The talonavicular and subtalar joints: The ‘‘calcaneopedal unit’’ concept

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Summary The talonavicular (TN) joint and the three subtalar (ST) joints are linked anatomically and functionally. Together they form the subtalar joint complex, where movement occurs between the calcaneopedal unit (CPU) (entire foot except the talus) and the talotibiofibular unit (talus held tightly by the ankle mortise). Many are unaware of the TN joint’s dual membership: it is a component of the subtalar joint complex (talocalcaneonavicular joint) and also the transverse tarsal joint (with the calcaneal-cuboid joint). The anatomy of the articulating surfaces, movement of the CPU when unloaded, shifts and changes in CPU shape with weight bearing, application to clinical tests and X-ray interpretation, and the pathophysiology applications to pes cavovarus, pes planovalgus and congenital talipes equinovarus (club foot) will be reviewed here. The CPU concept corresponds to a horizontal segmentation of the foot. This is a useful supplement to the two other segmentation methods: frontal (hindfoot, midfoot and forefoot) and sagittal (medial and lateral columns). This horizontal segmentation solves the issues with the ST joint complex, which straddles the hindfoot and midfoot, and also the issues with the dual membership of the TN joint. This concept makes it easier to understand foot deformities, better interpret the clinical and radiological signs and deduce logical treatments. © 2013 Published by Elsevier Masson SAS.

Introduction

The talonavicular (TN) joint is the only joint in the body that belongs to two separate joint entities: the transverse tarsal joint (also called the midtarsal joint or Chopart’s joint) and the subtalar joint complex (ST) [1–3]. The TN joint is anatomically and functionally linked to the calcaneocuboid joint to make up the transverse tarsal joint, which is at the junction between the hindfoot (talus and calcaneus) and the midfoot (cuboid, navicular and cuneiform bones). Furthermore, it is inextricably linked to the anterior ST joint to make up the acetabulum pedis [4,5]. The latter junction is combined with the middle and posterior ST joints to make up the ST joint complex, the site of movement between the ‘‘calcaneopedal unit’’ (CPU) (entire foot except talus) and
the talus, which is held within the ankle mortise to make up the talotibiofibular unit (TTFU) [2,6] (Fig. 1). Many are unaware of this dual membership of the TN joint, which leads to errors when interpreting X-rays [7–11] and a lack of consistency when explaining the relationships between the hindfoot and midfoot [10,12–16] (Fig. 2).

The ST joints have a fairly simple function when the foot is not loaded. The calcaneus is said to pitch, turn and roll under the talus [17]. The three basic movements of dorsiflexion/plantar flexion, abduction/adduction and pronation/supination are automatically associated in a unique eversion/inversion movement around the Henke axis (first described in 1859). Eversion combines dorsiflexion, abduction and pronation of the foot, while inversion combines plantar flexion, adduction and supination. However, this only applies to the unloaded foot (when examining a seated or lying subject).

The function of the ST joints in the loaded foot and during walking is completely different. They have been studied relatively little and are relatively complex [18,19]. Some of the distinct features of these joints have been somewhat forgotten:

- previously described interaction with the TN joint [1–3];
- role in the twisting-untwisting of the foot (flattening of the loaded foot and hollowing of the unloaded foot) [1,20];
- role in the axial rotation movements of the leg [18].

To our knowledge, no published studies have summarized the subtle mechanisms of the ST joint complex in a clear and easy to understand manner, probably because of a lack of understanding about the CPU concept [2,6,21]. However, this concept was known early on. Duchenne de Boulogne [22] made clear reference to it in 1867: "The foot turns around the leg axis such that its anterior end goes inwards and the heel outwards". Strasser [23] characterized this concept with diagrams in 1917 and then, MacConnail and...
Basmajian [20] revisited this concept and called it the lamina pedis in 1945. Hicks [1] and then Inman et al. [19,24] completely integrated the CPU concept in their functional anatomy work, although they did not use the proper terminology.

But it was only in 1950 that two pediatric surgeons (Meary and Queneau) came up with a name for the foot bones excluding the talus [in 2]. Conversely, Kapandji remained silent on this subject [12]. Only a few initiated surgeons, such as Rigault [25] and Pouliquen [26] used the term CPU to explain the pathophysiology of foot deformities in the 1960s and 1970s. From then on, this concept has been used and accepted in France by surgeons operating both on adults [21] and children [6].

The goal of this review is to show that the CPU concept is the key to understanding, not only the physiology of the normal foot but also the pathophysiology of most foot deformities. This will make clinical analysis and X-ray interpretation easier and result in a more suitable treatment approach.

Anatomy of the subtalar joint complex

It consists of four inextricably linked joints: the three ST joints (posterior, middle, anterior) and the TN joint [3]. These four joints work in a synergistic manner and form the joint complex where the movements between the CPU and TTFU occur.

Talus and its articular facets

The talus, which has no muscle insertions, has articular facets with the ankle mortise for flexion-extension movements and with the CPU for ST joint movements. It consists of multiple articular facets that fit perfectly with the corresponding facets of the CPU.

Calcaneopedal unit and its articular facets

The CPU consists of the calcaneus, midfoot and forefoot, which are solidly united by the calcaneocuboidal ligaments, bifurcate ligament and the plantar calcaneonavicular (spring) ligament (Fig. 1).

The posterior articular facet (previously called the talaric portion) has an oval shape and an oblique long axis aimed forwards and inwards.

The anterior calcaneal facet has either one or two distinct surfaces (proximal, supported by the sustentaculum tali) and distal, supported by the anterior calcaneal apophysis.

The dorsal side of the plantar calcaneonavicular ligament is encased with articular cartilage; the insertion of the base of the deltoid ligament is on its medial side. The proximal articular facet of the navicular has a round, concave shape that, in combination with the dorsal side of the spring ligament and the anterior calcaneal articular facets, forms a round cavity for the head of the talus: this is the acetabulum pedis [4,5].

Foot segmentation

The CPU concept adds a horizontal division to the foot, which supplements the other foot segmentation methods that cannot explain by themselves the subtalar mechanisms (Fig. 3):

- frontal division into three segments: hindfoot (calcaneus and talus), midfoot (navicular, cuboid and cuneiform bones) and forefoot (metatarsals and toes) (separated by the Chopart and Lisfranc joint lines);
- longitudinal division into a more flexible medial column (first three metatarsals, cuneiform bones, navicular and talus) and a stiffer lateral column (lateral two metatarsals, cuboid and calcaneus).

Movements of the CPU

Unloaded

The basic CPU movements relative to the TTFU occur around Henke’s axis (angled downwards, backwards and outwards). The inversion movement, which results in the tip of the foot pointing downwards and inwards, is accompanied by an opposite movement of the posterior calcaneal tuberosity that moves upwards and outwards. The pivot point is the interosseous talocalcaneal ligament (Fig. 1). During inversion, active movements between the CPU and the TTFU are driven by posterior tibialis and triceps surae muscles; during eversion, the fibularis (peroneus) brevis, extensor hallucis longus, fibularis tertius and extensor digitorum longus participate.

Loaded (weight bearing)

A simplified functional model of the subtalar joint complex in a weight bearing subject was developed by Close et al. [19]. It consisted of two pieces of wood attached at a right angle with a hinge at a 45° angle; the axial rotation of one board leads to the rotation of the other. If we equate one
board to the foot and the other to the leg skeleton, it is easy
to see how supination or pronation of the foot automatically
leads to external rotation (with foot supination) or internal
rotation (with foot pronation) of the leg.

Another way to visualize this phenomenon is to ask a
standing subject to keep the feet firmly planted on the
ground, then turn completely to the right until the pectoral
girdle is pointed 90° relative to the initial frontal reference
eplane. The person’s right leg undergoes external
rotation above the CPU with the foot becoming arched, even
cavovarus. The left leg undergoes internal rotation above
the CPU with the foot simultaneously flattening into valgus
planus (Fig. 4).

These basic points must be fully understood. During walking,
the lower legs continuously rotate around the leg axis,
alternating from one side to another. The ST joint complex
allows the foot to conform to the ground. The CPU transforms
the axial rotation movements above it through its
longitudinal axis.

Other features of the CPU and its clinical
implications

Plasticity

This is multifactorial.

Variable geometry of the calcaneonavicular (spring) ligament: this ligament, which participates in the formation of the talocalcaneonavicular joint, can stretch out and accept a larger part of the head of the talus when the latter moves medially into the sole of the foot. Conversely, the ligament area can become smaller when the head of the talus rises up on the anterior calcaneal apophysis [27].

Multisegmental makeup of the CPU: the numerous ligaments that join the CPU bones together supply it with the

remarkable plasticity required by the movements of each of
its constituent joints.

Change in CPU shape during loading of the foot

This is the twisting-untwisting phenomenon of the lamina pedis described by MacConnail et al. (Fig. 5). Not knowing

Figure 5 Lamina pedis helix according to MacConnail during weight bearing. Top: when the leg (TTFU) internally rotates (IR), the CPU untwists with calcaneal pronation (PRO) and forefoot supination (SUP). Bottom: when the leg externally rotates (ER), the opposite happens – the CPU twists more.
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becoming more prominent, while simultaneously reducing the calcaneal valgus, inducing pronation of the midfoot and forefoot and inducing external rotation of the TTFU.

Manual rotation of the leg: in a weight bearing subject, manually turning the leg inwards leads to flattening of the foot, while turning it outwards brings the talus back above the CPU, which leads to the medial arch becoming more prominent, calcaneal varus because of the morphology of the posterior subtalar joint and relative pronation of the midfoot and forefoot to maintain foot contact with the ground. This test is used to evaluate CPU plasticity and ST joint complex flexibility (Figs. 4 and 5).

Application to interpreting foot x-rays

The CPU concept can be used to better analyze A/P X-rays in a weight bearing subject (dorsoplantar view of foot). Three angle measurements are currently being used:

- talocalcaneal angle, which directly reflects on the adduction—abduction of the calcaneus under the talus, meaning the CPU under the TTFU;
- talar-first metatarsal angle, which historically reflects on footrest adduction—abduction [7—11]. This interpretation is only partially correct. Because of the dual membership of the TN joint, changes in this angle can either come from the midtarsal area or the ST joint, in other words, indicating CPU adduction—abduction [2,6,21,29];
- calcaneo-fifth metatarsal angle that, opposite to the talar-first metatarsal angle, inherently only involves the CPU and excludes subtalar contributions. This reveals the adduction—abduction movements of the foot relative to the hindfoot. In older children and adults, bone maturation easily allows the contribution of either the calcaneocuboid or cuboidometatarsal joints or both, to be determined.

As for talonavicular coverage, and contrary to standard interpretations that deem, this a forefoot problem, the CPU concept helps us realize that CPU (thus hindfoot) adduction—abduction under the TTFU can also change it.

Various CPU morphotypes

The calcaneal angle of incidence with the ground varies from one person to another and can explain the various CPU shapes [30] (Fig. 7). With a larger angle and erected calcaneus, the CPU is spontaneously arched: this is a physiological pes cavus or high instep. With a smaller angle, the lateral column stays near the ground and a physiological flat foot morphotype can be observed. One must keep these two extreme forms (CPU with erected calcaneus and CPU with horizontal calcaneus) in mind when faced with a congenital or acquired foot deformity in an adult or child. It is important to determine what can be attributed to morphotype and what can be attributed to the deformity itself, since many potential combinations exist.

Clinical manipulations

Passive extension of the big toe (Jack’s test) restores the medial arch. This finding can be erroneously interpreted as being related to the hallux flexor longus tendon [28]. In fact, dorsal hyperflexion of the big toe increases the tension on the plantar fascia and brings the posterior calcaneal tuberosity forwards, which leads to the medial arch becoming more prominent, while simultaneously reducing the calcaneal valgus, inducing pronation of the midfoot and forefoot and inducing external rotation of the TTFU.
Pathophysiology applications

The CPU concept sheds new light on the pathophysiology and treatment of the primary foot deformities, either acquired (pes cavus, flat foot) or congenital (club foot), and challenges certain ideas or commonly encountered errors.

Pes cavovarus (or medial cavus deformity)

Pathophysiology and clinical findings

This is an acquired deformity that is almost always neurological in nature. The CPU takes a helix form (non-reducible pronation of the forefoot and calcaneal varus) in combination with secondary (or adaptive) external rotation of the TTFU [31]. The most common form is observed during Charcot-Marie-Tooth disease with early involvement of intrinsic muscles, especially interosseous ones. The morphology of the foot will typically change with growth. The foot, normal at birth, becomes planovalgus towards 3 or 4 years of age, but during a heel-walking test, a dynamic medial pes cavus can already be observed. Towards 6 to 8 years of age, the foot gradually becomes cavovarus and the defects can become increasingly severe until the end of the growth phase.

In its most advanced form, the medial cavus deformity is visible because of the specific CPU deformity: there is a non-reducible pronation of the forefoot. This preferential verticalization of the medial metatarsal, which can explain the medial cavus deformity, is in keeping with an early structural deformity of the cuneiform bones, where their anterior and posterior articular facets no longer parallel so, they converge towards the sole. This is the primum movens (cause) of a deformity, which is non-reducible. During the ground support phase, forefoot pronation induces a varus seesaw motion (supination and adduction) of the entire CPU, which leads to talar varus and excessive loading on the lateral side of the foot. Thus, the CPU is the seat of a twisting motion with forefoot pronation and hindfoot supination. Simultaneous supination and adduction movements of the CPU lead the talus into relative abduction (that is to say external rotation of the TTFU) but also in dorsiflexion (horizontal displacement of talus) (Fig. 8). These components of the deformity are secondary and can be reduced initially.

In summary, the array of typical abnormal features of pes cavovarus is the following: forefoot pronation, medial cavus deformity with the intermediate cuneiform bone being at the apex, supination-varus of the hindfoot and external rotation of the TTFU above the CPU at the ground. The cavus, varus and claw toe deformity become worse when the foot is unloaded (swing phase of gait or when lying down, especially at night). In this situation, treatment with a night realignment brace can be beneficial [31].

If not treated, the bone deformities and joint displacements can become worse because of growth and the underlying neurological pathology (often progressive). Secondary abnormalities (supination-varus of the hindfoot and external rotation of the TTFU above the CPU) that are initially reducible will gradually become non-reducible. The CPU adduction is gradually completed by midtarsal adduction with convexity of the lateral side of the foot and shortening of the medial column relative to the lateral column. As the child grows, the two leg bones twist externally to compensate for the subtalar adduction.
X-rays
Radiological evaluation of the medial pes cavus during standing is challenging because a lateral view will underestimate the cavus deformity, even though it is clinically undeniable. This radiological paradox can be explained by abnormalities in the horizontal plane. Méary’s angle (formed by the longitudinal axes of the talus and first metatarsal to quantify the anterior cavus deformity) cannot be measured correctly because the talus and first metatarsal are no longer in the same sagittal plane because of the CPU adduction and external TTFU rotation. To measure the medial cavus deformity on X-rays, an angled-board configuration must be used. The entire CPU is loaded with pronation—abduction (Fig. 9) to restore the normal relationships between the TTFU and CPU so as to bring the talus back into the same sagittal plane as the first metatarsal [31]. This X-ray while standing on an angled-board can be used to measure Méary’s angle if the frontal adaptations are reducible (Fig. 10). A standard, standing dorsoplantar view shows the closure of the talocalcaneal angle while the angled-board test more or less completely restores this discrepancy; the reducible or incompletely reducible nature of the hindfoot varus-supination and the TTFU external rotation can be evaluated now (Fig. 11).

Treatment
A pes cavovarus can be treated conservatively if started early enough (before the age of 12). The foot deformity is corrected with a walking cast that untwists the CPU and externally rotates it under the TTFU; the correction is then maintained with a night realignment brace.

Surgical treatment consists of untwisting the CPU knowing that the apex of the cavus deformity is located at the intermediate cuneiform bone. Selective plantar release can be combined with opening-wedge osteotomy of the three cuneiform bones to extend the medial column, completely straighten the forefoot pronation and correct the cavus deformity. A valgus calcaneal osteotomy must be performed here because the calcaneal supination is rarely fully reducible. In some cases, partial release of the midtarsal joint with or without shortening of the lateral column by closing wedge osteotomy of the calcaneus must also be performed [32]. A night realignment brace must be used until the end of the growth period to prevent recurrence because of the gradual nature of the causal neurological condition [32]. A pes cavovarus at maturity is an indication for dorsal tarsectomy (associated with calcaneal osteotomy, plantar fasciotomy and often first metatarsal osteotomy); the goal is to avoid the need for a triple arthrodesis (subtalar, talonavicular and calcaneocuboid).

Pes planovalgus
Pathophysiology and clinical findings
Pes planovalgus is a deformity that is typically acquired when walking starts or around 3–4 years of age and is rarely

Figure 9 Lateral angled-board test for right pes cavovarus.

Figure 10 Lateral X-rays of loaded pes cavovarus: standard view (top) and with lateral angled-board (bottom).
due to a neurological condition. The idiopathic form is often called hypermobile flatfoot because the deformity is visible on a loaded foot and disappears completely when the foot is unloaded.

This acquired deformity of the CPU is reversed from the one in pes cavovarus. In the pes planovalgus, the CPU helix untwists (Fig. 12) with forefoot supination and hindfoot pronation, and with calcaneal valgus associated with internal TTFU rotation above the CPU (which corresponds to abduction of the CPU). Various tests can be performed on a loaded foot to determine if the pes planovalgus is reducible. External rotation of the leg moves the talus into abduction and dorsiflexion on the CPU, which makes the calcaneal valgus disappear and the medial arch of the sole reappear.

Passive hyperextension of the hallux brings about the same sequence of events.

Spontaneous progression of hypermobile flatfoot often occurs between the age of 7 and 11, and results in partial or total correction. In some cases, especially with neurological involvement (cerebral palsy or neurological deficit), the structural deformities become worse.

X-rays
The following aspects are visible on X-rays:

- lateral view—horizontal displacement of the first metatarsal, downward angle of the talus with an obtuse Méary’s angle dorsally and structural deformity of the navicular and/or cuneiform bones;
- A/P view—variable increase in the talocalcaneal divergence corresponding to CPU abduction under the TTFU. This can be combined with midfoot and forefoot abduction located at the CPU itself and characterized by the angle between the lateral edge of the calcaneus and longitudinal M5 axis being smaller laterally and shortening of the lateral column relative to the medial column. Lateral displacement of the navicular bone relative to the head of the talus indicates the amount of abduction but not its location (subtalar or midtarsal) because of the talonavicular joint’s dual membership (Fig. 13).

A new radiological classification system for pes planovalgus (correlation of the A/P and lateral views) has identified four deformity patterns: subtalar pes planus, midtarsal pes planus, mixed pes planus (combination of the previous two abnormalities) and pes planocavus (sag of medial column and cavus deformity of lateral column) [29].
Treatment
The severe forms of pes planovalgus can be surgically corrected using various procedures [33], with the indications derived from the above-described classification system:

- the Grice procedure by talocalcaneal coalition is not recommended because it leads to delayed effects on the tibiotalar joint [34];
- the Judet technique, also called the "rider" (temporary talocalcaneal fixation) is burdened by a recurrence rate that cannot be ignored. The subtalar pattern may be its most appropriate indication [25]. Arthrosis (subtalar implant) is an alternative that should be carefully evaluated [35];
- calcaneal lengthening according to Evans results in correction of most of the defects, but postoperative stiffness is sometimes observed because of variability in anterior talocalcaneal joint anatomy [36]. The most appropriate indication would be the midtalar pattern and the mixed pes planus pattern if combined with a medial column shortening;
- medial arch shortening (ostotomies/cuneonavicular fusion or cuneiform bone osteotomy) will be indicated in cases of pes planovarus and could be combined with the Evans procedure in mixed forms.

Congenital talipes equinovarus (CTEV)

Pathophysiology
The reasoning needed to understand the pathophysiology of CTEV is different because this is a congenital deformity that appears many months before birth. This deformity is not affected by walking and weight bearing. Conversely, because it is a three-dimensional deformity with three distinct defects (equinus, supination and adduction), it seems essential to take into account MacConaill’s diadochol (successive) movement law [20] by integrating all the tibiotalar, subtalar and transverse tarsal joints into an enarthrosis. This law stipulates that successive movements about two of the three reference axes, which automatically generate a movement in the third plane, without any movements being required about the third reference axis. Applying it to CTEV (previously untreated and independent of age) leads to the conclusion that one of the three basic deformities (supination) is "false" or "relative" [2,37] (Fig. 14). Most of the supination in CTEV (other than a minor component of subtalar origin accompanying the CPU adduction) is in fact created automatically by the combination of tibiotalar equinus deformity (indisputable) and a significant adduction of the foot, meaning the CPU, but also a midtarsal adduction. When assessing the severity of the deformity in a newborn, it is not logical to separately evaluate the equinus deformity and the supination, as proposed by Dimeglio et al. [38]. The procedure used to correct the supination is a manipulation that is almost exclusively located at the talocrural joint. The Dimeglio classification system should be modified to only grade the true fundamental clubfoot deformities: equinus, CPU adduction and midtarsal adduction.

The CTEV adduction can be located in four separate joints, not taking into account the bone deformities [2,37]: adduction in the ST joint complex, midtarsal adduction, naviculocuneiform adduction, tarsometatarsal adduction. In most cases, the CTEV adduction is located in two places: CPU adduction under the TTFU and midtarsal adduction. The CPU adduction is recognized and evaluated in the Dimeglio classification system, but not always well understood, because in one case [39], the term CPU was replaced by "midfoot", which leads to confusion.

Fibrous knots
The dual membership of the TN joint (Fig. 2) helps us understand why, in CTEV, the medial end of the navicular makes contact with the medial malleolus. Talonavicular adduction consists of the addition of two defects (midtarsal and CPU), which explains the constitutive soft tissue retraction of the anteromedial fibrous knots. Similarly, the CPU concept, which revolves around the talocalcaneal interosseous ligament under the TTFU, helps us understand why the calcaneal tuberosity gets closer to the lateral malleolus and leads to the description of the postero medial fibrous knots with concentrated soft tissue retraction [40,41]. Conversely, we have shown that in the posteromedial area of CTEV, there is no retraction. The soft tissue structures between the medial malleolus and calcaneus have a long history of being surgically released because of their suspected retraction. We have also described an anterolateral fibrous knot. When the CPU is significantly adducted under the talus, some
structures (lateral part of the anterior subtalar joint capsule and main tibiocalcaneal fascicle of the extensor retinaculum) can be retracted as a result of this subtalar adduction and need to be surgically released. All the other retracted soft tissues in CTEV are located in the anteromedial fibrous knot, besides, the navicular tuberosity and medial malleolus with adhesions of the flexor digitorum longus sheath, shortening of the tibialis posterior tendon and retraction of all the tibionavicular, talonavicular and calcaneonavicular ligament structures (Fig. 15).

Treatment
One important treatment application involves the immobilization of the knee in splints and casts (long leg system) relative to the current use of short leg splints and walking casts [42]. In the short leg system, the foot seems to be held properly but the TTFU can turn into external rotation above the CPU, which is adduction and varus. To address this fau
ty notion of stabilization, the TTFU rotation must be neutralized by placing it in maximum external rotation with the knee flexed in the immobilization system. From then on, it is possible to turn the CPU under the TTFU so that the CPU remains in abduction (and thereby eversion) relative to the TTFU.

Conclusions
The CPU concept introduces a horizontal division to the foot that adds useful information to the standard frontal and longitudinal divisions. If the surgeon is unaware of this concept, he/she lacks a means to understand foot deformities and misalignments, which could result in erroneous clinical and radiological interpretations and lead to inappropriate treatments.

Disclosure of interest
The authors declare that they have no conflicts of interest concerning this article.

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