MINI-SYMPOSIUM: THE FOOT

(i) The structure and function of the foot in relation to injury

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Summary The supportive function of the foot is provided by the bones, joints and ligaments of the midfoot, the central tarsometatarsal joints, and the midtarsal joint. Subtalar, talonavicular, and medial and lateral tarsometatarsal flexibility allows the foot to adjust to uneven ground and for the changing shape of the foot during heel elevation and propulsion. The plantar aponeurosis and deep transverse intermetatarsal ligaments support the foot and also have dynamic functions in stabilisation and movements.

The foot is subject to a wide spectrum of injury severity from different injury mechanisms, producing various patterns of injury. The goals of management are to provide pain relief and restore function where possible. Understanding the structure and function of the foot helps us understand how these injuries can occur, how its function will be affected as a consequence, and enables us to define basic principles of management.

Introduction

Our feet need to be stable and supportive, flexible, and energy efficient to be able to support body weight, withstand the forces generated by contact with the ground, propel us forward, and cope with uneven surfaces and various types of footwear. To achieve this they must be stable and supportive, flexible, and energy efficient.

Injuries to the foot are common, and many of them resolve with little need for active management. Unfortunately, some apparently innocuous injuries lead to persistent symptoms and disability if left untreated. Conversely severe injuries can present difficulties in determining the extent of injury and priorities in treatment. My aims are to describe the basic structure and function of the foot, concentrating on the bones, joints and ligament mechanisms. From this we can see how injury can occur, how function may be affected as a consequence, and define principles in the management of skeletal injury in the foot.
Structure

The foot is considered as having three main parts (Fig. 1). The hindfoot articulates with the midfoot through the talonavicular and calcaneocuboid (midtarsal) joints, and the forefoot with the midfoot through the tarsometatarsal joints.

Hindfoot

In the hindfoot there are three distinct articular facets between the talus and os calcis, the anterior, middle and posterior. Functionally they act as a highly congruent subtalar joint providing supination and pronation of the heel. The joint is supported by a number of ligaments, the most important of which are the interosseous ligament in the sinus tarsi canal and the medial ligament, which forms the deepest part of the deltoid ligament (Fig. 2). The os calcis also provides attachment for important structures such as the tendo Achillis and plantar aponeurosis.

Midfoot

The bones of the midfoot, the navicular, cuneiforms and cuboid, are all firmly attached to each other. The joint between the cuboid and navicular is usually a fibrous joint, but all others are flat synovial joints. The ligamentous attachments, particularly the plantar and interosseous ligaments, are strong and allow little movement between individual bones.

The two joints of the midtarsal joint are quite different, but work together with the subtalar joint to allow movement between the hindfoot and midfoot. The talar head is slightly egg shaped but the talonavicular joint behaves as a ball and socket joint with no unique axis of motion. The capsular ligaments between the talus and navicular are relatively weak. The talar head is instead stabilised in a deep socket comprising the corresponding articular surface of the navicular, the anterior articular facet of the os calcis, and the intervening calcaneonavicular ligaments, including the navicular band of the bifurcate ligament (Fig. 3). The navicular is firmly attached to the os calcis and so the interosseous and medial ligaments of the subtalar joint also function to hold the talar head in relation to it. Rotation essentially occurs about a centre within the talar head, restricted by the constraints of the calcaneocuboid and subtalar joints. Tibialis posterior is the only significant
muscle attached to the midfoot through the
tuberosity of the navicular. The calcaneocuboid
joint is a saddle shaped joint with a dorsal lip from
the anterior process of the os calcis. The joint
allows some sliding motion and abducts and
adducts with subtalar movement in the weight-
bearing foot. Stability of the joint is provided by
the shape of the articular surfaces, and the strong
long and short plantar ligaments (Fig. 4) attached
to the underside of the os calcis which extend to
the underside of the cuboid and the central three
metatarsals.

Forefoot

The metatarsals articulate with the midfoot by a
row of joints across the foot. The 2nd, and to a
lesser degree the 3rd, are firmly attached to their
respective cuneiforms with strong ligaments. The
base of the 2nd metatarsal, wedged between the
medial and lateral cuneiforms, also has strong
ligamentous attachments to each of these.3 The
plantar ligaments, and in particular the Lisfranc
ligament between the medial cuneiform and 2nd
metatarsal are particularly important in stabilising
the tarsometatarsal joints (Fig. 5). The 1st, 4th,
and 5th metatarsals are more mobile, capable of
some flexion and extension, as well as abduction
on the medial and lateral sides of the forefoot.4
Tibialis anterior and the peroneal tendons are
attached to metatarsals and may act to move the
tarsometatarsal joints, but like all long tendons will
also have effects at the midtarsal and hindfoot
joints. The intrinsic muscles, arising in part from
the midfoot and hindfoot as well as the forefoot,
are of minor importance in terms of strength in the
normal foot, but are of major significance in terms
of swelling and compartment syndrome in the
injured foot.

The metatarsophalangeal joints are sloppy hinge
joints providing flexion/extension movement as
well as a small amount of abduction/adduction.
They are supported by collateral ligaments. The
plantar capsule of each joint is thickened to form
the plantar plates and these are all connected to
each other by the broad deep transverse inter-
metatarsal ligaments (Fig. 6). The medial and
lateral ends of this transverse structure merge with
the collateral ligaments of, respectively, the 1st
and 5th MTP joints, which helps to prevent splaying
of the metatarsals.5 The plantar plates also provide
distal attachment for the plantar aponeurosis,
important in stabilising the longitudinal arch and
in the function of the foot.
Function

The foot as a support

The foot is clearly a complex structure with flexible and non-flexible parts whose functions are interdependent. In order to provide support for standing and a lever for propulsion the foot needs to be firm and stable. The bones of the midfoot, all firmly attached to each other, are central to this supportive function through the midtarsal and tarsometatarsal joints. The midtarsal joint provides stability between the hindfoot and midfoot. How this occurs is poorly understood. The concept of parallel and crossing joint axes, that is widely promoted,6 (for which there is no published supporting scientific evidence) has been discounted by van Langelaan.1 Stability is probably primarily a function of the calcaneocuboid joint. The shape of the articulating surfaces and the plantar ligaments, such as the long and short plantar ligaments and plantar aponeurosis which are under tension on weight bearing, are likely to be important in stabilising this joint.4,7 Once the midtarsal joint is stabilised on weight bearing the foot becomes a firm supportive structure from the heel to the central metatarsal heads owing to the relative immobility of the joints in the midfoot and 2nd and 3rd tarsometatarsal joints (Fig. 7).

Flexibility in the foot

As well as being a firm supportive structure the foot needs to be flexible in order to cope with irregular walking surfaces and again for propulsion. Joints move and the foot changes shape as we walk.

The heels pronate slightly on heel strike, motion being limited by the supporting ligaments of the subtalar joint. Pronation of the subtalar joint is also limited by the shape of the forefoot as it contacts the ground and the stability of the midtarsal joint. As heel elevation begins, primarily under the influence of the gastrocnemius–soleus complex, the subtalar joint starts to supinate, and this steadily increases as the heel elevates. This pronation and supination of the subtalar joint is dependent on the congruity of the joint and motion at the midtarsal joint, in particular the talonavicular joint. Tibialis posterior is the most effective active supinator of the hindfoot assisted by the gastrocnemius–soleus and long flexors. The plantar aponeurosis also contributes to this heel supination as a consequence of the windlass mechanism.8

Extra-articular ligament mechanisms

The main extra-articular ligaments are the plantar aponeurosis and the deep transverse intermetatarsal ligaments in the forefoot. They support the arch of the foot and prevent splaying of the forefoot. In addition to these static functions they have important dynamic functions in the foot.

When the toes are extended at the MTP joints the arch of the foot elevates and the heel supinates. This is a consequence of the plantar aponeurosis being pulled around the metatarsal heads (Fig. 8). The metatarsal heads must, therefore, move closer to the heel. This is known as the windlass mechanism.9 When the toes are extended during heel elevation in gait the same change in shape of the foot occurs, and the windlass mechanism contributes to the supination of the heel.

Figure 7 Plantar view of the foot. The shaded bones provide structural support on weight bearing through the strong plantar ligaments such as the long and short plantar ligaments. The un-shaded bones remain mobile at their articulations.

Figure 8 Diagram illustrating the windlass mechanism. When the toe is extended the foot shortens and the arch rises.
When the forefoot is bearing weight tension is generated in plantar ligaments including the plantar aponeurosis, and is probably important in stabilising the midtarsal joint. As the plantar aponeurosis is attached to the proximal phalanges, flexion occurs at the MTP joints, keeping the toes on the ground (Fig. 9). This is known as the reversed windlass mechanism, which is probably the strongest flexor of the MTP joints. Tension increases as the heel rises and is released at toe off, assisting propulsion.

The primary stabiliser of the first metatarsal is the deep transverse intermetatarsal ligament, controlling sagittal as well as transverse plane movements. The plantar aponeurosis also reduces the sagittal plane movement of the 1st metatarsal. This stabilising effect increases as the hallux is extended, and abolished by plantar aponeurosis division. After heel elevation, when only the metatarsal heads and toes are in contact with the ground, the importance of stability of the 1st metatarsal, along with the 2nd and 3rd, increases as heel elevation increases, until final push-off.

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These dynamic functions of the plantar aponeurosis are dependent on the flexibility of the MTP joints and the length of the skeleton of the foot.

**Injury to the foot**

The foot may suffer acute injury or overuse type injuries such as stress fractures and ligament and tendon damage. Twisting and bending forces in various directions produce different injury patterns. Compression or crushing forces tend to cause more severe injuries with a greater soft tissue component. Compression forces can be combined with twisting or bending and may cause more significant damage. The severity of injury is also clearly related to the energy of injury ranging from simple falls to falls from a height and motor vehicle accidents.

Pronation and supination forces most commonly cause injury around the ankle, but damage can occur in the foot. Avulsion fractures at the base of the 5th metatarsal are common. Less common are fractures of the anterior process of the os calcis or the lateral process of the talus and unfortunately frequently missed. These are probably ligament avulsion fractures. Although the precise mechanism for lateral process fractures of the talus is uncertain it is usually associated with injury to the lateral ligament complex of the ankle. These fractures give rise to persisting symptoms, which may be related to impingement, joint surface damage or alteration in joint stability.

**Tarsometatarsal joint**

Plantarflexion injuries of the foot occur from longitudinal loading of the foot in a plantarflexed position. This can occur when weight bearing on the extreme plantarflexed foot, or if a force is directed against the back of the heel when the heel is elevated and the forefoot is in contact with the ground as may occur in sport (Fig. 10). Injury tends to occur at the tarsometatarsal joints where there is rupture of the weaker dorsal ligaments causing the metatarsals to plantarflex and displace dorsally. Abduction or adduction stress as a consequence of the limb or body moving about an immobilised forefoot, such as in a stirrup, can also injury the tarsometatarsal joint. Various patterns of injury are seen including partial or complete injuries and divergent injuries. The dorsal intermetatarsal ligaments between the bases of the 2–5th metatarsals tend to keep the lateral four metatarsals together so that the 1st ray may not be injured or be displaced in a different direction.

Although tarsometatarsal joint injuries are often considered to be high-energy injuries, this is not necessarily the case. It is becoming increasingly recognised that low energy trauma, causing minimally displaced injuries, and those where instability can only be demonstrated on stress radiographs from rupture of Lisfranc’s ligament, can give rise to chronic symptoms. Anatomic reduction and fixation has been shown to improve the outcome of these injuries, but the most important factor is probably restoration of stability between the bases of the 2nd and 3rd metatarsals and the cuneiforms to reconstruct the supportive function of the foot.
Midtarsal joint injuries are less common than tarsometatarsal injuries. Minor avulsion fractures may be seen around the talonavicular joint or lateral aspect of the cuboid and these heal readily with functional treatment. Significant injury to the midtarsal joint generally requires high-energy trauma. The most frequent mechanism appears to be medially directed bending stress with or without some degree of longitudinal compression. Lateral or plantar bending, or crushing can also cause midtarsal joint injury. Injury usually results in fracture of articulating bones and the navicular is most frequently damaged as a result of compression against the talar head. Split and comminuted fractures occur. Comminution usually affects the plantar lateral aspect of the bone in the region of the attachment of the plantar calcaneonavicular ligament and the navicular component of the bifurcate ligament. With loss of these plantar ligament attachments the dorsomedial fragment is often displaced by the intact tibialis posterior (Fig. 11). The disruption and loss of thickness of the navicular may lead to adduction of the forefoot or loss of arch height. It is important to try to restore the stability and function of the talonavicular joint by reduction and fixation of the navicular, with bone grafting if necessary, in order to restore stability and flexibility at the subtalar and midtarsal joints. With comminuted fractures this may be difficult, but the rigidity of the midfoot can sometimes be utilised to enhance fixation by using buttress plates bridging the naviculocuneiform joints to secure congruity of the talonavicular joint (Fig. 12).
Injury to the midtarsal joint by lateral bending causes compression fractures of the cuboid or anterior process of the os calcis, and are often associated with avulsion fractures of the tuberosity of the navicular. Bone grafting and fixation are often required to restore the length of the lateral side, alignment of the foot, and stability of the calcaneocuboid joint, important for midtarsal stability on weight bearing and heel elevation.

Injuries to the hindfoot

Talus fracture
Dorsiflexion forces may cause injury around the ankle or hindfoot. The strength of the plantar ligamentous structures probably protects the midfoot and forefoot from acute injury. High-energy trauma can result in fracture of the neck or body of the talus. The mechanism involves impingement of the anterior tibia against the anterior talus, but in the experimental situation compression under the heel is also required to generate these fracture patterns (Fig. 13). More severe fracture patterns are seen if there is a supination component to the trauma. One of the main concerns following such fractures is damage to the vulnerable vascularity of the body of the talus.

Os calcis fracture
Crushing or compression can cause major injuries to the foot. The forefoot is most frequently damaged by external compression forces, but axial loading under the heel can cause significant injury to the hindfoot and to the os calcis itself. Os calcis fractures are frequently comminuted, displaced and involve the subtalar and sometimes the calcaneocuboid joint. The pattern of fracture is a consequence of the anatomy of the bones and the subtalar joint. The strongest ligamentous attachments between the talus and os calcis, the medial ligament and interosseous ligament, are both medial to the main load-bearing posterior facet of the subtalar joint. Under axial loading a sagittal split, or primary fracture line, occurs separating the medial sustentacular fragment from the lateral articular fragment (Fig. 14). The lateral process of the talus impinges in the angle of Gissane to produce a second primary fracture line separating the anterior and posterior parts of the os calcis. The articular fragment becomes impacted in the tuberosity fragment which in turn comes to lie between the sustentacular and articular fragments and must be distracted from this position if the articular fragment is to be reduced. The sustentacular fragment remains in its anatomical
relationship with the talus by virtue of the medial and interosseous ligaments.

Subtalar joint
Subtalar dislocation, in reality a combined subtalar and talonavicular dislocation, occurs as a result of high-energy trauma. Displacement in these injuries is usually in a medial direction due to the greater capacity for inversion at the subtalar joint and the relative strength of the medial ligament. Once the interosseous ligament of the subtalar joint ruptures the talar head can be dislocated from its osseoligamentous socket. The navicular remains attached to the hindfoot because of the strength of the calcaneonavicular ligaments.

Fracture of the talar neck or body, subtalar dislocation, and intra-articular os calcis fracture all affect the subtalar joint. Reduction of subtalar dislocation is clearly important, and this may need to be an open procedure to relocate any tendon entrapment. The urge to achieve early movement in the joint must be countered against the risk of hindfoot instability and so the current recommendation is for 4–6 weeks immobilisation. By contrast instability of the subtalar joint after os calcis fracture is a consequence of persisting depression of the articular fragment, because the interosseous and medial ligaments usually remain intact. The primary aim of surgical reconstruction of these fractures is to restore congruity to the joint to avoid instability and allow normal movement. As the joint is a highly congruent multifacetated articulation it seems that a highly accurate reduction is required in order to achieve this, and the margin for error may be less than 1 mm.17 Other aims of surgery are to restore the height and alignment of the heel to restore normal function to the tendo Achilles and theoretically also to the plantar aponeurosis, as well as to reduce lateral impingement and improve shoe fitting.

Crush injury
The rigidity of the midfoot protects it from twisting and bending forces with damage occurring either at the more mobile midtarsal joint or the tarsometatarsal joints. It can, however, be damaged by crushing injuries producing complex and varied fractures and dislocations through the midfoot bones. Such injuries usually also involve either the midtarsal or tarsometatarsal joints. Reduction and fixation of these injuries is important for restoring the supportive function of the foot, but the timing of this must be determined with regard to the soft tissue injury.

Fractures of the metatarsals are common and may be the result of crush injury or overuse. Crushing is associated with greater degrees of soft tissue injury with the risk of compartment syndrome, multiple fractures, and displacement. The more distal the fracture the greater the risk of displacement and there is a tendency for plantar displacement and shortening because of tension in the plantar structures including the plantar aponeurosis, which is likely to be exacerbated by soft tissue swelling (Fig. 15). Displaced fractures can cause significant problems, not only from irregularity of the height of metatarsal heads causing metatarsalgia, but from shortening which may compromise the function of the plantar aponeurosis. This may be a contributory factor in the development of secondary claw toe deformity from loss of the reversed windlass mechanism. The supporting and dynamic functions of the plantar aponeurosis at the midfoot and hindfoot may also be impaired. Displacement of more than 3–4 mm or angulation greater than 10° should be reduced.18

Conclusions
In managing the injured foot our aims should be to relieve pain, and restore stability and flexibility to bones and joints. Joints should be reduced and stabilised—non-flexible ones so that their supportive function can be restored; flexible ones so that they are congruent, allowing restoration of motion without instability. The length and alignment of bones should be restored and maintained for the proper functioning of the extra-articular ligamentous systems—the plantar aponeurosis and deep transverse intermetatarsal ligament complex.

Where normal function of part of the foot cannot be restored this should be done with an understanding of how this will affect the function of the foot as a whole. Arthrodesis of a non-flexible joint will have minimal impact on foot function, but
arthrodensis of a normally flexible joint, although it may be necessary in order to provide pain relief and stability, will have some effect on foot function.

Stability can be achieved with appropriate reduction and fixation techniques, but stiffness remains a common sequel to the badly injured foot and may be aggravated by surgery and immobilisation. The merits of surgical fixation of fractures and dislocations in the foot must be weighed against the risks of surgery and further soft tissue disruption. With a proper understanding of the structure and function of the foot a balanced judgement can be made regarding surgery and the techniques that might be used.

**Practice points**

- Restore structural stability to the calcaneocuboid, midfoot, and tarsometatarsal joints.
- Restore stability and flexibility to the subtalar, talonavicular, and metatarsophalangeal joints.
- Restore skeletal length and alignment to preserve the supportive and dynamic functions of the plantar aponeurosis.

**References**


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