Metatarsal Malunion

Alexandre Leme Godoy-Santos, MD, PhD[a,b,*], Martim Pinto, MD[c], Rafael Barban Sposeto, MD[a]

KEYWORDS

• Metatarsal • Fracture • Malunion • Treatment • Fixation

KEY POINTS

- Metatarsal fractures account for almost 50% of all foot fractures; the most frequent trauma mechanism for central metatarsal fractures is a direct trauma.
- Care should be taken when evaluating patients with higher energy accidents, as they are often associated with serious soft-tissue damage and adjacent joint injuries, such as Lisfranc injuries.
- Metatarsal malunions resulting from fractures or osteotomies can be quite challenging as shortening or flexion though as small as 2 mm can lead to painful long-term metatarsalgia.
- Malunions on the axial plane (varus/valgus) are usually better tolerated than the ones on the coronal plane, especially plantar flexion deformity.
- The treatment aim—surgical or nonsurgical—is to reduce the pain and improve gait function.

INTRODUCTION

Metatarsal fractures are common foot injuries that account for almost 50% of all foot fractures, although, in the elderly Caucasian women population they account for up to 88.5%, and are commonly a consequence of low-energy trauma, such as a fall from standing height or a simple twist.[1,2] Furthermore, sports injuries and direct blow account for 18% of all metatarsal fractures.[1] When looking uniquely at central metatarsal fractures (second [M2], third [M3], and fourth [M4] metatarsals), the most common mechanism of injury is a direct trauma, as opposed to indirect torsional one.[3]

Oftentimes, simple fractures show minimal displacement due to the strong ligamentous insertions anchoring between metatarsals. As such, these low-grade displacement

[a] Departamento de Ortopedia e Traumatologia, Hospital das Clinicas, Faculdade de Medicina, Universidade de Sao Paulo, R. Dr. Ovídio Pires de Campos, 333, São Paulo 05403-010, Brazil; [b] Programa Aparelho Locomotor, Hospital Israelita Albert Einstein, Av. Alebrt Einstein, 627, São Paulo 05652- 900, Brazil; [c] Departamento de Ortopedia e Traumatologia Hospital Vila Franca de Xira, Estrada Carlos Lima Costa, n2, Vila Franca de Xira 2600-009, Portugal
* Corresponding author. Lab. Prof. Manlio Mario Marco Napoli, Departamento de Ortopedia e Traumatologia, Hospital das Clinicas, Faculdade de Medicina, Universidade de Sao Paulo, R. Ovidio Pires de Campos, 333, 05403-010, Sao Paulo, Brazil.
E-mail address: alexandrelemegodoy@gmail.com

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fractures may be successfully treated without resorting to surgery.[4] In contrast, with higher energy, fractures tend to be multiple and more displaced. When there is more than 3 to 4 mm of displacement and 10° of angulation, surgical treatment is recommended.[5] The main goal of surgically treating unstable fractures is to reduce the metatarsal formula which in mandatory for pain-free ambulation.[6] Care should be taken when evaluating these patients with higher energy accidents, as they are often associated with serious soft-tissue damage and adjacent joint injuries, such as Lisfranc ones.[1]

As in other fractures/osteotomies, metatarsal malunions consist of injuries that have healed in an unacceptable position, either due to rotation, angulation, shortening, or lengthening.[7] Malunions can be consequent to fractures, or osteotomies that are frequently used in everyday practice, for surgical correction of forefoot pathology, either for first (M1) or lesser metatarsals. Nonetheless, these can be quite challenging as shortening, flexion, or extension malunions, though as small as 2 mm, can lead to painful long-term metatarsalgia.[8–11] Moreover, that is even more important when using an oscillating saw, as these typically generate a defect of at least 1 mm.[12] Certain metatarsal osteotomies may develop dorsal angulation malunions with an incidence of up to 82%.[13]

Most of the available research articles regarding metatarsal fractures are specifically directed toward Lisfranc injuries or to fractures of the fifth metatarsal base. Unfortunately, there is scarce literature available regarding metatarsal malunion.[6,14–17]

The aim of this article is to discuss the lateral metatarsal malunion related to trauma.

ANATOMY AND BIOMECHANICS

To fully understand the consequences of a metatarsal malunion, it is mandatory to comprehend the metatarsal anatomy and biomechanics.

The metatarsals are prismoid-shaped bones, located on the forefoot, bridging the tarsal bones to the phalanges. The strong ligamentous and muscle insertions provide stability, leaving the M2 and M3 metatarsals relatively immobile on the sagittal plane, when comparing to the fourth (M4) and fifth (M5). This increased mobility of the tarsometatarsal joint of the M4 and M5 metatarsals leads to greater adaptability to the ground, on this plane.[14,18] For the same reason, diaphyseal metatarsal fractures tend to displace less, when lumbricals and interosseous muscles as well as the ligamentous insertions remain intact. On the other hand, head and neck fractures tend to displace more due to action of the flexor tendons.[18]

The metatarsals are the only long bones that play their role of load-bearing at an axis that is perpendicular to their longitudinal axis. As such, there are 2 major deforming forces that must be resisted, especially during the metatarsal healing process. These forces are shear and bending, and they are generated across the metatarsal bone, while weight bearing. These forces tend to displace fractures/osteotomies that are not stable under physiologic loading, resulting in malunion.[19]

Lelièvre first described the harmonious arch that is seen on the axial plane of the foot—the distal metatarsal parabola.[20] This ideal outline is curved anteriorly with the M2 being longer than the M1 and greater than the M3. The M3 is longer than the M4 and the M5 is the shortest overall.

The M1, M4, and M5 heads are disposed in the same line and the M2 is more extended than the M3, which is more extended than the M4, when we are evaluating the coronal plane with weight-bearing.[21]

Changes to the physiologic aforedescribed disposition, on either plane of the metatarsals, directly influences how the weight is distributed to the forefoot. That said, following a malunion, when a disruption of the load distribution is seen, structures of the forefoot become overloaded and metatarsalgia occurs.[22,23]

Metatarsal heads are loaded through the mid-stance and even more so during the heel-off phase of gait.[24] On the coronal plane, if the relative position of the metatarsal head is closer to the ground than all others, an increased pressure will be transferred by that metatarsal head and “standing” or “static” metatarsalgia develops.[23] On the other hand, when changing the metatarsal head position on the axial plane, due to changes in length, a “propulsive” metatarsalgia tends to develop.[23,25]

During gait, the M1 is subject to 2 times the force burden as its 4 lateral counterparts, magnifying the necessity for appropriate reduction/reconstruction of this bone after a fracture/osteotomy.[24]

Following an M1 osteotomy, dorsiflexion and shortening are the most recurrent malunion deformities, leading to a shift in weight distribution toward the lesser metatarsals, generating transfer lesions.[17,24,26] It is worth mentioning that a shortening as small 2 or 3 mm is enough to cause transfer lesions.[8–11] Likewise, dorsal malunion may also trigger restricted dorsiflexion of the metatarsophalangeal joint due to articular incongruence, osteophytes, and dorsal impingement.[27] With this in mind, it can be easily concluded that it is of paramount importance to reestablish the alignment of M1, to fully restore its weight-bearing function while walking. This is because small variations in length or elevation often lead to drastic effects on the function and performance of the M1, during gait.

Despite the lesser load being transferred to the ground through each individual lateral rays, deformities behave similarly. Plantarflexion of the distal fragment leads to excess load through the metatarsophalangeal joint that may bring an unmanageable plantar keratosis.[23] Dorsiflexion of the distal fragment reduces load on the respective metatarsal producing an overload metatarsalgia on the nearby metatarsal heads.[23]

Malunions on the axial plane (varus/valgus) are usually better tolerated than the ones on the coronal plane and may lead to shoe toe box or adjacent toe impingement.[16,17]

HISTORY AND PHYSICAL EXAMINATION

Depending on the location and deformity caused by the malunion, it can result in different clinical manifestations.

When there is a flexion, extension, shortening, or lengthening malunion, it may result in pathologic forefoot load distribution.[17,27,28] Patients complain of mechanical metatarsalgia caused by stress on bone and overlying soft tissue due to incorrect distribution of weight on the forefoot during repeated cycles of gait. It is usually associated with intractable plantar keratosis, as a sign of overload.[28]

It is of utmost importance to carefully observe the patients gait. As gait progresses from first, passing through second to third rocker, pressure is transferred from the hindfoot anteriorly to the forefoot, where the metatarsal(s) head(s) bear an increased load. A thorough assessment of the plantar keratosis is essential. A plantar keratotic lesion distal to the metatarsal head toward the first phalanx, indicates dysfunction/overload during third rocker phase of gait, a “propulsive” metatarsalgia.[25,28] Nevertheless, a more diffuse lesion right below the metatarsal head is a sign of excess plantar pressure during the second rocker phase of gait, a “static” metatarsalgia.[25,28]

The location of the keratotic lesion is of great importance, as it guides the surgeon toward the available treatment options: a “propulsive” metatarsalgia tends to be associated with relative length malunion, whereas a “static” metatarsalgia is associated with a relative flexion malunion.[29]

Dorsal metatarsal malunion or post-traumatic arthritis may also present with decreased metatarsophalangeal range of motion, dorsal osteophytes, and deformity.[27] Notwithstanding, care must be taken upon palpation of the metatarsal heads, the intermetatarsal gaps, and checking the range of motion of the metatarsophalangeal joints.

Varus and valgus malunions of the central metatarsals tend to result in next toe impingement. Besides, if the same deformity is present on the M1 or the M5, it also manifests with shoe toe box impingement.[17]

Finally, a complete foot and ankle examination is necessary to assess for co-pathologies as they may change treatment options, such as alignment of the lower limb and hindfoot with the patient standing, joints' flexibility/range of motion, gastrocnemius, and/or soleus muscles tightness. The neurologic and vascular assessment should be performed.

IMAGE INVESTIGATION

Image investigation identifies the source of pain and deformity in the patient's forefoot and helps to quantify and qualify the malunion. Proximal malunions are more prone to evolve with greater deformities due to increased moment arm. Therefore, locating the deformity in the metatarsal (head, neck, proximal metaphysis, or diaphysis) is important.

The images will allow us to understand the planes and axes of the deformity, shortening, and osteoarthritis signs—essential information to strategize surgical planning.

Radiograph

Weight-bearing radiograph is essential for metatarsal malunion investigation.[30] One should acquire at least 4 incidences (anteroposterior, lateral, oblique, and axial) to evaluate the axial, sagittal, and coronal planes.[29]

Anteroposterior view

The metatarsal formula in the axial plane can be evaluated in this view, assessing the relative lengths of each metatarsal. Therefore, it enables to plan the lengthening of the metatarsal (**Fig. 1**).

Malalignments in the axial plane are also evaluated in the anteroposterior view. In patients with metatarsal malunion and metatarsalgia, the malalignment is usually in the axial plane and associated with shortening and deviation on the sagittal plane[3] (**Fig. 2**).

Lateral and oblique views

The deformities in flexion or extension on the sagittal plane are evaluated on the lateral radiograph. These malalignments are prone to changes in the load distribution on the forefoot, creating overloads in the adjacent metatarsals and pain.[3,17,27]

On the lateral view, all 5 metatarsals are overlapped, and it may be challenging to understand which central metatarsal is misaligned. The oblique view helps to seek the deformed metatarsal.

Axial view

Several investigators[20,21,31–37] propose different radiographic techniques to perform an axial view. It is useful to visualize the disposition of the metatarsal heads in the coronal plane. Some of them are non–weight-bearing radiographs, and others promote an excessive extension of the metatarsophalangeal joints, creating an incorrect alignment.[38]

The ideal axial radiographic technique is done weight-bearing, positioning the forefoot on the ground plane, and extending the metatarsophalangeal joints limited to the physiologic gait pattern.[21,38]

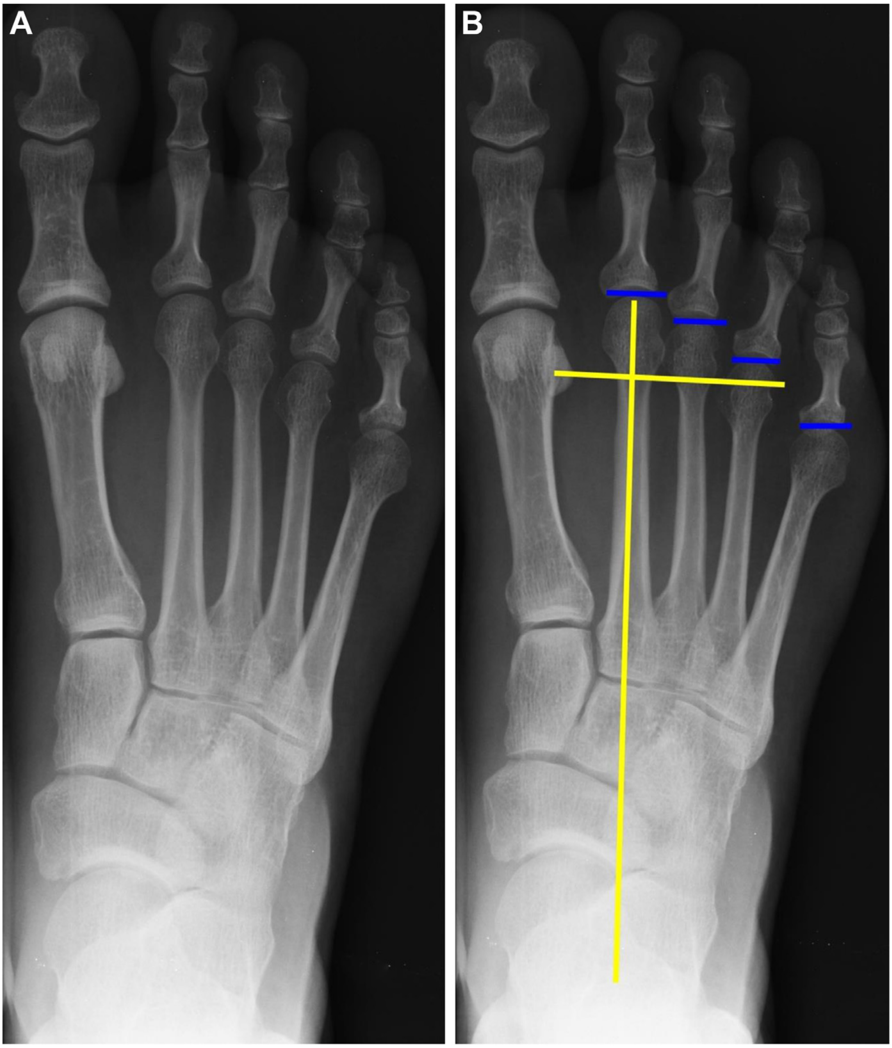

Fig. 1. (*A*) Weight-bearing anteroposterior foot X-Ray. (*B*) Metatarsal formula measurements, as described by Maestro and colleagues M2>M3>M4>M5. The distance between the metatarsals varies following a geometric progression ratio of 2. These parameters must be used for diagnosis, planning, and surgical procedures.

Therefore, using these parameters, one could evaluate the normal position of the metatarsal heads in the coronal plane, expecting M1, M4, and M5 disposed in the same line and M2 more extended than M3, which is more extended than M4. In a metatarsal malunion, when a misalignment is seen on the axial view, it must be corrected if surgical treatment is considered (Fig. 3).

Computed Tomography

Computed tomography (CT) provides more precise malalignment evaluation.

On distal malunions, head, or neck, we must seek dorsal osteophytes or a large amount of bone formation due to consolidation. This dorsal bone excess may impinge

Fig. 2. M2 and M3 malunion in abduction, evaluated on weight-bearing anteroposterior view.

on the proximal phalanx during the metatarsophalangeal dorsiflexion, causing pain and decreased range of motion.[39] Because the CT is able to take many sequential thin cuts, they provide a precise view to evaluate these possible bone formations.

The anteroposterior radiograph sufficiently quantifies the metatarsal axial plane deviations. Nevertheless, sagittal and coronal planes deviations are better quantified

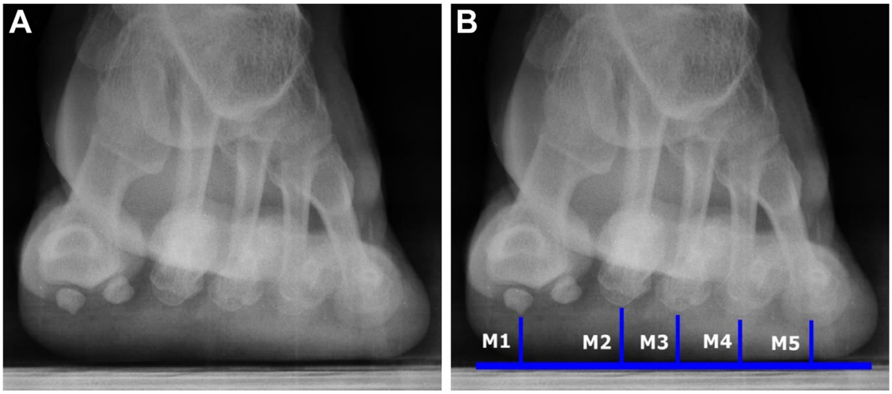

Fig. 3. (*A*) Weight-bearing axial X-Ray of the foot—evaluating the coronal plane. (*B*) Metatarsal formula measurements on the coronal plane. The M2 and M3 usually are more distant from the ground than M1, M4, and M5. These parameters must be observed for diagnosis, planning, and surgical intervention.

with a CT. It is possible to observe the sagittal plane of the specific malunited metatarsal and measure the malalignment angle to plan the amount of surgical correction needed (**Fig. 4**).

Weight-bearing CT gathers the precision of the thin cuts of the CT in a foot with physiologic load. It allows a 3-dimensional interpretation of the relative position of each foot bone, with load.[40–42] There is an increasing number of studies focused on the forefoot, most of them related to hallux valgus.[40,41,43–46]

Unfortunately, most CTs available are non-weight bearing, providing a partial evaluation of the foot architecture.[40,44,45] However, it does not interfere in the metatarsal malunion angles measures.

MRI

The MRI adds the soft tissue assessment to the CT. In patients with metatarsal malunion that is associated with metatarsophalangeal joint deformity, plantar plate or tendinous lesions should be investigated. On the other hand, patients with metatarsal malunion that is associated with articular pain and stiffness, cartilage defects and osteoarthritis should be evaluated.[29]

This information helps to assess functional impairment and surgical planning, as it adds eventual soft-tissue procedures to bone malalignment correction.

TREATMENT

The treatment aim is to reduce the pain and improve gait function.[39,47]

Nonsurgical

Forefoot pain is a consequence of an impaired weight distribution due to misalignment of the metatarsal malunion.[12,39,48] Therefore, the treatment strategy focuses on a modification of weight distribution to relieve the overloaded structures on the forefoot.[16,26,47,49]

Few studies describe the benefits of weight redistribution (nonoperative treatment) for the improvement of metatarsalgia secondary to malunion. Nevertheless, the concepts of general metatarsalgia conservative treatment can be used.[16] Since there is an acquired anatomic deviation, expecting worse results with nonsurgical treatment of a metatarsalgia secondary to metatarsal malunion is reasonable.

We can change the weight distribution nonsurgically with stiff sole shoes, rocker shoes,[50] metatarsal pads, and insoles with retro capital elevations.[16,51,52] Other approaches with analgesics, nonsteroidal anti-inflammatory drugs (NSAIDs), and physical therapy are also indicated to relieve metatarsalgia.[53–56]

Männikö and Sahlman ,[51] in a retrospective cohort, studied 25 patients with metatarsalgia, treated with insoles associated with a metatarsal pad, for at least 1 year of

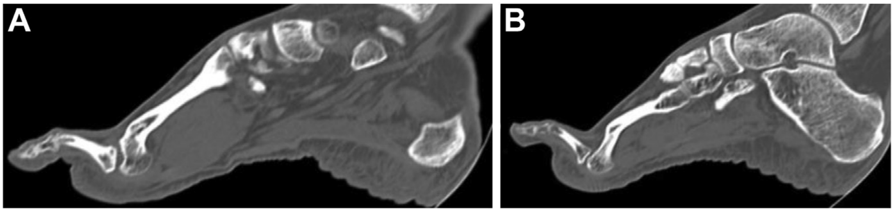

Fig. 4. (*A*) Sagittal computed tomography, M2 with a 90° flexion metaphyseal malunion: (*B*) Sagittal computed tomography, M3 with a flexion diaphyseal malunion.

follow-up. Forty-eight percent kept the use for more than 1 year. In the remaining group of patients, 20% were surgically treated, 8% had stopped the use because they had not improved enough, and 20% had not improved. The American Orthopaedic Foot and Ankle Society score improved in 88% of the patients.

Sobhani and colleagues,[50] in a comparative study with 18 women, who practiced noncompetitive running, evaluated the differences in the plantar load in a rocker shoe. Using an insole with sensors, they compared the plantar load distribution in a regular shoe when running, with the same shoe model with a stiffened rocker profile inserted. The sensors showed a decrease of 12% in the maximal mean pressure in the central and lateral forefoot ($P<.001$).

It is important to notice that the aforementioned results are related to general metatarsalgia management and treatment, and not specifically to the metatarsalgia caused by metatarsal malunion. Nevertheless, this can be helpful when advising conservative treatment options that could relieve pain and decrease the forefoot overload in cases of metatarsal malunion. Surgical treatment is then indicated, if the conservative treatment options fail to relieve metatarsal pain.[16,39]

Surgical

The aim of surgical treatment is to relieve pain by correcting the acquired deformity[48] (**Fig. 5**).

Osteotomy position and conformation

Usually, the osteotomy is performed in the deformity apex when the metatarsal malunion causes deviation.[12,16,39] Performing the osteotomy at another point of the metatarsal is possible. However, it would take a second deformity to align the metatarsal axis in all its planes.

The metaphyseal region has a higher degree of vascularization and a larger cross-sectional area. Thus, osteotomies in this anatomic region are more likely to heal appropriately, than ones in the diaphyseal region.[12] Thereby, one should expect a longer consolidation time for diaphyseal osteotomies and use stiffer fixation methods, in order to maintain the position obtained during surgery until achieving bone union and total healing.[39]

The osteotomy should ideally allow for correction in all of the affected planes, especially the sagittal and coronal. Some osteotomy types lead to intrinsically unstable results and should be avoided when possible. More stable osteotomy approaches should be preferred when dealing with malunions.[12,16,39]

Complete osteotomies allow correction in all 3 planes, thus correcting rotation, but these are more challenging and unstable. The incomplete osteotomies have the advantage of being more stable, as one cortical remains intact, but in these cases, correction can be achieved only on the perpendicular plane of the osteotomy.[12,39,47]

The incomplete osteotomies are generally performed using wedges. The resection of a dorsal wedge at the level of the deformity apex in a plantar flexed malunion, while keeping the plantar cortical intact, is an effective approach to correction (**Fig. 6**). Nonetheless, this option does not provide lengthening, as most of the correction is in the sagittal plane.[12] An open wedge osteotomy functions similarly to dorsiflexed malunions, with additional chances of nonunion, related to the graft.[24]

Resecting a plantar wedge is technically demanding because the approach remains dorsal, and the osteotomy needs to be complete, thus adding instability. Also, this option can be performed in a dorsiflexed malunion when using a reliable fixation.[49]

Regarding the osteotomy shape, firstly, the transverse is a complete osteotomy with a great correction potential in the 3 planes. Still, in cases of malunion with metatarsal

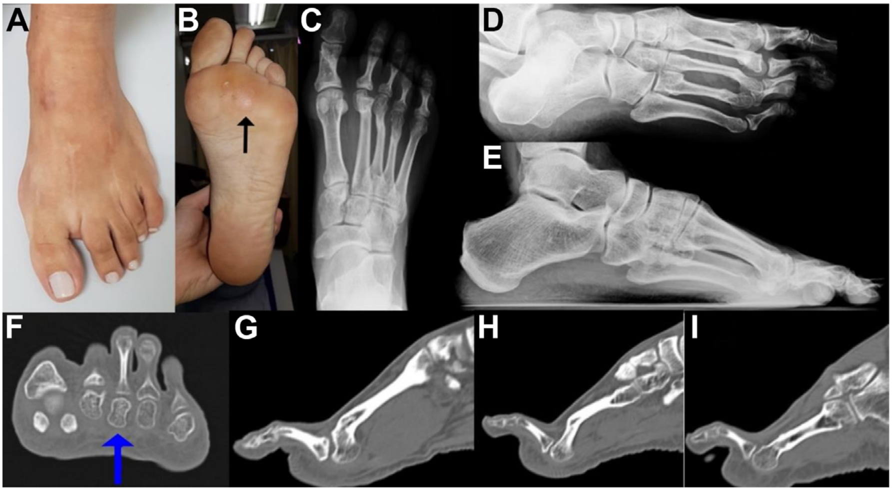

Fig. 5. Preoperative evaluation for surgical planning. (*A*) Clinical dorsal view of the foot. (*B*) Clinical plantar view of the foot, with a callosity under the M3 head. Plantar foot pressure point (*black arrow*). (*C*) Weight-bearing anteroposterior radiographic foot view. M2, M3, and M4 with malunion and alteration of the metatarsal formula. (*D*) Weight-bearing oblique radiographic foot view. M2 and M3 severally flexed. (*E*) Weight-bearing lateral radiographic foot view. It is possible to note a misalignment, but it is challenging to identify which metatarsal is deformed. (*F*) Coronal computed tomography view. The arrow marks the M3 head flexed, changing the metatarsals heads relation. (*G*) M2 sagittal computed tomography view. The location and quantification of the deformity, (*H*) M3 sagittal computed tomography view. Te location and quantification of the deformity. (*I*) M4 sagittal computed tomography view. One should note that there is no M4 malunion.

shortening, this type of osteotomy does not provide lengthening. If metatarsal shortening is associated with the deformity and a transverse osteotomy is chosen, a block of bone graft is an option to lengthen the metatarsal.[39]

Secondly, an oblique osteotomy, in the axial or sagittal planes, offers the option of lengthening with a large contact area of bone.[16,47,48] The direction of the oblique osteotomy in the axial plane (visualized on lateral view) must be carefully planned; an osteotomy proximal and dorsal to plantar and distal is intrinsically unstable with load, and probably will consolidate with extension of the distal fragment.[12,47] The proximal and plantar to distal and dorsal conformation is preferred, as it is more stable.

Lastly, an oblique osteotomy in the sagittal plane (visualized on anteroposterior view) provides a lengthening correction option and alignment in the sagittal plane, correcting extension or flexion of the distal metatarsal.[12,47] The oblique osteotomy in the axial plane can correct extension and flexion misalignments, but a wedge must be associated.

Fixation options

The Kirschner wires, locking plates, and screws are the most commonly used implants in metatarsal fractures and osteotomies.[57] Nevertheless, there is a paucity of biomechanical and clinical studies related to the fixation of lateral metatarsal malunions.

Murphy and Fallat[16] described 2 cases of surgical treatment options for metatarsal malunions. Both of these resorted to resecting a wedge at the apex of the deformity. In

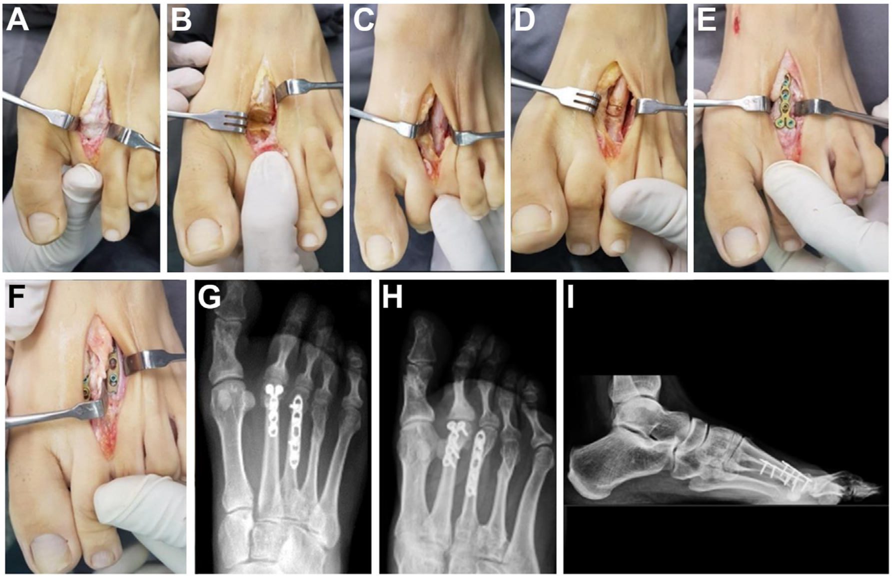

Fig. 6. Metatarsal malunion surgical correction: (*A*) longitudinal incision between M2 and M3 provided access for both metatarsals. Note the M2 dorsal apex malunion. (*B*) Incomplete closing wedge osteotomy at the M2 deformity apex. (*C*) M3 visualization provided by the incision. (*D*) Delimitation of M3 incomplete closing wedge osteotomy at the deformity apex. (*E*) M2 fixation with a 2.7-mm locking plate. As the distal M2 segment was short, a "T" plate was chosen, affording more stability. (*F*) M3 fixation with a 2.7-mm locking plate. (*G*) The fourth-month postoperative weight-bearing foot X-Ray (anteroposterior view). Note the metatarsal formula reestablished and complete osteotomy consolidation. (*H*) The fourth-month postoperative weight-bearing foot X-Ray (oblique view). Note the correction of the flexion deformity. (*I*) The fourth-month postoperative weight-bearing foot X-Ray (lateral view). Note the metatarsal formula reestablished and complete osteotomy consolidation.

1 patient, they fixed M2 with a 2.7-mm plate, compressing the osteotomy; the M3 and M4 were fixed with Kirschner wires, using the relative stability concept. In the second patient, only Kirschner wires were used for fixation. Both patients at the 1-year follow-up had radiographic consolidation and a substantial decrease in forefoot pain.

Trost and colleagues[57] evaluated 72 metatarsals (M2 to M5), equally distributed in 4 groups, in a biomechanical cadaveric study. They compared the stiffness and failure strength of 4 types of fixation: Kirschner wire 1.6 mm, titanium elastic nail 1.5 mm, 2.4-mm locking plate, and an intramedullary bone stabilization system. The locking plate fixation provided a stiffer construction and higher failure strength.

Despite the lack of evidence about which is the better fixation principle (regarding both relative and absolute stability) and which is the best osteosynthesis in the surgical correction of metatarsal malunions, it is reasonable to assume that one should choose the most stable fixation to maintain the reduction position until the end of the healing process.

The locking mini-plates have advantages relating to stability,[57,58] since they afford more screw working length and more screws are located in each metatarsal segment. The plate can be used as a relative stability or an absolute stability device (by axial compression through the plate) or as a neutralizing plate (associated with a compression screw) (see Fig. 6).

The locking mini-plates have disadvantages related to the extension of the incision and soft tissue dissection.[16,57] Often, the osteotomies used to correct metatarsal malunion are performed with open accesses, to better visualize and more accurately reduce the metatarsal. Thereby, the positioning and fixation of the plate add minor soft-tissue trauma.

The Kirschner wire fixation can be performed to correct metatarsal malunion[16,47] with the advantage of causing less soft-tissue dissection, when comparing to the plates,[57] but provides less stability, with a possible loss of correction at the end of the treatment.

Minimally invasive techniques are gaining space in the clinical practice and the foot and ankle literature, with its promising results and they may be an option to correct metatarsal malunions. However, the authors did not find literature evidence for the superiority in using minimally invasive techniques, when compared to open procedures in the treatment of metatarsal malunion.[59,60]

Postoperative management

A reliable fixation offers early protected weight-bearing. The authors prefer performing fixation with plates and, whenever possible, absolute stability to allow early weight-bearing with a flat stiff sole sandal.

The weight-bearing may begin after soft tissue healing, usually around the 10th postoperative day. Full weight-bearing is allowed if protected by a flat stiff sole orthopedic sandal, if the patient is able to tolerate it.

The sandal must be used until radiographic consolidation signs are evident, usually between the second and the third postoperative months.

Physical therapy may begin on the first postoperative day, with attention to the metatarsophalangeal mobility to avoid adherence to the extensor tendons.

CLINICS CARE POINTS

- In decision-making for metatarsal fractures, it is essential to take into count that diaphyseal metatarsal fractures tend to displace less when the lumbrical and interosseous muscles, as well as the ligamentous attachments, remain intact. On the other hand, head and neck fractures tend to displace more due to the action of the flexor tendons.
- The benefits of early weight-bearing redistribution are clear for the improvement of metatarsalgia secondary to malunion. Nevertheless, concepts of general metatarsalgia conservative treatment can be used such as stiff sole shoes and rocker shoes, and approaches associated with analgesic and NSAIDs.
- In decision-making for metatarsal malunion, the osteotomy should ideally allow for correction in all of the affected planes, especially the sagittal and coronal. Some osteotomy types are intrinsically unstable and should be avoided when possible. More stable osteotomy approaches should be preferred when dealing with malunions.
- Finally, despite the lack of evidence about which is the better fixation principle (regarding both relative and absolute stability) and which is the best osteosynthesis in the surgical correction of metatarsal malunions, it is reasonable to assume that one should choose the most stable fixation to maintain the reduction position until the end of the healing process with less soft-tissue and bone dissection.

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