomy, new technologies that incorporate computational calculation have been reported. Dobbe et al reported a computational assisted method for 3D planning and realizing a single cut rotational osteotomy with a patient specific cutting guide using plastic bone [12]. They found the system is easily applicable, accurate, reproducible, and cheaper when compared with previous navigation systems. The clamshell osteotomy is also a good option in longer segment malunions [13]. The dome osteotomy works best in metaphyseal bone and has less of a role in correction of diaphyseal deformity [8].

Technical considerations

While a variety of options exist for fixation of the corrected limb (Table 1) our group has had significant experience with the use of ringed external fixation. Below we will review our experience and the technical considerations for correction of diaphyseal osteotomy after post-traumatic malalignment.

Why the circular external fixation in the lower limb deformities correction?

The circular ExFix frames are very “biological” in the correction management and moreover easy enough to be removed at the end of the treatment, not leaving any devices in the patient’s body. The frames are very stable so that the patient can be allowed full weightbearing early. As they are open to operators, the surgeon can perform additional corrections while the frames are in place.

While the traditional circular external fixators according to the Ilizarov call for a very thorough planning, made up somehow of rigid consecutive steps (angles, length, torsion, and translation), entailing a long learning curve, the hexapodal (derived from the Greek, like saying 6-legged) systems allow the surgeon to face the deformity as a unique problem and to perform the correction simultaneously in different planes. In order to run the synchronous multiplanar corrections, a computer with dedicated software is needed.

The theoretical cornerstone of the hexapodal frames is the Stewart platform, a structure based on 2 platforms hinged together by means of 6 telescopic cylinders with universal joints at their ends. The Stewart platform was invented to allow 6° degrees of freedom (x, lateral, y, longitudinal, z vertical, plus the possibilities of pitch, roll, and yaw) in moving an object (a radar antenna or a flight simulator in the

Table 1 Summary of articles relating to post-traumatic malalignment of femur and tibia

Author/references	Study design	Femur/tibia	Follow-up	Instruments	Results	Complication
Tall et al [14] Ort Trauma Surg Res. 2012; 98:784	Prospective	16/0	1 y	Open osteotomy + Kuntscher nail	-All healed in 90 days except one at 120 days	-One bended nail needed nail exchange
Dobbe et al [12] Med Biol Eng Comput. 2011; 49:1363–70.	Experiment (software, plastic bone)	0/5	-	CAS patient specific cutting guide	-Easily applicable, accurate, reproducible, and is a good alternative for complex and expensive navigation systems.	NA
Russel et al [13] JBJS Am Surg Tech. 2010; 92:158–74	Prospective	4/6	2.5 y	-Clamshell osteotomy	-All healed in 6 months	-2 superficial infections
Johnson JE et al [15] JBJS 1994;76:379–89.	Retrospective	1/24	5.3 y	-AO-ASIF distractor then plate or intramedullary nail	-92 % healed	-1 deep infection -1 neuroparaxia -2 fail plate
Sanders et al [16] JBJS Am 1995 77; 2: 240–6.	Retrospective	0/12	2.1 y	-Oblique osteotomy + external fixator to correct malalignment then plate	-10 in 12 healed in 4.5 mo	-2 failed (both had poor compliance) -1 intraop vascular inj
Buijze et al [17] J Bone Joint Surg Am. 2011; 93:485–92.	Retrospective	2/6	20 y	-Debride + AO external fixator	-All healed	-None
Feldman et al [18] J Orthop Trauma. 2003; 17:549–54.	Retrospective	0/11	3.2 y	-Taylor spatial frame	-All healed	-3 superficial pin tract infections
Borelli et al [19] COR 2009; 467:1056–63.	Retrospective	0/9 (distal tibia)	3 mo	-Iliac tricortical one graft and plate	-All healed	-1 tibiofibula arthritis -1 wound dehiscence -1 malunion
Johnson EE et al [20] COR 1987;215: 223–32.	Prospective	0/7	9 mo	-Close wedge osteotomy and plate	-All healed with good alignment	-None
Lark et al [21] J Surg Orthop Adv. 2013; 22:316–20.	Retrospective + radiograph study (Ilizarov vs Taylor SF)	50 patients (malunion + nonunion)	-	Ilizarov and Taylor spatial frame (TSF)	-93 % healed Good alignment and leg length -No radiograph different btw Ilizarov and TSF	-2 pts needed further fixations -2 amputations -overall 50 % had complications (mostly pin tract infections)
Seybold et al [22] Unfallchirurg. 2008;12:985–6, 988–95.	Retrospective	0/6	25.3 mo	TSF	-All healed with good alignment	-3 pin-site infections -2 insufficient callus formations -1 pinhole stress fracture -2 deep infections -1 cortical perforations
Wu CC1 et al [23] Arch Orthop Trauma Surg. 2000;120:152–6.	Prospective	0/37	1 y	Close wedge osteotomy + Reamed IM nail	- All healed	-None
Wu CC et al [3] Arch Orthop Trauma Surg. 2001;121): 265–70.	Prospective or retrospective	24/0	1 y	Transverse osteotomy + Reamed IM nail + Bone graft	-All healed	-None
Chiodo et al [24] COR. 2003;406: 185–94.	Retrospective	6/0	49 mo	Oblique osteotomy + lag screws and plate	-All healed	-None
Yasui et al [25] J Orthop Sci. 2000;5:104–7.	Prospective	22 pts (33 legs)	-	Percutaneous multidrilling osteotomy + ext fix	-All healed	-None

origins) in relation to a basis assumed to be parallel to the ground; this means that our object is free to move in a virtually complete hemisphere.

Anatomic and geometric parameters

Clinical and radiological exams

The clinical examination is focused on the macroscopic limb deformities and the length discrepancy, the gait abnormalities, and the joint instabilities (especially knee and ankle). The examination should be carried out with the patient lying down in a supine position and with the patient standing: very often joint instability can change the pattern of the deformities with the upright patient.

The imaging is based on the AP teleradiography of both lower limbs in standing position with the patellae “looking” forward along parallel lines (the “zenith” position). Sometimes a lateral teleradiography is needed, with the knee fully extended. If a leg length discrepancy is present, a wedge should be put under the shorter limb in order to get the pelvis parallel to the ground (the height of the wedge is, obviously, the amount of the discrepancy). If a torsional abnormality is suspected, a CT scan focused on the limb rotation in comparison with the patient’s physiology (the unaffected side) should be performed. The general rules are effective both for the traditional Ilizarov technique and for the hexapodal frames.

Lower limb alignment

The lower limbs mechanical axis is the line connecting the center of the femoral head with the center of the tibial pilon. This line doesn’t run exactly in the center of the knee, but should be a little medial (about 8 mm). The Mechanical Axis Deviation (MAD) is the valgus/varus indicator.

The tibia mechanical axis is the line connecting the knee center with the tibial pilon center. The tibia anatomic axis is the mid diaphysis line, both in AP and in lateral views. Normally, the tibia anatomic axis runs, in the AP view, from the medial tibial spine and to a point 4 mm medial to the center of the ankle and, in the lateral view, from a point located at the limit between the anterior fifth and the posterior four-fifths to the top of the tibial pilon dome.

The femur mechanical axis connects the center of the femoral head with the knee center in the frontal plane, while it runs from the center of the femoral head to the junction between the anterior third with the posterior two-thirds of a line drawn at the greater AP condyles dimension in the sagittal plane (around the Install line in the lateral X-ray view). The femur anatomic axis is the midshaft line in AP view. From lateral, it is bow-shaped, with an anterior convexity as it gets more difficult to be located. Normally, the femur anatomic

axis makes a 4°–6° angle with the femur mechanical axis, in the AP view.

Every deformity divides the segment into some (2 or more) smaller parts, that can be put in reference to the anatomic axis. In general the anatomic axis permits an easier deformity calculation.

When the deformity is close to a joint (knee or ankle), the segment toward the joint is usually too short to be calculated. In this case our attention should be focused on the joint orientation, as the angle between the joint line and a certain axis (Fig. 1). To get this measurement some references are needed:

- (1) which axis we are taking in exam, anatomic (a) or mechanical (m);
- (2) which side of the axis we are at, lateral (L) or medial (M) in the frontal plane, anterior (A) or posterior (P) in the sagittal plane;
- (3) which part of the joint, in relation to the bone (femur or tibia), are we considering, proximal (P) or distal (D);
- (4) which bone, femur (F) or tibia (T).

Taking in examining the condyles of the femur, their angular position will be defined by the mechanical Lateral Distal Femur Angle (mLDFA, 88°, 85°–90° in the healthy femur), by the anatomic Lateral Distal Femur Angle (aLDFA, 81°, 79°–83°), and the mechanical Posterior Distal Femur Angle (mPDFA, 83°, 79°–87°). The tibial plateau will be determined by the mechanical Medial Proximal Tibia Angle (mMPTA, physiologically 87°, 85°–90°) and the anatomic Posterior Proximal Tibia Angle (aPPTA, 81°, 77°–84°). The tibial pilon position arises from the anatomic Lateral Distal Tibia Angle (aLDTA, 89°, 86°–92°) and the anatomic Anterior Distal Tibia Angle (aADTA, 80°, 78°–82°) [21].

Very often we set the unaffected side measurements as the endpoint, rather than the average population values [26].

The angular deformity and the “Center of Rotation of Angulation” (CORA)

The intersection between the axis of the abnormal segments, both in the frontal and in the sagittal plane, is the Center of Rotation of Angulation (CORA) [21].

If the osteotomy is performed at the CORA, both the mechanical and the anatomic axis will be corrected. If the osteotomy is made away from the CORA, there will be a variable lateral/medial or posterior/anterior shift of the reference segment, resulting in a various amount of mechanical or anatomic deformation from the physiology.

If the correction hinges are put on the convexity of the vertex, there will be a lengthening associated with the angular restore and its amount will depend on the distance between the hinge and the vertex (if the distance gets higher, the lengthening will increase). As the bone has its own width, we are forced to put the hinges at least on the tangential line on the

Fig. 1 Female, 20 years, malunion distal left femur (Salter Harris fracture 8 years earlier): (1) 7° valgus, 22 mm shortening, no axial deformity. (2) The CORA is in close proximity to the intercondylar notch. (3) Teleradiography 38 days since surgery, 31 days after the beginning of the correction. The osteotomy was performed necessarily proximal to the CORA (see point 2), a certain amount of lateral shift was expected. Some degrees of anatomic varus, limb mechanical axis, and lengthening restoration

convexity, because if we shift the hinges to the concave side, the result will be a closing movement and an overpressure at the osteotomy site, with a very difficult or impossible correction.

The translation (lateral/medial or posterior/anterior shift)

The perpendicular line between the anatomic axis of the proximal fragment and the anatomic axis of the distal segment at the latter proximal top defines the value of the translation. This is useful because it is almost impossible that the lateral shift takes place between 2 parallel fragments.

The limb length discrepancy

If no angular deformity is detected the limbs length discrepancy comes from the comparison between the anatomic axis of the segments on both sides. When the inequality is associated with an angular deviation, the correct limb length is inferred by the sum of the segments' length measured on the convexity of the deformity: if the sum corresponds to the length of the healthy side, the angular deviation(s) is(are) the only issue(s).

When the deformity is complex (multiple planes deviation), usually the length discrepancy is the last parameter to be corrected. This means that the planning and the treatment program have to be focused on the angles first.

The rotational deformity

The rotational deformities are those that arise around the longitudinal axis of the bone. Plain X-rays very seldom assess exactly the issue, CT scan focused on torsions can be an important tool, but only the thorough clinical examination is capable of appraising the patient's need [27].

General rules in the pre-operative planning

The reference fragment

Usually the position of the distal fragment in relation to the proximal one defines the deformity. When dealing with a hexapodalic frame this is partially true, as the reference

fragment could be proximal or distal upon the surgeon's decision. The other fragment will be called corresponding or moving. In general, the smallest one is assumed to be the reference fragment.

The origin and the corresponding point

The origin is a point conventionally put along the reference fragment axis and should be the fulcrum of every correction. It should be clearly pinpointed both in the AP and in the lateral view (for instance it could be the CORA or a bone anatomic spot).

On the corresponding fragment one will find the corresponding point, considered to be coinciding with the origin before the deformity arose.

Planning methods

Five planning methods are commonly used to assess the 6 deformity parameters and to plan the circular frame correction:

- (1) the fracture method: 2 points are pinpointed on the 2 fragments after the frame application, frequently adopted in the trauma, but anyway useful for simple translational corrections, very intuitive [28];
- (2) the CORAgin method: the origin lies on the CORA, the corresponding point is to be located (assessments are performed before surgery) [26] (Fig. 2);
- (3) the CORAsponding method: the corresponding point is on the CORA, the origin is to be located (before surgery) [26];

Fig. 2 The CORAgin method

- (4) the virtual hinge method: the origin and the corresponding point coincide at the same point on the convex side of the bone (before surgery), very easy when the issue is just a monoplanar correction, with a minimal need for translation [26];
- (5) Line of Closest Approach (LOCA): it is focused on the spot where the osteotomy minimizes the bone shift during the correction (before surgery). This approach gives a comprehensive overview of the deformity, taking to one perspective the multiple points of view on the bone. It gets the most when facing an important torsional axial deformity [29].

In all, the 5 methods the torsion deformity is assessed by the association of the clinical data put together torsion-focused CT results.

Surgical technique

Patient positioning and preparation

The patient should be put in the supine position on a radiotransparent surgical bed, with a soft support under the buttock of the affected side in order to counterbalance the tendency to external rotation.

The tourniquet could be put in place, but not inflated, to be used in case of emergency. An inflated tourniquet can be an obstacle if it conceals vascular damage provoked by a wire or a screw.

When draping a patient who will undergo a tibia correction, the patella has to be visible in order to correctly assess the clinical torsions.

In general a line drawn from the middle of the patella put in vertical position to the second intermetatarsal space with the ankle 90° extended should assure a sufficiently reliable rotational alignment, but the best option is the comparison with the unaffected side.

To evaluate the femur physiological rotation we suggest taking a fluoroscopy shot of the proximal healthy femur with the patella at the “zenith” position before starting the operation. This will be useful if compared with the affected side while performing surgery.

Before starting, it is advisable to take some fluoroscopy images of the affected limb with metallic localizers in order to mark anatomic spots, the joint lines, the bone axes, and the site of the planned osteotomy on the patient's skin.

Procedure

While facing a correction with an external frame, monolateral, traditional circular, or hexapodalic, an essential issue is the

stability of the interface between the bone and the device. A “light” frame, with few screws, half-pins or wires may not be the best mechanical option, even if it looks comfortable for the patient, as it may sometimes lead to failure.

The way to get stability is the tripod, a 3-dimensional structure where a monoplanar hold is associated with another clutch lying in another plane. The tripod guarantees a certain stiffness of the set bone-frame, neutralizing the physical tendency to reciprocal rotation during the correction.

Following these principles, each single segment of the tibia/femur is firmly held at 2 different levels by means of:

- (1) 1 ring at 1 level united to another ring more proximal or distal, each of the 2 in connection to the bone with at least 2 tensioned wires;
- (2) 1 ring, fixed to the bone with 2 or more tensioned wires, connected to a clamp joined to the bone through a screw or a half pin;
- (3) 2 different rings attached to the bone by screws or half-pins.

There is a widespread consensus about 2-ring- based hexapodalic frames [28, 30, 31]. This tendency, may very well be efficient in the geometric perspective; its risk, however, is that it can be poor in terms of bone grip. In this case, it is advisable to broaden the bone hold by some screws as far (proximal or distal) as the anatomic settings allow. When putting the screws between the rings, these should not interfere with the telescopic rods and their future planned movements.

In the wire-based rings, the most stable construction is achieved when the wires form a 90° angle. This is a theoretical goal, as very often wires application depends on the anatomic site and the need to prevent nerves and vessels from crossing.

Our rule in tensioning the wires is to stay below 100 kilograms in the epiphysis (usually around 90) and below 130 (around 120) kilograms in the diaphysis.

Approaching the joints, the articular capsules should not be transfixed. In general, 10 mm proximal to the ankle joint line and 15 mm distal to the knee joint line could be considered as safe zones. Inserting the wires in the distal femur, the surgeon has to keep in mind the position and the anatomy of the intercondylar notch, as this needs to be respected both in flexion and in extension.

The possibility of stretching skin and soft tissues at their interface with wires or with screws has to be avoided, even anticipating the regular joint motion and the future frame evolution: even though everything is going fine with the patient motionless and supine on the operating bed, a strain could happen with walking and moving the limb, and with the external fixator evolving while correcting the bone deformity. One solution could be a small incision made from the entrance point in the direction of the hypothesized overstress.

For joint stiffness prevention it is recommended that wires and screws in proximity of the articulations are to be inserted

through the flexor muscles with the extended joint and through the extensor muscles with the bent joint.

When using screws, our advice is for hydroxyapatite coating of the threaded surface, as it greatly improves the bone-screw tightness when a long treatment is planned. The screw's diameter should be at least 5 mm [32].

The Construct

In general, the rings' inner diameter should exceed the maximum limb width of about 2 cm on every side. Considering the possible limb swelling, it is always better to leave a little bit more space. In certain selected cases, a 2/3 ring can be adopted for allowing a full range of motion, especially in the knee. Attention should be paid, in case of using 5/8 rings, to not over-tighten the wires because this can cause a ring collapse.

When planning a hexapodalic frame, the first rings to be chosen are the ones in relation to the segments to be corrected. They can be the same size or different in measures, while in a traditional Ilizarov assemblage all the rings share the same diameter.

After having identified the reference segment, the ring in the case of a hexapodalic frame, or the tripod in the case of a traditional circular apparatus, become the reference for other parts of the fixator.

The reference ring/tripod has to be perpendicular to the diaphyseal axis in the 2 traditional views (frontal and sagittal). The wire that allows for this position must lie on the same side of the ring (completely superior or inferior). In order to get the right-angles in the 2 planes, the frontal perpendicularity is taken first, then, in the lateral view, the ring is rotated until it is perpendicular to the lateral diaphyseal axis.

In inserting wires, the surgeon has to remember to apply a rubber tap around the wires on their entrance and exit sides before locking them to the rings. The rubber tap will be useful in keep the dressing sealed to the skin and, moreover, to localize the olive side when the wire has to be removed (the olive side will be tagged by a rounded cut).

When using screws instead of wires, as they are stiffer, to be perpendicular in the 2 views, the first inserted screw has to lie completely in the sagittal or in the frontal same plane of 1 of the 2 diaphyseal axes, orthogonal to 1 of these 2. Differently the rotation around the first screw axis would take the ring in an oblique plane in reference to the other axis.

In case of a hexapodalic frame a master tab (ie, an 8 cm rod), that would be the referring target for all the future corrections, has to be put anterior and in line with 1 of the 2 diaphyseal axis.

The correct positioning of the reference tripod is very similar in the general concepts.

The Osteotomy

Once the frame has been assembled and implanted according to plan, osteotomy has to be completed. The 2 most popular

techniques are the use of a Gigli saw and the De Bastiani (chisel-based) technique.

Before performing the bone cut, all the lengths of the rods (usually 4) or of the telescopic struts (6) surrounding the osteotomy site have to be recorded, therefore, the rod nuts or the gauge ballpoints have to be released, in order to free the osteotomy site from any structural block.

We advise the use of the De Bastiani technique [33] because there are some advantages in terms of biology. First, the periosteum is cut for a very modest breach, preserving the external bone circulation. Second, it is based on a very limited use of the drill, at a low-rotation speed, preventing heat damage.

Once the level of the osteotomy is chosen, a very small longitudinal incision (about the width of a medium chisel) is made. The bone is then bored with a 4.5 mm drill bit through the greater axial diameter. The soft tissues protection is assured by a sleeve, which is, furthermore, useful in aiming the drill.

In order to prevent over-perforation beyond the far cortex when the drill bit bumps into the latter, a safety ring is locked over the drill bit, about 5–8 mm from the protection sleeve's entering hole (this distance corresponds approximately to the width of a bone cortex). This way the drill bit tip cannot run much over the far cortex. The same procedure is then repeated some more times changing the entrance angle. The bone is now weakened in the entire circumference, so the osteotomy can be completed by means of a chisel.

When the osteotomy is complete, the rod nuts or the gauge ballpoints are locked again according with measurements earlier recorded.

The fibula osteotomy

The fibula osteotomy is nearly always associated to the tibia osteotomy. Very seldom is a fibula resection needed. It can be performed at a different level from the tibia osteotomy, usually about 8–10 cm proximal to the tibio-fibular distal syndesmosis as the surgical approach gets easier. If the fibula osteotomy is very far distal, while the tibial one is proximal, there is the risk for an important lateral migration of the distal tip the proximal fibular stump, causing a painful and anti-aesthetic lateral distal bump.

Different from the fibula resection for the tibia non-unions, in corrections the osteotomy is oblique. In the case of a rotational abnormality, over compression at the osteotomy site needs to be avoided. For an external rotation deformity the slope has to be carved in the direction of the anterior-posterior and proximal-distal; if the rotation is internal the cut will be posterior-anterior and proximal-distal.

In all cases where traction will be acted on the fibula osteotomy or when a considerable correction is planned, both the proximal and the distal tibio-fibular joints are to be stabilized with a transfixing wire or with a lag screw.

The structural danger in this procedure is mainly the interosseous artery. A good tip could be to inflate the tourniquet when performing the fibula osteotomy and to deflate it before the wound closure. If the bleeding control gets complicated, it is better to put some hemostatic dressing with some compression and to postpone the wound closure at the end of the surgery (after the frame application and the tibia osteotomy) to verify the effectiveness of the procedure.

Axial deformity

While the frame application is the first step of a relatively long-term therapy for gradually correcting angles, about 15° of the internal or external rotation can be possibly treated acutely in the operating room after having performed the osteotomy(ies). This option has to be conducted by an experienced surgeon and one has to be careful of nerves and vessels torsion and of any possible anatomic and local issues (ie, scars). The deformity has to be thoroughly assessed pre-operatively with an angle-focused CT-scan, comparative of both limbs.

The procedure relies on the surgeon's experience in comparing anatomic and radiological landmarks, or, more precisely, the need for an angular correction tool that has to be applied on the rings [34].

The same angular correction tool can be used if the decision is to go through a gradual postoperative treatment.

In case of a hexapodal frame, the axial deformity, together with the frontal and sagittal components, will be managed by the correction software at the same time.

Postsurgical management

Usually correction is started 5–10 days after surgery. After another 7–10 days, a 2P X-ray control is prescribed in order to check the start of the correction.

In pure lengthening, the speed for correction is ordinarily 0.50/0.75/1.00 mm per day, that is one-half or three-quarters or 1 complete turn of each correcting nuts. It would be better if turning the nuts was partitioned in 3 or 4 times in a day, but this calls for very collaborative patients. Facing a tibia or a femur, different anatomic and biological conditions, age, and coexisting patients' pathologies will lead to different protocols.

When performing axial corrections, the turning rate varies on the expected angular speed (the farther the turning nuts are from the CORA, the faster the turning rate will need to be). Very often, if the deformity is multiplanar, the hinges and correcting nuts will need to be changed during the treatment. The angular correction with a traditional circular frame is strongly dependent on the surgeon's experience, a relatively frequent X-ray revaluation, and on a very well-organized and accessible outpatient clinic.

When using hexapodal frames, things are different, meaning that, as they are all software-based, the surgeon

Fig. 3 Male, 43 years. Malunion right tibia after open Gustilo-Anderson III A fracture (2 years earlier), 18° valgus, 35 mm shortening. (1) Preoperative teleradiography. (2) The chisel for the De Bastiani

osteotomy (corticotomy) under fluoroscopy. (3) Postoperative X-ray control. (4) Teleradiography at the end of the correction (35 days after the operation, 28 days after the beginning of the correction)

enters into the computer some anatomic, geometric, and frame-related data and decides on the correction rates and anatomic endpoints. As there are some different devices available, it would be impossible to describe each single one. In general, the patient's personal records, bone and side, frontal, sagittal, axial angles of the deformity, amount of shortening, frame identifying factors (rings diameters, position, and length of the telescopic struts), position of the reference ring in relation to the origin (lateral/medial, anterior/posterior and axial frame offset) are the input parameters. The software will provide some different options, like the final frame appearance and the correction rate. It is the surgeon's task to optimize the frame management. The software is even capable of anticipating the need for a strut change, with some days of tolerance, enabling the team to plan a well-established outpatient examinations agenda (Fig. 3).

The patient needs to be educated in scrubbing the interface between skin and screws or wires every 2–3 days with iodopovidone in the first phases, and even once a week with a chlorhexidine solution later on as the inflammation regresses. The interface will be dressed with clean gauze sealing. The frame has to be cleaned every 1 or 2 weeks with physiologic solution.

The rehabilitation

In general the patient would be allowed to apply full weight-bearing as soon as tolerated, unless anatomic or pathologic conditions or the frame instability advise differently. Indeed, this latter condition should be considered a complication and the surgeon has to fix it somehow, possibly with a new operation.

It is well known that corrections and especially lengthenings can provoke alterations in soft tissues, particularly the muscles.

The establishing of scars is a very important issue, because, while tying up different anatomic structures, it will significantly limit the joints movement. The hip, knee, and ankle should be kept at their full (until the limits of a possible frame impingement) range of motion. An early passive motion program is established and the patient should be encouraged to regain active movements as soon as possible.

The physiotherapist should focus on the patient's posture and on his/her gait scheme.

To counterbalance the tendency of foot plantar flexion, especially in the lengthenings [35], we recommend an anti-equinus soft foot support connected by means of some elastics to the frame, which allows for active ankle motion.

Frame removal

Before the removal 3 conditions have to be satisfied (the "three-legged stool rule"):

- (1) a reasonable time has passed since the end of the correction (usually at least 3 months);
- (2) a 4-projections X-ray demonstrates a good callus formation;
- (3) the clinical test, by means of strong stresses at the correction site, all the struts open, the frame still in place, proves absolute stability.

Once the resolution is taken, the patient will be scheduled for the operation room. The anesthesiologists in our service usually opt for a light and short narcosis, or, more rarely, for a spinal anesthesia or a nerve block.

All the wires and the screws are unlocked, the wires are cut short to the skin. The wire has to be cut on the opposite side of the olive, if the latter is present. When wire and screws are free, they can be removed. A plaster cast is very seldom needed.

Usually we recommend to the patients to avoid overload or important torsion stresses for the first month after frame removal. We reevaluate clinically and with a 2-projections X-ray 2 months after frame removal.

Conclusions

Basically, a post-traumatic deformity can be treated with an all-in-one open surgical procedure, by means of internal plates, or with a gradual, minimally invasive, external frame-based approach.

The external frame strategy offers some advantages in terms of biology and precision of the correction, while it is quite demanding for the patient and needs a very skilled surgeons' team.

In this paper we give a brief overview of the technical waypoints, in the planning as well as in the operating room, and of the anatomic landmarks that should be respected in an external fixator treatment.

Compliance with Ethics Guidelines

Conflict of Interest Matthew D. Karam and Saran Tantavisut declare that they have no conflict of interest.

Daniele Santoro reports previous travel accommodations were paid for by Smith & Nephew, outside of the submitted work. Domenico Aloj collaborated to write a Taylor Spatial Frame Italian manual for Smith and Nephew, outside of the submitted work. D. Aloj was not monetarily compensated for the manual.

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References

Papers of particular interest, published recently, have been highlighted as:

- Of importance

- Butcher CC, Atkins RM. Principle of deformity correction. *Curr Orthop*. 2003;17:418–35.
- Weiss RJ, Montgomery SM, Al Dabbagh Z, Jansson KA. National data of 6409 Swedish inpatients with femoral shaft fractures: stable incidence between 1998 and 2004. *Injury*. 2009;40:304–8.
- Wu CC. An improved surgical technique to treat femoral shaft malunion: revised reamed intramedullary nailing technique. *Arch Orthop Trauma Surg*. 2001;121:265–70.
- Court-Brown CM, McBirnie J. The epidemiology of tibial fractures. *J Bone Joint Surg (Br)*. 1995;77:417–21.
- Milner SA, Davis TR, Muir KR, Greenwood DC, Doherty M. Long-term outcome after tibial shaft fracture: is malunion important? *J Bone Joint Surg Am*. 2002;84-A:971–80.
- Koval K, Zuckerman J. *Handbook of Fractures*. 3rd ed. Philadelphia: Lippincott Williams and Wilkins; 2006. p. 394.
- Winguist RA. Closed intramedullary osteotomies of the femur. *Clin Orthop*. 1986;212:155–64.
- Chapman MW. *Chapman's Orthopaedic Surgery Volume 1. Chapter Malunion and Nonunion*. Philadelphia: Lippincott Williams and Wilkins; 2001. p. 847–1001.
- Knight JL. A precision guide-pin technique for wedge and rotator osteotomy of the femur and tibia. *Clin Orthop Relat Res*. 1991;262:248–55.
- Pullisetti TD, Onwochei MO, Ebraheim NA, Humphries C, Coombs RJ. Mathematical precision in rotational corrective osteotomy of the femur. *J Orthop Trauma*. 1998;12:360–2.
- Sangeorzan BJ, Sangeorzan BP, Hansen Jr ST, Judd RP. Mathematically directed single-cut osteotomy for correction of tibial malunion. *J Orthop Trauma*. 1989;3:267–75.
- Dobbe JG, Pre KJ, Kloen P, Blankevoort L, Streekstra GJ. Computer-assisted and patient-specific 3-D planning and evaluation of a single-cut rotational osteotomy for complex long-bone deformity. *Med Biol Eng Comput*. 2011;49:1363–70.
- Russel GV, Graves ML, Archdeacon MT, Barei DP, Brian Jr GA, Poster SE. The clamshell osteotomy: a new technique to correct complex diaphyseal malunions: surgical technique. *J Bone Joint Surg*. 2010;92(Suppl 1 Pt 2):158–75.
- Tall M, Ouedraogo I, Nd Kasse A, Tekpa BJ, Bonkoungou G, Belem S, et al. Femur malunion treated with open osteotomy and intramedullary nailing in developing countries. *Orthop Traumatol Surg Res*. 2012;98:784–7.
- Johnson JE. Acute shortening of shorten lower extremities after malunion or nonunion of a fracture. *J Bone Joint Surg*. 1994;76:379–89.
- Sanders R, Anglen JO, Mark JB. Oblique osteotomy for the correction of tibial malunion. *J Bone Joint Surg Am*. 1995;77:240–6.
- Buijze GA, Richardson S, Jupiter JB. Successful reconstruction for complex malunions and nonunions of the tibia and femur. *J Bone Joint Surg Am*. 2011;93:485–92.
- Feldman DS, Shin SS, Madan S, Koval KJ. Correction of tibial malunion and nonunion with six-axis analysis deformity correction using the Taylor Spatial Frame. *J Orthop Trauma*. 2003;17:549–54.
- Borrelli Jr J, Leduc S, Gregush R, Ricci WM. Tricortical bone grafts for treatment of malaligned tibias and fibulas. *Clin Orthop Relat Res*. 2009;467:1056–63.
- Johnson EE. Multi-plane correctional osteotomy of the tibia for diaphyseal malunion. *Clin Orthop Relat Res*. 1987;215:223–32.
- Lark RK, Lewis Jr JS, Watters TS, Fitch RD. Radiographic outcomes of ring external fixation for malunion and nonunion. *J Surg Orthop Adv*. 2013;22:316–20.
- Seybold D, Gessmann J, Ozokyay L, Muhr G, Graf M. The Taylor spatial frame. Correction of post-traumatic deformities of the tibia and hindfoot. *Unfallchirurg*. 2008;111:985–6.
- Wu CC, Chen WJ, Shih CH. Tibial shaft malunion treated with reamed intramedullary nailing: a revised technique. *Arch Orthop Trauma Surg*. 2000;120:152–6.
- Chiodo CP, Jupiter JB, Alvarez G, Chandler HP. Oblique osteotomy for multiplanar correction of malunions of the femoral shaft. *Clin Orthop Relat Res*. 2003;406:185–94.
- Yasui N, Nakase T, Kawabata H, Shibata T, Helland P, Ochi T. A technique of percutaneous multi-drilling osteotomy for limb lengthening and deformity correction. *J Orthop Sci*. 2000;5:04–7.
- Paley D. *Principles of deformity correction*. Berlin: Springer; 2002.
- Leonardi F, Rivera F, Zorzan A, Ali SM. Bilateral double osteotomy in severe torsional malalignment syndrome: 16 years follow-up. *J Orthop Traumatol*. 2014;5:131–6.
- Taylor JC. Correction of general deformity with the Taylor Spatial Frame Fixator. Available at: www.jcharlestaylor.com. 2002.
- Taylor JC. Treatment of tibial malunions: characterization by a graphical method. Available at: www.jcharlestaylor.com. 2011. *This article provides surgeons a useful tool for anticipating the real deformity aspect from a multi-dimensional perspective.*
- Ganger R, Radler C, Speigner B, Grill F. Correction of post-traumatic lower limb deformities using the Taylor spatial frame. *Int Orthop*. 2010;34:723–30.
- Marangoz S, Feldman DS, Sala DA, Hyman JE, Vitale MG. Femoral deformity correction in children and young adults using Taylor Spatial Frame. *Clin Orthop Relat Res*. 2008;466:3018–24.
- Magyar G, Toksvig-Larsen S, Moroni A. Hydroxyapatite coating of threaded pins enhances fixation. *J Bone Joint Surg (Br)*. 1997;79:487–9.
- De Bastiani G, Aldegheri R, Renzi-Brivio L, Trivella G. Limb lengthening by callus distraction (callotaxis). *J Pediatr Orthop*. 1987;7:129–34.
- Shtarker H, Volpin G, Stolerio J, Kaushansky A, Samchukov M. Correction of combined angular and rotational deformities by the Ilizarov method. *Clin Orthop Relat Res*. 2002;402:184–95.
- Green SA. Postoperative management during limb lengthening. *Orthop Clin N Am*. 1991;22:723–34.