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Lower Limb – Foot

1. Foot

With regard to the foot, the vector resultants acting on the tibio-tarsal joint, the medial plantar arch, the anterior plantar arch, and the hallux will be examined.

1.1 Tibio-tarsal joint

The vector dominance at the tibio-tarsal joint, both in terms of the number of muscles acting and the Work force and Power they can express, is directed toward plantar flexion and supination.

Flexor-extensor dominance

Dorsiflexion muscles	**Plantar flexion muscles**	**Vector dominance**
Tibialis anterior	Triceps surae	Plantar flexion
Extensor digitorum longus	Fibularis longus	
Extensor hallucis longus	Fibularis brevis	
	Flexor digitorum longus	
	Tibialis posterior	

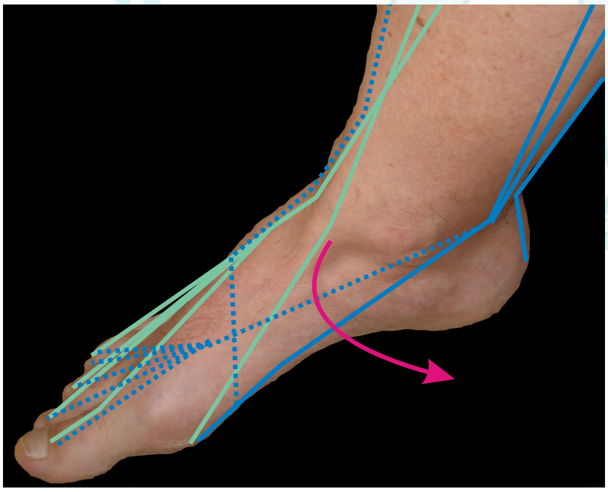

Figure 22: Flexor-extensor dominance
Dorsiflexors of the tibio-tarsal joint: tibialis anterior, extensor digitorum longus, extensor hallucis longus, green. Plantar flexors of the tibio-tarsal joint: triceps surae, tibialis posterior, fibularis longus and brevis, flexor digitorum longus, blue. Vector dominance is in favour of plantar flexion.

Pronator-supinator dominance

Supination muscles	Pronation muscles	Vector dominance
Triceps surae	Fibularis longus	Supination
Tibialis posterior	Fibularis brevis	
Flexor hallucis longus	Extensor digitorum longus	
Flexor digitorum longus	Fibularis tertius	
Tibialis anterior		

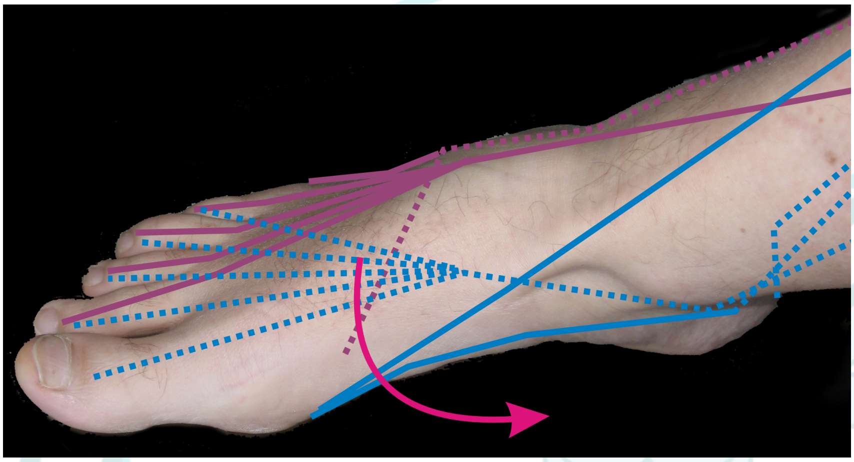

Figure 23: Pronator-supinator dominance
Pronation of the tibio-tarsal joint: fibularis brevis and longus, extensor digitorum communis, violet. Supination of the tibio-tarsal joint: triceps surae, tibialis anterior, tibialis posterior, flexor digitorum longus, and flexor hallucis longus, blue. Vector dominance is in favour of supination.

1.2 Adaptive strategies of the tibio-tarsal joint

If the muscles acting on the tibio-tarsal joint enter into excessive tension and subsequent shortening, the vector dominance in supination and plantar flexion is such that it cannot be balanced by the direct antagonists.

In this case, in order to place the plantar surface of the foot on the ground in upright stance, the system must use adaptive strategies by modifying the femoro-tibio-fibular articular sequence.

In the presence of shortening of the plantar flexors and supinators, plantar support becomes possible mainly through hyperextension with internal rotation of the knee.

Fig.1 Fig:2

Figure 24: Adaptive strategy Shortening of the plantar flexors and supinators of the foot cannot be balanced by the direct antagonists, fig. 1. Plantar support on the ground, fig. 2, can occur through hyperextension with internal rotation of the knee.

1.3 Medial plantar arch

The muscles capable of modifying the medial plantar arch are divided into three groups:

Anterior leg muscles: tibialis anterior, extensor digitorum longus, fibularis longus.
Posterior leg muscles: triceps surae, tibialis posterior, flexor hallucis longus, flexor digitorum longus.
Plantar foot muscles: abductor hallucis, flexor hallucis brevis, adductor hallucis, quadratus plantae.

Specific action of the muscles on the medial arch

Muscle	Action when shortened	Effect on the medial arch	Effect on the knee
Tibialis anterior	Supination	Increased cavus	Varus
Extensor digitorum longus	Its tendons pass beneath the extensor retinacula. Taking a fixed point at this level, the muscle can determine subluxation of the cuneiforms	Increased cavus	
Fibularis longus	Its tendon inserts on the first metatarsal	Increased cavus	Varus

	and medial cuneiform. With this course it resembles the string of an arch, Kummer, which, if shortened, while pronating the tibio-tarsal joint also increases and stabilizes the plantar vault		
Fibularis brevis	Inserting on the fifth metatarsal, it pronates the tibio-tarsal joint but has no direct or indirect effect on the medial arch	No effect	Varus
Triceps surae	Strong supinator of the calcaneus	Increased cavus as a mechanical resultant of calcaneal supination	Valgus
Tibialis posterior	Supination	Increased cavus	Valgus
Flexor hallucis longus; flexor digitorum longus	In addition to plantar flexing the hallux and toes, they plantar-flex and supinate the foot	Increased cavus	
Abductor hallucis	It is the main muscle of the medial plantar eminence. It acts like the string of an arch tensioned between calcaneus and hallux and, when shortened, increases the medial arch	Increased cavus	
Flexor hallucis brevis; adductor hallucis; quadratus plantae	Although shorter, with regard to the medial arch they act like the abductor hallucis	Increased cavus	

1.4 Biomechanical peculiarity of the medial arch

As shown above, the muscles acting on the medial plantar arch all act in the direction of supporting it.

In all the joints analysed so far, even when vectorially unbalanced, the acting forces are antagonistic to one another.
The medial arch has the peculiarity that all muscular vectors act in summation.

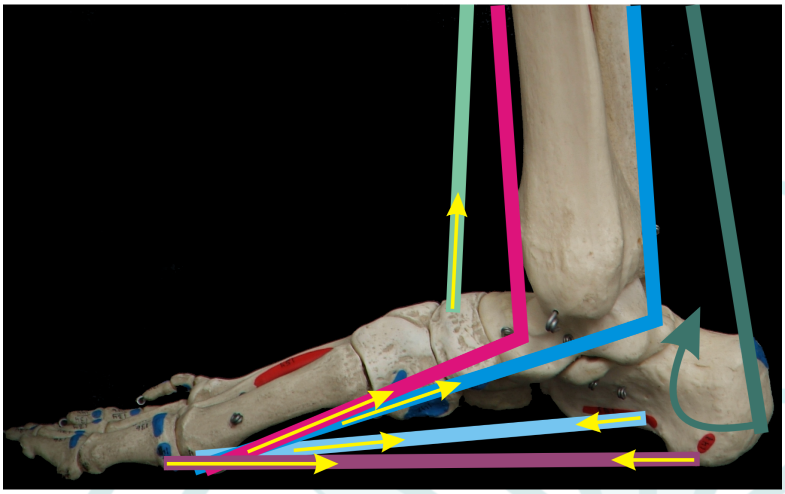

Figure 25: Support vectors of the medial arch
Abductor hallucis: violet; quadratus plantae: light blue; triceps surae: dark green; tibialis posterior, flexor hallucis longus, and flexor digitorum longus: blue; tibialis anterior: magenta; extensor digitorum longus: light green. The arrows indicate the force lines, all directed toward support of the medial arch.

Engineering principle of the medial arch

From an engineering point of view, this is not surprising: since the medial arch is intended to support the entire body weight, in upright stance the body barycentre is discharged at the apex of the medial arch, it is understandable that all the "tie rods" act in support of the ligaments and of the bony arch configuration.

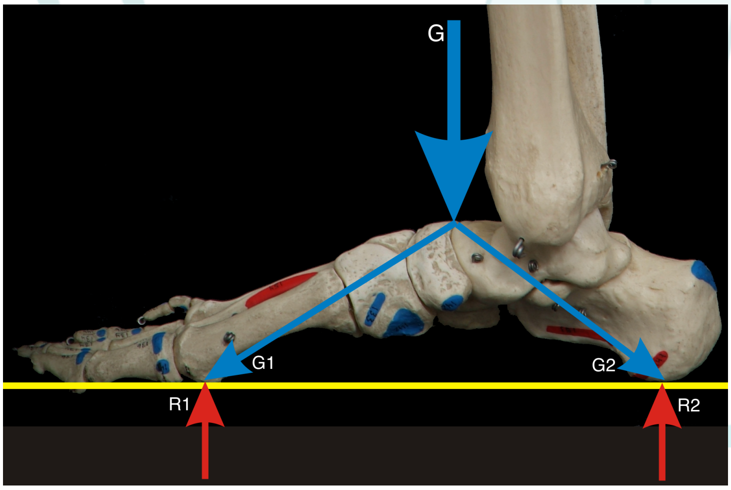

Figure 26: Distribution of forces on the medial arch
If skeletal alignment respects the physiological sequence, the overall body force G is applied at the apex of the medial arch. From here it is divided tridimensionally, unloading toward the lateral border of the foot, the anterior arch, and the calcaneus, where it meets the equal and opposite forces R expressed by the support surface. Forces G1 and G2 and R1 and R2, if not balanced by the musculo-ligamentous forces acting on the plantar arch, would cause the arch to collapse.

Architectural principle of the arch

Architecturally, an arch can sustain great vertical loads provided that its bases are stable; otherwise, the arch collapses.

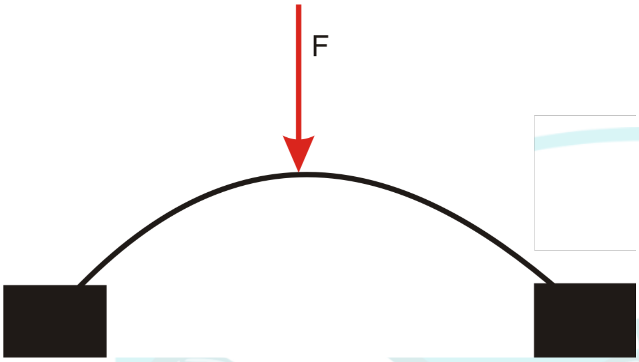

Figure 27: Stability of the arch with blocked bases
If the bases are blocked, the arch structure can sustain great vertical loads, as in the pylons of Roman bridges or the columns in church vaults. In the plantar vault, rigid bases are replaced by tie rods capable of better supporting dynamic stresses, as in modern bridges.

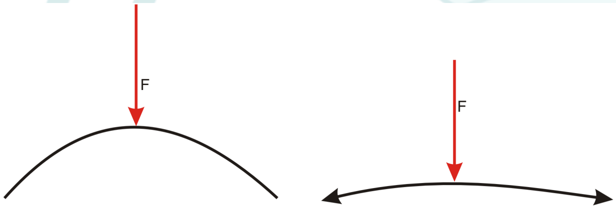

Figure 28: Collapse of the arch with unsupported bases
If the bases are unsupported, the vertical load causes the arch to collapse.

Muscular action is therefore directed toward supporting the bases.
Moreover, because the medial plantar arch is not made up of a single bone, which would make it stable but rigid and unsuitable for dynamic stresses, musculo-ligamentous tension assumes even greater importance, since, if expressed at the minimum necessary level, it dynamically stabilizes the plantar vault.

1.5 Flat foot

Since the action of all the acting muscles is directed toward support of the medial arch, in the absence of specific pathology, collapse of the plantar vault must be determined by a structural osseous deformation of sufficient magnitude to prevent the muscular "tie rods" from forming the arch.
When, on the contrary, peripheral neurological paralysis with consequent muscular inactivity or another specific pathological condition is present, collapse clearly has a different origin.
It is therefore necessary, in the presence of a flat footprint, to distinguish whether it is caused by true flatfoot, with collapse of the plantar vault, or by hypertrophy of the plantar vault muscles as the expression of an adaptive mechanism secondary to other problems.

Figures 29 and 30: Feet with a flat footprint

Differential assessment of flat foot

First manual investigation: the first investigation is manual and aimed at perceiving the position of the arch:

- in the case of true collapse of the vault, the talus, navicular, and cuneiforms appear horizontally aligned;
- otherwise, the bony arch appears intact and palpation reveals hypertrophy of the plantar muscles.

Figure 31: Palpatory investigation
Palpation makes it possible to perceive the bony course of the arch and distinguish it from possible muscular hypertrophy.

Adaptive mechanism of apparent flat foot

If the arch proves intact and the flat footprint is the expression of muscular hypertrophy, possible adaptive mechanisms must then be analysed.

Clinical example: in upright stance, in the same patient as above, marked internal rotation of the femurs is observed.
When active correction of femoral internal rotation is requested, the feet, especially the right, show marked cavus.

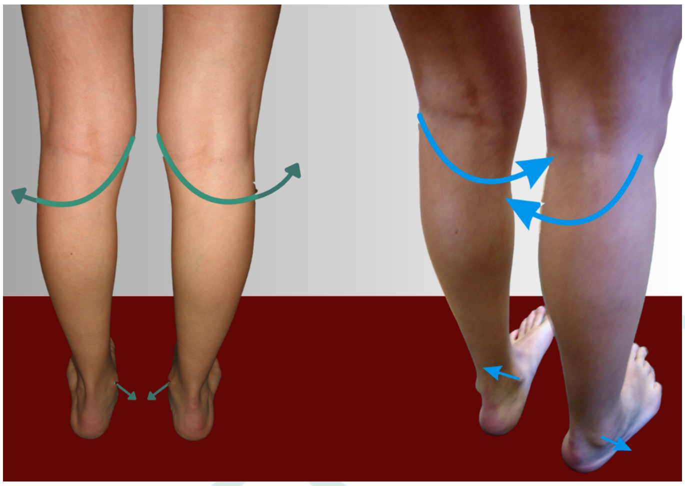

Figure 32: Femoral derotation test
Left photograph: in addition to the flat footprint, marked femoral internal rotation can be observed. Right photograph: by actively or passively derotating the femur, the load shifts onto the lateral border of the feet, revealing excessive cavus.

Compensatory mechanism

In this case, an adaptive mechanism is observed: with the femurs correctly positioned, the feet show excessive cavus, with loading on the lateral border due to the tension of the supinators and the intrinsic plantar muscles.
The pronator muscles of the tibio-tarsal joint, being vectorially subdominant relative to the supinators, cannot balance them and allow physiological plantar support on the ground.
Moreover, the strongest pronator, the fibularis longus, also contributes to excessive cavus.
In order to allow the foot a more functional support, femoral internal rotators intervene as substitutes for the pronators, and the calcaneus shows a non-primary valgus, as a consequence of internal rotation of the lower limb.

Clinical implications

In this case, then, the apparent flat foot is caused by a cavus foot compensated proximally through femoral and tibial rotation, with the use of muscles not acting directly on the foot.
It is through linear study of muscular vectors that one can analyse whether articular balance can be ensured by antagonistic muscles acting on the joint itself or whether, as in the case of apparent flat foot, this balance occurs through the use of muscles acting elsewhere.
In situations of this kind, correction of the apparent flattening by external means could produce worsening compensations in other body districts.
Such an intervention must therefore be assessed not only at the skeletal district of application, but across the whole body system.

1.6 Anterior plantar arch

On the anterior arch, vector dominance is expressed differently from the medial arch.

Support of the anterior arch

The bases of the arch, first and fifth metatarsals, are supported not only by the ligaments but only by the oblique head of the adductor hallucis.

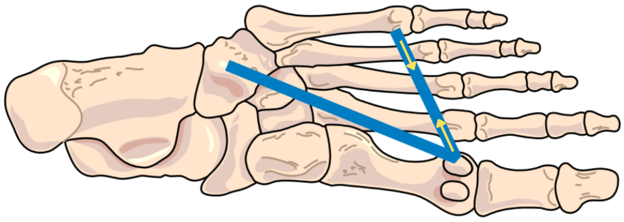

Figure 33: Support of the anterior arch
The oblique portion of the adductor hallucis, blue, is the only supporting "tie rod" for the bases, first and fifth metatarsals, of the anterior arch, yellow arrows.

Action of the toe muscles

All the other muscles act on the toes:

- extensor digitorum longus and brevis: dorsiflex the toes;
- extensor hallucis longus and brevis: dorsiflex the hallux;
- lumbricals and interossei: the former dorsiflex the proximal phalanx and plantar-flex the middle phalanx, the latter adduct or abduct the metatarsals;
- flexor digitorum longus: plantar-flexes the distal phalanx;
- flexor digitorum brevis: plantar-flexes the middle phalanx.

Shortening of these muscles determines vector dominance in dorsiflexion of the proximal phalanx and plantar flexion of the middle and distal phalanges.

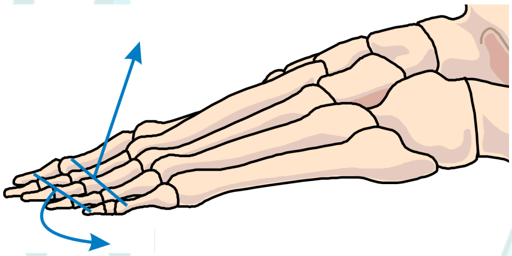

Figure 34: Action of the toe muscles
Shortening of the muscles acting on the toes determines a global resultant in dorsiflexion of the proximal phalanx and plantar flexion of the second and third phalanges.

Mechanism of collapse of the anterior arch

Dorsiflexion of the proximal phalanx of the toes determines a mechanical push on the metatarsals, projecting them toward the ground.
This push is reinforced, under load, by the portion of the global force G that is discharged onto the anterior arch.
In this case, the force supporting the bases of the arch, the transverse portion of the adductor hallucis, is subdominant.
The first and fifth metatarsals move apart and the anterior arch flattens.

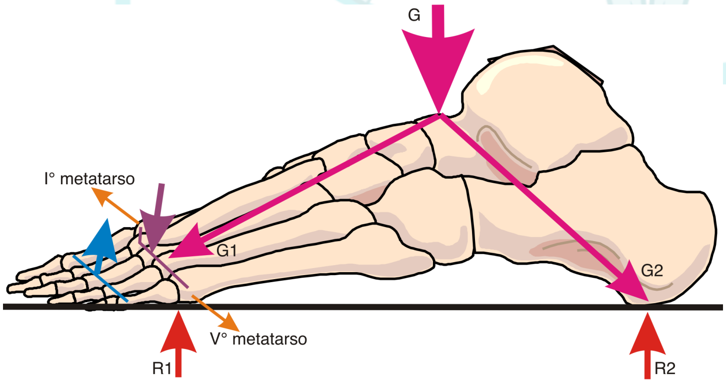

Figure 35: Collapse of the anterior arch
Dorsiflexion of the proximal phalanges, blue arrow, determines sinking of the metatarsals, purple arrow, and the consequent separation of the first and fifth metatarsals, orange arrows. The transverse portion of the adductor hallucis is subdominant in balancing the mechanical pushes and the arch collapses. Collapse of the arch is reinforced by the forces G1 and R1.

1.7 Hallux

Lateral stability of the hallux is under the control of the adductor and abductor hallucis, extensor hallucis longus and brevis, and flexor hallucis longus and brevis.

Specific actions of the hallux muscles

Taking as reference the axis of the foot, extending from the centre of the heel to the second toe:

- extensor hallucis longus and flexor hallucis longus adduct the distal phalanx of the hallux;
- extensor hallucis brevis and abductor hallucis abduct the first metatarsal and the proximal phalanx of the hallux;
- adductor hallucis and flexor hallucis brevis adduct the first metatarsal and the proximal phalanx of the hallux.

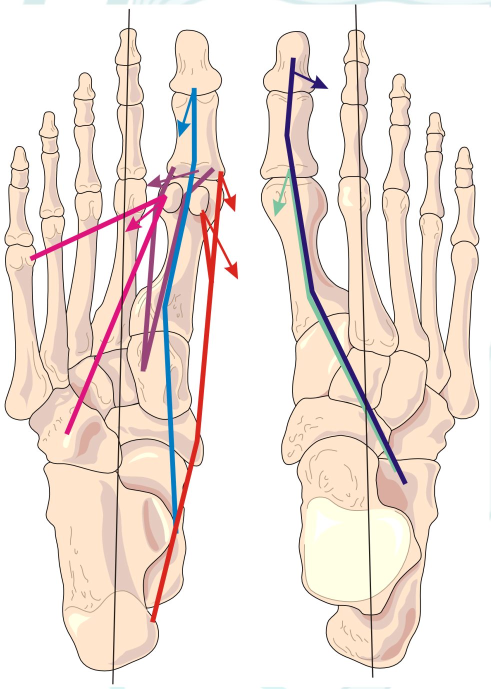

Figure 36: Hallux muscles
Left, plantar view: abductor hallucis, red; adductor hallucis, magenta; flexor hallucis brevis, violet; flexor hallucis longus, blue.
Right, dorsal view: extensor hallucis longus, dark blue; extensor hallucis brevis, green.

Mechanism of hallux valgus

Systemic shortening of these muscles determines a resultant and vector dominance expressed as abduction of the first metatarsal and adduction of the distal phalanx of the hallux, hallux valgus. Collapse of the anterior plantar arch, by determining abduction, relative to the second toe, of the first and fifth metatarsals, accentuates the angular deviation of the hallux. The two patterns often present together.

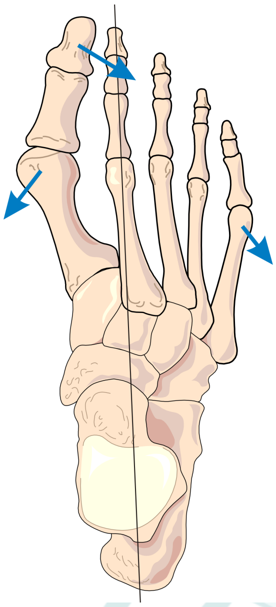

Figure 37: Hallux valgus
Considering the axis from the centre of the heel to the second toe, shortening of the muscles acting on the hallux has a global resultant determining abduction of the first metatarsal and adduction of the distal phalanx. Since hallux valgus and flattening of the anterior plantar arch often appear as associated patterns, abduction of the fifth metatarsal is also present.

Evaluation of primary causes

At the assessment stage, it is also important to determine whether the associated pattern, hallux valgus with collapse of the anterior arch, is determined primarily by selective shortening of the muscles acting in these districts or is instead a consequence of anteriorization of the global force G applied to the body barycentre.
This force, unlike what occurs at the medial arch, is opposed only by the adductor hallucis in its transverse portion.
The potential of the adductor hallucis is insufficient to oppose the force of the whole body weight and, consequently, in extreme cases the metatarsals from the second to the fourth may come into contact with the ground.
Once the arch has flattened, the global force G is distributed to all the metatarsal heads, where it is balanced by the force R, likewise distributed over all the metatarsal heads.

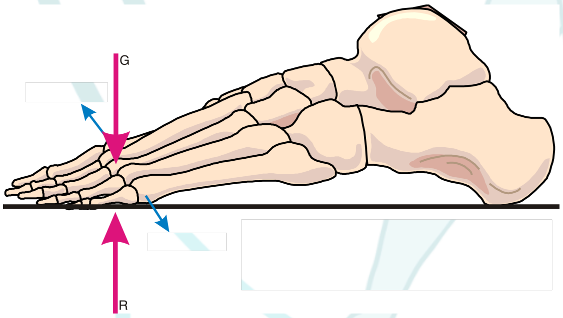

Figure 38: Anteriorization of the barycentre
Collapse of the anterior plantar arch may be induced mechanically by anteriorization of the global force G applied to the body barycentre.

Note on reversibility of shortening

As for all the districts analysed, the muscular shortenings described in the lower limb are potentially reversible through appropriate therapeutic techniques acting on tissue remodeling mechanisms and proprioceptive recalibration.
Correct identification of the primary causes, whether proximal or distal, directs intervention toward stable resolution of the alterations.

2. Conclusions of the chapter

Analysis of the lower limb reveals a hierarchy of complexity ranging from the sophisticated biomechanics of the hip, through the involvement of the knee joint, to the specific adaptive mechanisms of the foot.

Particularly significant is the observation that, in the medial plantar arch, all muscular vectors act in summation in favour of support, unlike every other joint in the body where antagonisms are present. This engineering principle reflects the need to support the whole body weight.

Understanding adaptive mechanisms, such as that of the “compensated flat foot” through femoral rotations, demonstrates the importance of systemic evaluation that considers the interconnections between all the districts of the lower limb, while application of vector principles confirms that the observed alterations follow precise physical laws.

Muscular dominances determine predictable skeletal configurations: from the mechanism of functional inversion of the knee flexors under load, to the uniqueness of the medial arch where all vectors converge in summation, to the adaptive mechanisms that use distant muscles to compensate for local imbalances.

These principles show that, also in the lower limb, subjected to the loads of upright stance and gait, it is shortened muscles that determine skeletal alterations through physically demonstrable mechanisms that are potentially reversible with appropriate treatment of the primary causes.

3. Chapter summary

Monoarticular hip muscles as active ligaments
Monoarticular muscles with a short force line act mainly in articular stabilization, behaving as dynamic ligaments capable of adapting to intra-articular stresses at the coxo-femoral joint.

Knee alterations with obligatory repercussions on the hip
Valgus, varus, hyperextension, and flexion of the knee necessarily modify force distribution in the acetabulum, creating localized compression and potential mechanical conflicts at the hip joint.

Piriformis syndrome: a double mechanism
It may manifest both in femoral internal rotation-abduction, with the piriformis under tension for containment, and in knee varus, with the piriformis shortened in order to maintain effectiveness. In both cases, compression of the sciatic nerve may result.

Progression of patterns of knee axis alteration
Sequence of worsening: internal rotation-hyperextension, then flexion-external rotation. A knee that appears well positioned may in reality have exhausted the first two directions and shifted into the latter ones.

Medial arch: all vectors in summation, in the absence of specific pathology
It is the only jointal structure in which all muscles act toward support, without antagonism. This is an engineering principle for supporting the whole body weight at the apex of the arch.

Apparent flat foot as an adaptive mechanism
It may be the expression of a cavus foot compensated through femoro-tibial internal rotation. Muscles not acting directly on the foot substitute for insufficient pronators.

Anterior arch: collapse due to flexor dominance of the toes
Dorsiflexion of the proximal phalanx determines a push on the metatarsals. The adductor hallucis, the only transverse support, is insufficient to balance the dominance.

Hallux valgus: result of muscular dominance
The hallux valgus pattern reflects the resultant of the dominant muscular vectors acting on the first metatarsal and on the phalanges.

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