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Special Article

# The search for the holy grail in cavovarus foot

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## Abstract

**Introduction:** The surgical treatment of cavovarus foot is complex and multifactorial, requiring a personalized approach that respects its biomechanical and neuromuscular intricacies. Despite numerous techniques described, achieving a plantigrade, pain-free, and functionally stable foot remains the ultimate goal—the so-called "holy grail" of treatment.

**Methods:** This narrative review outlines a stepwise strategy for the surgical correction of cavovarus foot, emphasizing the role of soft tissue releases, tendon transfers, osteotomies, and fusions. The intervention sequence is tailored according to deformity flexibility, apex location, and muscular imbalance patterns, drawing from principles refined in managing Charcot-Marie-Tooth disease and adapted to other etiologies.

**Results:** Adequate soft tissue release—especially of the Achilles tendon, plantar fascia, and medial restraints—precedes osseous realignment. Tendon transfers, such as those involving the posterior tibial tendon or peroneus longus, aim to neutralize deforming forces and preserve correction. Decisions between osteotomy and arthrodesis hinge on the rigidity and anatomical apex of the deformity, often requiring midfoot realignment. Toe deformities, particularly hallux malleus, are addressed through targeted techniques like the Jones procedure, following proximal correction.

**Conclusion:** Successful reconstruction of the cavovarus foot depends on a dynamic, intraoperatively responsive algorithm that integrates functional muscle assessment, sequential releases, and appropriate structural correction. Lessons learned from neuromuscular cases contribute significantly to optimizing outcomes in idiopathic or post-traumatic deformities.

**Level of evidence V; Experience-Based Expert Opinion.**

**Keywords:** Cavovarus foot; Charcot-Marie-Tooth disease; Tendon transfer; Osteotomy; Arthrodesis; Foot deformity.

## Introduction

The quest for an ideal treatment for cavovarus foot has been a constant challenge. Traditionally, the "holy grail" in managing this complex deformity has been restoring muscle balance, aiming to correct biomechanical changes and alleviate symptoms. However, the growing understanding of the influence of neuromotor dysfunction, especially Charcot-Marie-Tooth disease (CMT), in the etiology of cavovarus foot has challenged this classic view[1,2].

Cavovarus foot, characterized by an elevated medial longitudinal arch, hindfoot varus, and forefoot pronation and adduction, is frequently associated with a variety of conditions, including lateral ankle instability, fifth metatarsal stress fractures, and fibular tendinopathies[3]. Although muscle imbalance is a well-established etiological factor, recent studies have shown that CMT is present in a significantly higher percentage of patients with cavovarus foot than previously thought[2].

This narrative review proposes a new perspective: the true "holy grail" does not lie in the complete restoration of muscle balance—an often-unattainable goal—but rather in clinical reasoning centered on this concept, considering the influence of neuromotor dysfunction and the multifactorial etiology of the deformity[4]. By considering the underlying neuromotor basis, the treatment of cavovarus foot should follow an evolutionary algorithm, starting with a comprehensive

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diagnostic evaluation, including the identification of mechanical deformities[1,3], the analysis of the biomechanics inherent to the observed muscle imbalances, and the investigation of neuromotor pathologies, with emphasis on CMT[2].

Therapeutic options range from conservative approaches, such as physical therapy and the use of orthotics, to surgical interventions. Decisions about surgical treatment are based on the rationale of muscle balance and progress from restorative techniques with tendon transfers and osteotomies to reconstructive surgeries with arthrodesis and, in selected cases, arthroplasties[5]. The complexity of cavovarus foot requires an individualized approach, intending to create a plantigrade, mobile, stable, and pain-free foot[1].

In this narrative review, we will explore the reasoning behind this new perspective of the "holy grail" of cavovarus foot, which is based on the functional analysis, detailing the diagnosis from the triad of deformity, biomechanics, and neuromotor dysfunction, and, based on this framework, define the best therapeutic approach, based on known techniques and tools. The objective is to achieve a plantigrade, stable, and pain-free foot, capable of sustaining a functional gait and preserving the maximum joint mobility.

## Observed mechanical deformities

Mechanical deformities are a pillar in diagnosing cavovarus foot, guiding the understanding of the altered anatomy and biomechanics that sustain the pathology. The evaluation begins with a visual inspection and a detailed physical examination, essential elements to delineate the morphological profile of the foot[1,6]. The increase in the medial longitudinal arch, for example, manifests as a marked characteristic of the plantar curvature. Assessing the flexibility of this elevation is a crucial point to determine, as a rigid arch may signal more complex underlying structural or neurological causes, while a flexible arch may indicate greater responsiveness to conservative therapeutic approaches[3].

The forefoot presents supination and adduction in relation to the hindfoot, configuring an atypical load distribution pattern, leading the hindfoot to a varus deformity, contributing to a greater overload on the lateral column of the foot[3]. The frequent presence of claw toe deformities, especially in the hallux, derives from the imbalance between the intrinsic and extrinsic musculature of the foot[6]. Observing callosities in specific areas, such as the lateral region of the foot, metatarsal heads, and the dorsal aspects of the interphalangeal joints, reinforces these points of overload and excessive plantar pressure[7].

The overall flexibility of the foot is a crucial determinant, influencing the choice of therapeutic strategy. The Coleman block test offers valuable insights into the influence of the first ray on the hindfoot deformity. The elevation of the first ray during single-leg stance allows verifying whether the correction of the hindfoot varus is possible, indicating the flexibility of the deformity and the relevance of the first ray in its pathogenesis[6].

Radiographic evaluation offers a detailed view of the bone alignment and the intrinsic anatomical relationships of the foot. Weight-bearing radiographs, in anteroposterior and lateral views, are indispensable to measure angles such as Meary's angle, which assesses the sagittal alignment of the foot, Hibbs' angle, which assesses the sagittal alignment of the hindfoot, in addition to the calcaneal pitch, which estimates the height of the medial longitudinal arch[3]. The Saltzman view radiograph also provides important information regarding the analysis of the axial axis of the calcaneus in relation to the tibial axis, evidencing the degree of hindfoot varus (Table 1).

In selected cases, weight-bearing computed tomography (WBCT) emerges as an advanced diagnostic tool, offering a detailed three-dimensional assessment of the bone anatomy and joint relationships of the foot and ankle under weight-bearing conditions. WBCT allows identifying subtle and complex deformities that may not be evident in conventional radiographs, in addition to providing valuable information about weight-bearing distribution and joint alignment[8]. This imaging modality can be particularly useful in surgical planning, allowing a precise assessment of deformities and the simulation of different correction approaches.

## Biomechanics of cavovarus foot: integrated analysis of structure and function

The biomechanics of the cavovarus foot are intrinsically linked to its structural morphology, which manifests as an increase in the height of the medial longitudinal arch and, frequently, a hindfoot varus. This particular bone conformation directly influences the distribution of plantar pressures during the gait cycle, resulting in a characteristic pattern of overload in the lateral region of the foot and the metatarsal heads, as demonstrated by Fernández-Seguín et al.[9]. The analysis of the kinematics of the cavovarus foot reveals a lower ankle dorsiflexion and an increase in hindfoot inversion during the stance phase, which, according to Williams et al.[10], may contribute to joint instability and

**Table 1.** Radiographic measurement angles assessed in cavovarus foot evaluation

| Measurement | Description | Cavus foot |
|---|---|---|
| Meary angle | • Talus axis<br>• First metatarsal axis | • Negative (plantar flexion of the first ray) |
| Arch height | • Base of the medial cuneiform<br>• Base of the fifth metatarsal | • < 14 mm (plantar flexion of the first ray)<br>• Normal ≈ 10 mm |
| Fibula position | • Fibula position relative to the tibia | • Posterior (ankle in varus) |
| Calcaneal pitch angle | • Plantar surface of the calcaneus<br>• Support plane | • Increased (usually > 30°) |

increase the susceptibility to lateral ankle sprains. In addition, the assessment of the flexibility of the first ray and the strength of the intrinsic muscles of the foot are important components of the biomechanical analysis, as they can influence the progression of the deformity and the response to conservative treatment. The use of computational models and biomechanical simulations has been promising in evaluating the biomechanics of the cavovarus foot, allowing the analysis of different scenarios and the planning of personalized interventions.

The multi-segment foot model, proposed by Stebbins et al.[11], represents a valuable tool for the detailed analysis of the kinematics of the cavovarus foot, allowing the evaluation of the relative movement between the different bone segments. This model has demonstrated that the cavovarus foot presents a greater stiffness of the medial longitudinal arch and a greater compensatory mobility between the hindfoot and the midfoot. This greater compensatory mobility may be an attempt to absorb the impact and adapt the foot to different surfaces, but it can also lead to an overload of the midfoot joints. The analysis of muscle activity during gait can also provide important information about the biomechanics of the cavovarus foot. The evaluation of the strength and endurance of the intrinsic muscles of the foot is also important, as these muscles play a fundamental role in stabilizing the medial longitudinal arch and controlling foot pronation and supination.

The influence of the height of the plantar arch on the biomechanics of the lower limbs during running has been widely investigated. Studies have shown that individuals with cavovarus feet tend to present a greater ankle pronation and internal rotation of the tibia during running, which may increase the risk of injuries such as medial tibial stress syndrome and iliotibial band syndrome, as demonstrated by Nielsen et al[12]. The analysis of the ground reaction force during running reveals that cavovarus foot presents a more abrupt impact pattern, with a higher peak vertical force and a shorter contact time with the ground, which may indicate a lower capacity to absorb impact and a greater overload on the joints of the lower limb, as demonstrated by Cavanagh and Lafortune[13]. Using foot orthoses can alter the biomechanics of the cavovarus foot, reducing plantar pressure in the lateral region and increasing ankle dorsiflexion, as demonstrated by Gross et al.[14]. However, the effectiveness of foot orthoses in treating cavus foot is still controversial, with some studies showing benefits and others not. Future research should focus on developing more effective therapeutic interventions to correct the biomechanical changes of the cavovarus foot and reduce the risk of injuries.

## Neuromotor pathologies in cavovarus foot: unveiling the influence of Charcot-Marie-Tooth disease

The investigation of underlying neuromotor pathologies is critical in diagnosing cavovarus foot, especially in cases of atypical progression or suggestive family history. Among the various neuromotor conditions that may contribute to the development of this complex deformity, CMT disease stands out as a prevalent etiology, demanding an in-depth analysis of its mechanisms of action[2] (Table 2).

Charcot-Marie-Tooth disease, a heterogeneous group of hereditary neuropathies, exerts its impact on the cavovarus foot through a cascade of events that begin with the dysfunction of peripheral nerves. This neuropathy affects both motor and sensory nerves. The direct consequence of this dysfunction is the progressive degeneration of axons and myelin, essential structures for the efficient conduction of nerve impulses[15].

The degeneration of motor nerves leads to muscle weakness and atrophy, selectively affecting the intrinsic muscles of the foot and the leg. This selective weakness results in a characteristic muscle imbalance. In the cavovarus foot associated with CMT, a weakening of the tibialis anterior and peroneus brevis muscles is typically observed, while the tibialis posterior and peroneus longus muscles maintain their relative strength. This muscle imbalance is a key factor in the pathogenesis of a high-arched foot, as the unbalanced muscle forces act on the bone and joint structures of the foot, leading to progressive deformity[16].

The characteristic of CMT muscle imbalance contributes to the development of high-arched foot through several mechanisms such as the increase of the medial longitudinal arch by the weakness of the tibialis anterior muscle, responsible for dorsiflexion and inversion of the foot, which leads the tibialis posterior muscle to remain shortened and more potent contributing to the elevation of the medial longitudinal arch[16]. The weakness of the peroneus brevis muscle allows the inverting muscles, such as the tibialis posterior, to tilt the calcaneus medially, resulting in a hindfoot varus, favoring the mechanical overload on the lateral rays and base of the

**Table 2.** Cavovarus foot causes

| Neuromuscular | Traumatic |
|---|---|
| Charcot-Marie-Tooth Disease | Crush injury |
| Poliomyelitis | Post-burn contracture |
| Friedreich's ataxia | Malunion of talus neck fracture |
| Traumatic brain injury | Peroneal nerve injury |
| Spina bifida | |
| Syringomyelia | **Congenital** |
| Terminal filum lipoma | Congenital talipes equinovarus |
| Tethered cord syndrome | Tarsal coalition |
| Cerebral palsy | |
| Spinal cord tumor | **Idiopathic** |
| Stroke | |
| Amyotrophic lateral sclerosis | |
| Huntington's chorea | |
| Guillain-Barré syndrome | |
| Peripheral neuropathy | |

fifth metatarsal[16]. The imbalance between the intrinsic and extrinsic muscles of the toes, caused by the weakness of the intrinsic muscles, leads to flexion of the interphalangeal joints and extension of the metatarsophalangeal joint, resulting in claw toe deformities[16] (Table 3).

In addition to muscle imbalance, sensory neuropathy also plays an important role in the pathogenesis of cavovarus foot associated with CMT. The loss of protective sensation in the feet makes patients more susceptible to injuries and ulcers, especially in areas of increased pressure due to deformity. The lack of proprioception contributes to instability and increases the risk of sprains and falls[17].

## Conservative treatment: an approach centered on muscle balance

The conservative treatment of cavovarus foot plays a crucial role in relieving symptoms and preventing the progression of the deformity[1]. Clinical reasoning continues with the goal of re-establishing the best possible muscle balance. Conservative treatment aims to optimize foot function, considering the influence of neuromotor dysfunction and the multifactorial etiology of the condition[4].

Conservative interventions aim to correct or minimize biomechanical and neuromotor imbalances. Physical therapy, with muscle strengthening and stretching exercises, aims to optimize the function of the intrinsic muscles of the foot and improve the flexibility of shortened structures[3]. The use of custom orthoses and insoles is essential to redistribute plantar pressures, provide support to the medial longitudinal arch, and improve hindfoot stability[1]. The choice of orthosis should be individualized, and it is essential to assess the flexibility of deformity so that the chosen orthosis can change the mechanics and rebalance the deformities resulting from the deviations and muscle imbalances identified[3]. In patients with CMT, footwear adaptation and the use of assistive devices may be necessary to protect the foot and minimize the risk of injuries resulting from the loss of protective sensation[2].

Conservative treatment offers a valuable approach to control symptoms and improve the quality of life of patients with cavovarus foot. Clinical reasoning centered on muscle balance directs the choice of the most appropriate interventions for each patient[4]. The decision to proceed to surgical treatment should be based on the failure of conservative measures to achieve therapeutic goals, such as improving pain, function, and stability of the foot[5]. Ultimately, the success of high-arched foot treatment lies in individualizing the approach, intending to create a plantigrade, mobile, stable, and pain-free foot[1].

**Table 3.** Correlation between deformities and muscle imbalances in cavovarus foot

| Deformity | Weakness | Predominance |
|---|---|---|
| Increased medial Longitudinal arch | • Anterior tibial muscle | • Posterior tibial muscle (maintaining relative strength) |
| Hindfoot varus | • Peroneus brevis muscle | • Posterior tibial muscle<br>• Peroneus longus muscle |
| Claw toe | • Intrinsic muscles (e.g., lumbricals, interossei) | • Extrinsic extensors and flexors |

## Surgical treatment

Surgical treatment of cavovarus foot should be carefully individualized, although certain basic principles apply to all cases. Respecting the biomechanical and etiological complexity is a sine qua non condition for a good outcome[18]. The pillars of surgical planning are meticulous analysis of stiffness, muscle imbalances, and plantar weight-bearing distribution.

Generally, the surgical sequence follows a functional principle: release of soft tissues, hindfoot correction, adjustments in the midfoot, and, when necessary, realignment of the forefoot. The ultimate goal—the "holy grail"—is not simple radiographic normalization, often unattainable, but obtaining a plantigrade, stable, and pain-free foot, capable of sustaining a functional gait and preserving the maximum joint mobility of the lower limbs[19] (Table 4).

## Soft-tissue release - a primordial part

It is essential to perform an adequate release of soft tissues before correcting structural deformities. In most cases of long-standing cavovarus foot, shortening of the Achilles tendon and contraction of the medial and plantar tissues may occur. Not recognizing and addressing these changes is a common failure in the surgical strategy. In these cases, surgery should be initiated by releasing the Achilles tendon or gastrocnemius to correct the posterior variation mechanism and release the calcaneus. Percutaneous triple hemisection or open Z-plasty of the Achilles tendon and gastrocnemius recession can be performed selectively, according to the result of the Silfverskiöld test[3].

Next, attention should be directed to the persistent contracture of the plantar fascia, which results in shortening and stiffness of the foot. Usually, the plantar fascia exerts greater force on the first metatarsal in the midfoot region. Releasing it in this region may be more effective in improving bone positioning. The scissors are carefully introduced, without cutting movement, until the medial and lateral bands are completely released[1]. In more severe cases, where there is marked cavo-adducto-varus, it may also be necessary to release the fascia of the abductor hallucis tendon. Special attention should be paid to the plantar neurovascular bundle, which runs deep to the latter. In certain more rigid deformities, release of the fascia may not be sufficient, requiring complete detachment of the intrinsic muscles from their insertion in the calcaneus, as part of the correction strategy and as a facilitator for a subsequent calcaneal osteotomy.

Finally, the surgeon will need to analyze the possible sources of medial contractures, including the spring ligament, the flexor tendons, and the midfoot joints. Only then will the surgeon be able to determine which osteotomies should or should not be performed.

## Balancing deforming forces - the role of tendon transfers

Rebalancing muscle forces is an essential part of surgical reconstruction in cavovarus foot, especially in patients with established neuromuscular etiology, where dynamic imbalances frequently sustain and recur the deformity. In these cases, simple structural correction is not sufficient; it is necessary to redirect force vectors to preserve the alignment obtained and avoid recurrences[20].

The choice of tendon transfers should respect the present imbalance pattern, established after meticulous motor testing. The tendon to be transferred must have a strength grade of 4 or 5. When there is dominance of the tibialis posterior, its partial or total transfer to the dorsolateral region, such as the dorsum of the foot or lateral cuneiform, can restore the dorsiflexion symmetry. In cases of excessive action of the peroneus longus, responsible for accentuating plantar flexion of the first ray, its transfer to the peroneus brevis (with proper tensioning of both) helps to contain the plantar inclination of the forefoot and reduce varus[21].

The transfer of the tibialis anterior to a more lateral position may be indicated when there is asymmetric and dynamic dorsiflexion in gait, while the extensor digitorum longus can be repositioned to stabilize the hindfoot[22]. Other transfers can be performed depending on each case, such as the flexor digitorum longus or hallucis longus to the peroneus brevis (or base of the fifth metatarsal), and the extensor digitorum longus to the tibialis anterior (Figure 1).

Generally, the logic behind the transfers is not only compensatory, but preventive: by neutralizing deforming forces, a more balanced, lasting, and functional biomechanical environment is promoted. Ultimately, these strategies are fundamental to achieving not only anatomical correction but functional integrity of the foot over time.

**Table 4.** Surgical treatment options for cavovarus foot

| Choice of surgical methods | |
|---|---|
| **Soft-tissue release** | |
| Contracture of the plantar fascia | Open or percutaneous plantar fasciotomy |
| Overpull of the intrinsic muscle | Steindler stripping |
| Ankle varus deformity | Lateral ankle ligament reconstruction<br>Deltoid ligament release |
| Ankle equinus deformity | Gastrocnemius recession<br>Achilles tendon lengthening |
| Severe rigid deformity | Combined with other tendon release |
| **Bony reconstruction** | |
| **Forefoot deformity** | |
| The first tarsometatarsal equinus | First metatarsal dorsiflexion osteotomy |
| The multiple metatarsals equinus | Jahss osteotomy |
| **Midfoot deformity** | |
| The apex at the naviculo joint or cuneiforms | Cole/Japas/Akron/Myerson osteotomy*<br>Ilizarov external fixation |
| **Hindfoot deformity** | |
| Non-reducible mild heel varus | Dwyer osteotomy |
| Non-reducible severe heel varus | Z-shaped osteotomy |
| **Mixed deformity** | |
| Rigid deformity with osteoarthritis | Double or Triple arthrodesis<br>Naviculo-cuneiform arthrodesis |
| **Soft-tissue Balancing** | |
| Weakness of the peroneus brevis | Peroneus longus to brevis transfer |
| Overpower of the posterior tibial tendon | Posterior tibial tendon transfer |
| Claw-toes | Jones procedure<br>Hibbs procedure |

## Osteotomies or arthrodesis - the difficult decision in the "holy grail" of the cavovarus foot

The decision between performing osteotomy or arthrodesis when treating cavovarus foot requires careful evaluation of the flexibility and location of the apex of the deformity. Although tests such as the Coleman block are widely used to estimate the flexibility of the hindfoot (subtalar), their effectiveness in predicting adequate surgical correction is limited. In a series with 172 patients undergoing only osteotomies and tendon transfers, without arthrodesis, only 38% had satisfactory radiographic correction, which led the authors to question the isolated use of this test as a guide for decision-making[20]. Often, the best way to assess this flexibility is by manipulating the subtalar in varus-valgus, with the foot in physiological plantar flexion. The influence of this movement on the position of the forefoot is then appreciated. Generally, the more mobile the subtalar, the more the forefoot will be "equinized" with the hindfoot valgus.

Regarding the location of the apex of the deformity, it is common to perform extensor osteotomy of the first metatarsal, for example. Such osteotomy is convenient in subtle cases of high-arched foot, especially in the initial evolution of cases called forefoot-driven hindfoot varus, that is, cases in which the matrix deformity is in the forefoot and a globally flexible foot. Except for this situation, the apex of the deformity is always proximal, whether in the first tarsometatarsal joint, in the cuneiform, in the naviculo-cuneiform, or the talonavicular[23].

In mild and flexible deformities, with easily correctable subtalar and minimal supination of the midfoot, joint-preserving procedures are usually chosen. Especially if there is no adducto-varus deformity of the forefoot. This includes osteotomies of the calcaneus and first metatarsal, release of the plantar fascia, and tendon transfers, such as peroneus longus to brevis(24). However, even in these cases, if the apex of the deformity is located more proximally—such as in the tarsometatarsal, naviculo-cuneiform, or talonavicular joint—, a realignment directly at this level may be necessary, avoiding technically distal osteotomies outside the core.

Moderate deformity, in turn, is marked by accentuated cavus and supination in the midfoot and signs of overload on the lateral border of the foot. Invariably, there is a rotation in the midfoot, which is usually more accentuated than the hindfoot varus. In these cases, the osteotomies used for mild deformities rarely manage to adequately correct the rotation of the midfoot or the persistent hindfoot varus. Thus, midfoot osteotomy-arthrodesis, performed at the apex of the deformity, becomes the key treatment. The procedure usually involves arthrodesis of the naviculo-cuneiform joint and osteotomy of the cuneiforms, with removal of a dorsomedial wedge and manipulation of the cuboid to correct supination(25). It is important to assess the need for cuboid osteotomy because often the stiffness in the lateral column prevents adequate derotation, even if a reasonable extension is achieved in the medial and intermediate columns.

The same reasoning is verified in sub-corrected cases, in which the medial cuneiform-ground and fifth metatarsal-ground relationship remains unchanged even after certain procedures. To achieve this correction, it is important to remove a dorsal-based wedge towards the cuneiforms, tapering laterally to the cuboid, a region where no bone segment is removed. Regarding the hindfoot varus, often the combination of subtalar arthrodesis with valgus calcaneal osteotomy may be necessary to avoid undercorrections (Figure 2).

Therefore, the choice for arthrodesis is not only linked to the absolute stiffness of the foot but also to the location and complexity of the apex of the deformity. The surgical approach should aim three-dimensional realignment, with derotations that are intraosseous or intra-articular, avoiding compensations that result in residual deformities, such as persistence of subtalar varus or overload on the fifth metatarsal.

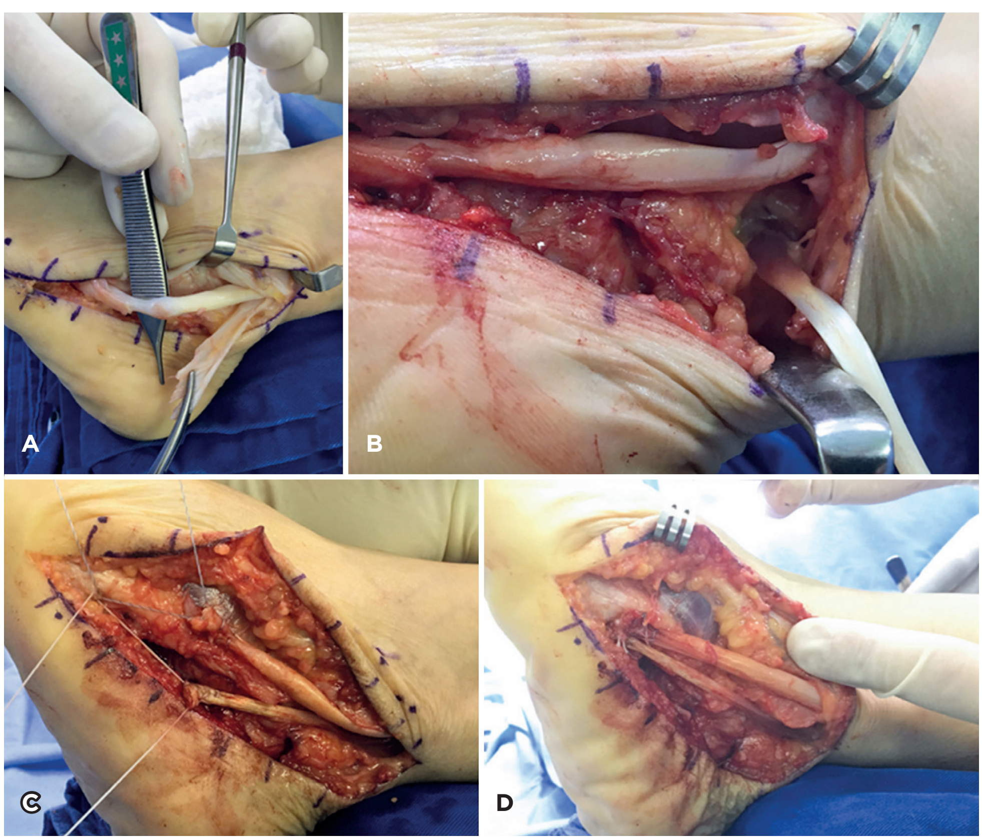

**Figure 1.** Example of tendon transfers. (A) An extensive peroneal tendon injury is seen. (B) The peroneus longus tendon is redirected to the peroneus brevis, and the flexor hallucis longus tendon is transferred laterally, posterior to the tibia/fibula. (C) Peroneus longus and flexor hallucis longus tendons are repaired and tensioned. (D) The peroneus longus is sutured to the remnant stump of the peroneus brevis, and the flexor hallucis longus is reinserted into the base of the fifth metatarsal.

Minimally invasive techniques have gained prominence in reconstructing the cavovarus foot, allowing structural corrections with less aggression to the soft tissues. On one hand, it seems attractive; at the same time, dispensing with soft tissue procedures can incur greater risks of recurrence[26]. Therefore, more robust studies are still lacking to determine which would be the best indications for this type of approach.

## The lesson learned from Charcot-Marie-Tooth in cavovarus foot

The surgical approach developed for cavovarus feet of neuromuscular origin, as in patients with CMT, has brought valuable contributions to treating cavovarus feet of other etiologies. The main lesson is the need for a dynamic algorithm, which respects the sequence of soft tissue release, intraoperative evaluation, and progressive surgical decisions, adjusted according to the anatomical response in real time[27].

In CMT, surgical reconstruction aims at three fundamental objectives: (1) restore a plantigrade foot, (2) stabilize the hindfoot, and (3) recover active ankle dorsiflexion. This triad can also guide complex surgeries of idiopathic or post-traumatic cavovarus feet, even in the absence of diagnosed neuropathy.

Soft tissue release can be initiated by lengthening the calcaneal tendon, which is often shortened and vectorially contributes to hindfoot varus. Next, a medial release of the midfoot, centered on the talonavicular joint, is considered essential to correct supination and adduction of the midfoot and enable adequate plantar support. This type of release, including the release of the spring ligament and the tibialis posterior tendon, should be considered in rigid cavovarus feet, even if non-neuromuscular[28]. In cases where ankle dorsiflexion is extremely weak, the flexor digitorum longus or hallucis longus tendon can also be released and used for transfer, together with the tibialis posterior, to the dorsum of the midfoot. Medial release of the subtalar joint can be performed in cases of greater rigidity, taking care not to overcorrect in hindfoot valgus.

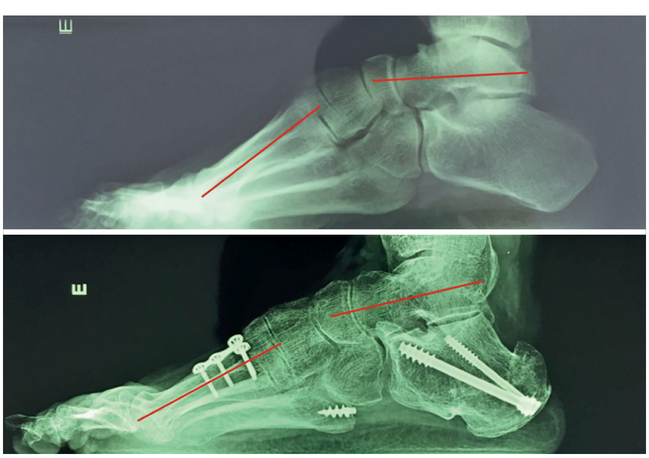

**Figure 2.** Example of satisfactory correction using a Z-shaped calcaneal osteotomy with wedge resection, along with a dorsal closing wedge osteotomy of the first metatarsal and tendon transfer of the peroneus longus to the base of the fifth metatarsal. Despite the first metatarsal osteotomy being performed away from the apex of the deformity, good correction was achieved.

Calcaneal osteotomy is another critical point. In CMT, the "C" morphology of the calcaneus demands combined osteotomies, lateral closing with translation, and valgus rotation. Although Z-shaped osteotomies of the calcaneus are an option, the "triple Dwyer" seems to act more on the apex of the calcaneal deformity.

The forefoot approach completes the sequence with the elevation of the first ray, usually by dorsal closing osteotomy. Extensor osteotomy of other metatarsals may also be necessary or even be done through the cuneiforms. The perception of the change in positioning of the forefoot throughout the surgery highlights the importance of not anticipating corrections before proximal corrections[29]. Only after all osteotomies have been fixed, should the surgeon finalize the tendon transfers, such as the tibialis posterior to the medial or intermediate cuneiform. Transferring the same to the lateral can cause excessive midfoot pronation if not well indicated. If the flexor digitorum longus (or hallucis longus) was released during the first surgical time, this can be used as a corrective force for the weakness of ankle dorsiflexion. Or even, transferred to the fibularis (or base of the fifth metatarsal) in the case of combined injury of these tendons, compromising eversion (Figure 3).

The surgical treatment of cavovarus foot associated with CMT offers a practical lesson on the principle of surgical sequence, extensive tissue release before bone corrections, and functional evaluation of the remaining muscles. These teachings become extremely valuable even in cases where the etiology of cavovarus foot is not neurological but presents comparable rigidity and complex deformity.

## Toe deformities in cavovarus foot - the surgical rationale

Deformities of the lesser toes in the context of a high-arched foot represent manifestations frequently related to neurological causes, resulting from complex muscle imbalances between intrinsic and extrinsic structures of the forefoot. Persistent hyperextension of the metatarsophalangeal joint combined with flexion of the proximal and distal interphalangeal joints configures the classic claw pattern, common in neuromuscular dysfunctions, but also observed in idiopathic or biomechanically induced forms. Pathogenesis involves factors such as shortening of the plantar fascia, failure of the reverse windlass mechanism, and progressive deterioration of the plantar plate, often aggravated by metatarsal imbalances, inadequate footwear, or concomitant hallux deformities[30].

The surgical approach to these deformities requires careful evaluation of reducibility, stability of the metatarsophalangeal, and involvement of the interphalangeal. In flexible deformities, tendon release techniques and arthrolysis are often effective. Percutaneous or open tenotomy of the extensor hallucis longus and brevis and flexor digitorum longus and brevis allows rebalancing of digital vector forces, and can be complemented by capsular arthrolysis. Tendon transfers, such as Girdlestone-Taylor (flexor digitorum longus to the dorsum of the proximal phalanx), act not only as anatomical correction but also as a functional tool, reestablishing the plantar moment in the stance gait phases. These transfers show good results both in toes with purely sagittal deformities and in cases with an axial component, such as the "crossover toe"[31].

In structured or rigid deformities, correction requires bone procedures and fusions. Arthrodesis of the proximal interphalangeal with intramedullary devices or Kirschner wires provides lasting alignment, often associated with joint excision in cases of advanced degeneration. In fixed mallet toes, the distal interphalangeal can be stabilized with wires or implants, and, when there is a risk of recurrent ulcers, terminalization (partial amputation) is considered. Metatarsal shortening osteotomy, notably Weil's, plays a central role in the treatment of metatarsophalangeal instability, both by restoring the metatarsal parabola and by facilitating joint reduction. Although effective, it is associated with complications such as floating toes, requiring attention in case selection and rehabilitation[30].

Minimally invasive approaches have been gaining ground, especially in tenotomies and distal osteotomies, with less tissue morbidity and reduced recovery time. However, the rate of complications such as residual edema and stiffness


**Figure 3.** Sequence of images in a case of Charcot-Marie-Tooth disease. This patient had a flexible deformity despite evident osteoarthritis in the tarsal joints. A particular feature was the severe loss of strength, especially in ankle dorsiflexion, resembling a flaccid paralysis. Classical osteotomies were chosen: first ray dorsal wedge osteotomy and triple Dwyer procedure (lateralization, elevation, and lateral wedge resection) of the calcaneus. Additionally, the peroneus longus was transferred to the base of the fifth metatarsal, and the posterior tibial tendon was transferred to the dorsum of the midfoot through the interosseous membrane. Due to the severe loss of ankle extensor strength, a tenosuspension of the peroneus brevis was performed, along with a tri-tendon anastomosis with the posterior tibial and anterior tibial tendons.

still demands critical evaluation and more studies. Regardless of the technique, there is a consensus that correction of proximal deformities (hindfoot and midfoot) should precede the treatment of the toes, as global biomechanical changes can directly influence digital alignment and function. A sequential, and eventually staged, approach, starting with the most proximal structures and progressing to the digital ones, allows a precise intraoperative reevaluation of residual deformities, optimizing functional and aesthetic results (Figures 4, 5, and 6).

## Hallux in cavovarus foot - when the great toe enters the "holy grail"

Hallux claw deformity, also called hallux malleus, is a frequent manifestation in patients with cavovarus foot, especially when associated with neuromuscular diseases such as CMT. This condition is characterized by hyperextension of the metatarsophalangeal joint combined with flexion of the distal interphalangeal joint, resulting in plantar overload under the head of the first metatarsal and on the tip of the hallux, predisposing to pain, callosities, and ulcers, especially in patients with sensory neuropathy[32].

The main cause of the deformity is the muscle imbalance between the extrinsic muscles, notably the extensor hallucis longus, the flexor hallucis longus, and the peroneus longus, and the intrinsic muscles, which, by losing their stabilizing function on the metatarsophalangeal joint, allow competing flexion and extension forces to deform the axis of the toe. Although etiology may be idiopathic, the neurological form is the most common, with CMT being the main associated disease.

The Jones procedure is the surgical technique of choice for treating this deformity when there is sufficient flexibility and functional impairment. It consists of transferring the extensor hallucis longus— sectioned distally—through a transverse tunnel through the neck of the first metatarsal, where it is fixed under physiological tension. This gesture removes the deforming extensor force on the metatarsophalangeal and repositions the extensor hallucis longus vector to exert a stabilizing and dorsiflexor effect on the first ray. The procedure is rarely performed in isolation, being frequently associated with arthrodesis of the interphalangeal joint of the hallux, to avoid compensatory deformities such as mallet toe of the hallux[33].

In cases where the first metatarsal presents a fixed position in plantar flexion, the Jones procedure should be complemented by a dorsiflexion osteotomy of the first metatarsal, as isolated tendon transfer is not able to elevate the first ray due to the persistent force of the intact peroneus longus tendon. Additionally, the procedure can be integrated into broader corrections of the cavovarus foot, including hindfoot osteotomies, plantar fascia releases, and tendon transfers of dorsiflexors, as part of a multiplanar reconstruction (Figure 7).

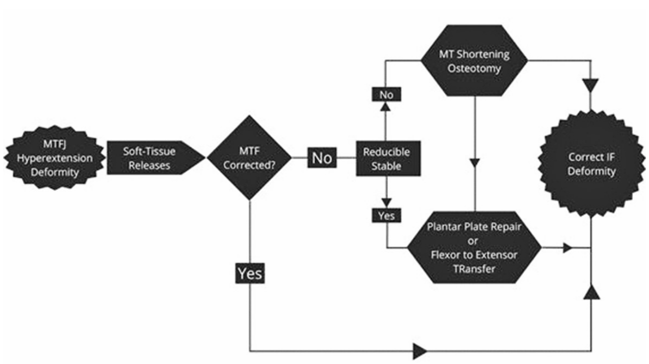


**Figure 4.** Algorithm for managing hyperextension deformity of the metatarsophalangeal joint. After correcting this deformity, any changes in the interphalangeal joints should be assessed and treated.

MTPJ: Metatarsophalangeal joint; IPJ: Interphalangeal joint; MT: Metatarsal.

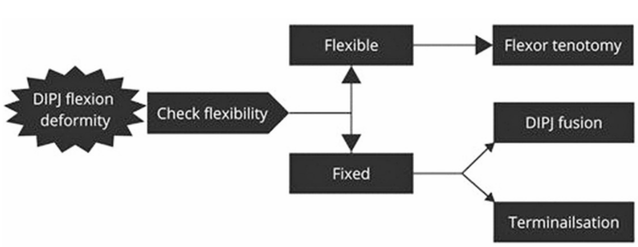


**Figure 5.** Algorithm for managing flexion deformities of the distal interphalangeal joint, as seen in mallet toe or as a component of claw toe.

DIPJ: Distal interphalangeal joint.

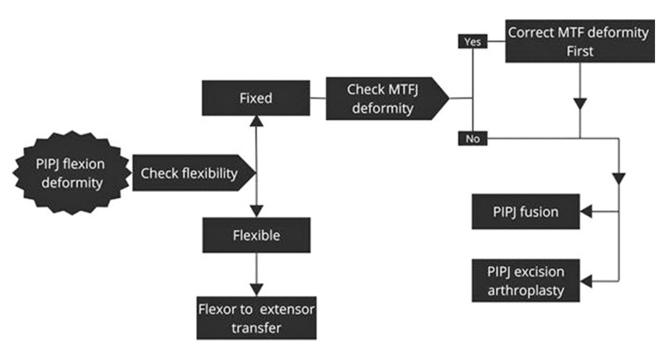


**Figure 6.** Algorithm for managing flexion deformities of the proximal interphalangeal joint, as in hammer or claw toe. In the presence of a fixed deformity, any associated changes in the metatarsophalangeal joint should be corrected first.

PIPJ: Proximal interphalangeal joint; MTPJ: Metatarsophalangeal joint.

**Figure 7.** Jones procedure for correction of hallux claw deformity. The extensor hallucis longus tendon is detached through the distal incision and reinserted proximally after being passed transversely across the neck of the first metatarsal.

## Conclusion

The growing understanding of the influence of neuromotor dysfunction, especially Charcot-Marie-Tooth disease, redefines the diagnostic and therapeutic approach, requiring an in-depth analysis encompassing mechanical deformities, biomechanics, and underlying neuromotor pathologies. Accurate diagnosis is an important step in studying cavovarus foot for the ideal treatment. The identification of mechanical deformities allows delineating the morphological profile of the foot and guiding the understanding of the altered anatomy. Biomechanical analysis, in turn, reveals changes in the distribution of plantar pressures and the kinematics of the foot, providing valuable information about function and susceptibility to injuries. Investigation of underlying neuromotor pathologies, as in Charcot-Marie-Tooth, assumes a prominent role in the diagnostic evaluation, by generating a cascade of events that begin with the dysfunction of peripheral nerves, leading to muscle weakness and characteristic imbalance.

Analyzing all the complex variables that lead to cavovarus foot in an integrated way, the therapeutic options diversify from conservative approaches to surgical interventions. Physical therapy and the use of orthoses aim to optimize foot function, correcting or minimizing biomechanical and neuromotor imbalances. Surgical treatment, carefully individualized, aims to obtain a plantigrade, stable, and pain-free foot.

The search for developing a dynamic algorithm, which respects the sequence of soft tissue release, intraoperative evaluation, and progressive surgical decisions, adjusted according to the anatomical response in real time, emerges as a fundamental principle to be followed. This flowchart of reasoning and surgical decision-making about reducibility, stability of metatarsophalangeal, and involvement of interphalangeal, combined with tendon release techniques, arthrodesis, and osteotomy, allows restoring alignment and digital function.

The search for the "holy grail" in treating cavovarus foot requires an individualized and multifaceted approach, which considers the influence of neuromotor dysfunction and the complex etiology of deformity. By adopting clinical reasoning centered on muscle balance and by applying the available techniques and tools judiciously, we can aspire to a plantigrade, mobile, stable, and pain-free foot, capable of sustaining a functional gait and preserving maximum joint mobility. Despite the challenges inherent in this journey, the growing understanding of the biomechanics and pathophysiology of cavovarus foot allows us to glimpse a promising future, with new therapeutic approaches and increasingly satisfactory results.

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