(vi) Anatomy and biomechanics of the foot and ankle

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Abstract

The foot is a complex anatomical and biomechanical structure. It functions to allow stable stance, ambulation and the effective transfer of force through the lower limb. A thorough understanding of how the foot and ankle achieve this is essential for planning surgery and avoiding the consequences of nerve injury, poor wound healing and disrupted function. This review looks at the current understanding of foot function in the context of gait, biomechanics and relevant surgical anatomy.

Keywords ankle; biomechanics; foot

Introduction

The foot is a complex anatomical structure. It acts to transmit force between the lower limb and the ground, allowing stable ambulation and stance. During gait the foot functions as a flexible shock-absorber, deforming to uneven surfaces before undergoing a series of biomechanical changes which allow it to act as a rigid lever to exert force.

The dense concentration of structures required for normal foot function makes the foot and ankle a treacherous area for the surgeon. A thorough understanding of the complex anatomy of this area is essential for safe surgical intervention.

Anatomy of the foot and ankle

Ankle

Ankle joint stability: the ankle joint gains its stability from bony congruence, the joint capsule as well as ligamentous support.

The inferior tibiofibular joint is a syndesmosis with three main supporting ligaments. Firstly the anterior inferior tibiofibular ligament (AITFL). This is a flat, strong ligament which runs from the anterior edge of the lateral malleolus to the anterolateral tubercle of the tibia. The posterior inferior tibiofibular ligament (PITFL) consists of both superficial and deep portions. The deep part runs from the posterior margin of the tibia to the osteochondral junction on the posteromedial aspect of the distal fibula, whilst the superficial part functions along with the AITFL to ensure that the fibula remains held tightly within the incisura of the tibia. The interosseous ligament is a thickening of the interosseous membrane. This ligament is more flexible and allows a subtle diastasis of the tibia and fibula during ankle dorsiflexion.[1]

Lateral ankle stability is conferred by the lateral ligament complex. This consists of the anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL) and the posterior talofibular ligament (PTFL). The ATFL is a thickening of the anterior capsule and its primary function is to resist inversion when the ankle is plantarflexed. The ligament runs anteriorly from the lateral malleolus to the talus at 45° to the frontal plane.[2] The ATFL also resists external tibial rotation and anterior draw of the talus. There is an angle of 105° between the ATFL and the CFL allowing the two ligaments to act synergistically. The CFL lies in a horizontal position during ankle plantarflexion but comes to lie in a vertical orientation during dorsiflexion. It remains under tension throughout this arc of movement, although the tension is greatest during ankle dorsiflexion where the ligament most-effectively resists inversion. During ankle plantarflexion the CFL also guides calcaneal inversion, which may be observed when a patient with normal feet stands on tip-toes. The PTFL runs from the lateral malleolus to the posterolateral talus.

The lateral ligament complex tends to fail in a predictable sequence during inversion injury. The sequence is ATFL, CFL and PTFL. Once the ATFL has ruptured there is a significant increase in internal hind-foot rotation which predisposes to further ligament injury.[3]

Major stabilizers on the medial side of the ankle joint are the medial malleolus and the deltoid ligament. The deltoid ligament is by far the strongest ligament stabilizing the ankle, with a tensile strength of 714N. This compares with the strongest lateral ligament, the CFL with a tensile strength of 346N.[4] The ligament is formed from superficial and deep parts. The superficial deltoid is divided into three slips which originate from the anteroinferior medial malleolus and insert into the navicular, calcaneonavicular ligament and the sustentaculum tali and tuberosity of the calcaneum respectively. The superficial deltoid acts mainly to prevent hind-foot eversion. The deep deltoid ligament originates from the posterior border of the anterior colliculus, intercollicular groove and posterior colliculus before running transversely to insert into the non-articular surface of the medial talus. The posteromedial aspect of the ligament is covered by the tibialis posterior tendon sheath.[5] Sectioning the deep deltoid ligament results in greatly increased lateral talar shift and external talar rotation.[6]

Applied anatomy of surgical approaches to the ankle

A number of different surgical approaches are used to access the ankle joint. These will be considered in a clockwise direction starting with the direct lateral approach to the distal fibula.

Laterally the fibula lies subcutaneously and approach to fractures here can be carried out in relative safety. There are however several important structures that must be considered when performing this simple approach. Running just posterior to the fibula are both the sural nerve and, accompanying it, the short saphenous vein. Identifying and protecting the vein with its less easily identified nerve is essential in order to prevent numbness on the lateral aspect of the foot or a painful neuroma. Another structure at risk with higher fibular fractures is the superficial peroneal nerve which exits the lateral compartment of

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the leg 15 cm above the ankle. More extensive dissection is this area may uncover the peroneal tendons in their common tendon sheath. These play an important role as dynamic stabilizers of both the medial and lateral longitudinal arches. Damage to these tendons is one of the causes of pain after ankle injury. This occurs by tendon dislocation, instability, tendinitis or rupture.

The anterolateral approach to the ankle is a useful approach which is extensile both proximally and distally to expose the fibula as well as the calcaneocuboid, talonavicular and talocalcaneal joints. This may be useful for approaching fractures of the talus as well as for triple fusion or ankle arthrodesis. The incision should be made 2 cm anterior to the fibula and curving downwards such that it passes 2 cm medial to the lateral malleolus and ends 2 cm medial to the base of the fifth metatarsal. The structures most at risk during this dissection are the dorsal cutaneous branches of the superficial peroneal nerve. These are superficial to the deep fascia and should be identified and protected. The deep fascia in this region is thickened by the superior and inferior extensor retinaculae. These should be incised to reveal the extensor muscles. Peroneus tertius is the most lateral of these and is supplied by the deep peroneal nerve. Identify the lateral margin of this muscle and retract the extensors medially to expose the distal fibula and ankle joint. From this position the anterior elements of the syndesmosis are visible. At the distal end of the wound the extensor digitorum brevis muscle is visible below the fat pad of the sinus tarsi. Excising the fat pad and detaching this muscle at its origin allows access to the mid-tarsal joints for arthrodesis (Figure 1).

The direct anterior approach to the ankle may be used for arthrodesis, fixation of pilon fractures or total ankle replacement. The malleoli may be used to centre the incision, which should be just through the skin. Care must be taken to avoid first the superficial peroneal nerve and secondly the neurovascular bundle formed from the anterior tibial artery (palpable as the dorsalis pedis pulse) and the deep peroneal nerve. The anterior tibial neurovascular bundle runs just medial to the extensor hallucis longus (EHL) tendon and crosses over at the level of the ankle joint to lie on the lateral side of the tendon between EHL and extensor digitorum longus (EDL). The deep peroneal nerve, which has supplied all the muscles in the anterior compartment of the leg, goes on to supply the skin of the first webspace in the foot. These structures are best approached from proximal to distal and once identified, should be retracted medially along with the EHL tendon. One other approach is to develop a plane between tibialis anterior (TA) and FHL, although care must be taken to protect the deep peroneal nerve at the proximal extent of the wound.

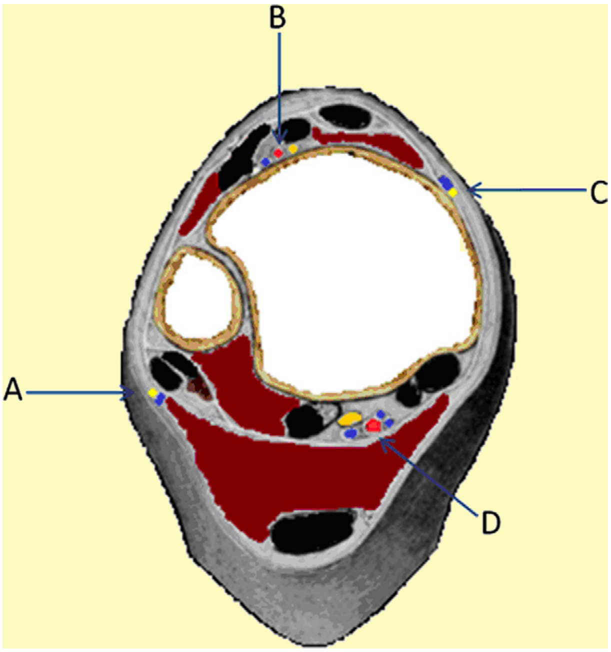

Figure 1 Neurovascular structures in a coronal section 1 cm proximal to the ankle joint. **A**: Superficial peroneal nerve. **B**: Anterior tibial artery and vein with the deep peroneal nerve. **C**: Long saphenous vein with saphenous nerve. **D**: Posterior tibial artery and vein with the tibial nerve.

A medial approach can be used for the fixation of medial malleolar fractures. This may be performed through an anterior, posterior or direct medial incision. The anterior incision allows visualization of the ankle joint, whilst the posterior incision allows visualization of the posterior tibia. For arthrodesis the direct medial approach may be used in combination with a medial malleolar osteotomy to improve access. Incisions in this area should curve anteriorly at the level of the tip of the medial malleolus and should avoid the most prominent part of the malleolus in order to avoid wound problems and discomfort from footwear. Anterior to the medial malleolus the great saphenous vein runs with the saphenous nerve. These should be identified carefully and protected. Behind the medial malleolus there is the retinaculum covering the tibialis posterior (TP) tendon. The retinaculum may be incised for access and later repaired but care should be taken to avoid damage to the TP tendon. This should be retracted anteriorly. The remaining structures behind the medial malleolus may be gently retracted posteriorly to allow limited access to the posterior tibia.

The structures running behind the medial malleolus may be approached through a **posteromedial approach**. This is useful in exploring soft tissue entrapment such as tarsal tunnel syndrome. The incision should be made between the Achilles tendon and the medial malleolus. This may be deepened into the fat which lies between the two structures. The deep fascia is incised and the flexor hallucis longus identified. The other long flexors have all become tendinous at this level and so FHL is easily identified. For this reason the muscle is sometimes known as the “beef to the heel”. The FHL muscle along with the neurovascular bundle containing the posterior tibial artery and nerve may then be retracted laterally whilst the FDL tendon is retracted medially. This allows access to the posterior tibia and joint capsule (Figure 2).

Finally, **the posterolateral approach** to the ankle is a useful approach for internal fixation, allowing fixation of both posterior malleolar fractures and distal fibular fractures through the same incision. The patient should be positioned prone and the incision made midway between the posterior border of the lateral malleolus and the Achilles tendon. There is an inter-nervous plane between the peroneus brevis (supplied by the superficial peroneal nerve) and the FHL tendon (supplied by the tibial nerve). At this level the peroneus longus and brevis run in a combined tendon sheath before passing under the peroneal retinaculum posterior to the lateral malleolus. Peroneus brevis continues to insert into the base of the fifth metatarsal whilst peroneus longus runs around the peroneal groove in the cuboid to insert into the medial cuneiform. Peroneus

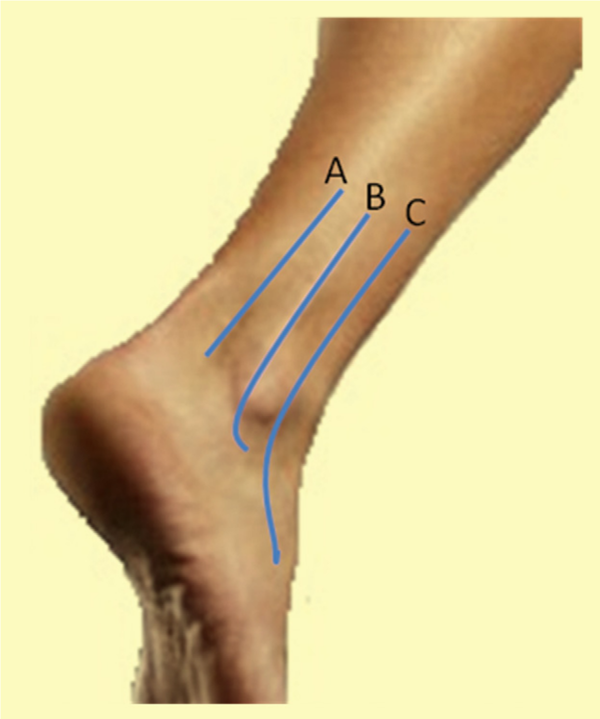

Figure 2 The posterolateral aspect of the ankle showing the sites for the posterolateral **A**: lateral **B**: and anterolateral **C**: Note the anterolateral approach is extensile to the mid-foot in order to expose the calcaneocuboid joint.

brevis may be identified as it lies anterior to peroneus longus and it is muscular much more distally than peroneus longus.

The sural nerve with the short saphenous vein accompanying it should be running anterior to the lateral malleolus and hence well-outside the scope of the incision.

The peroneal retinaculum should be incised and the tendons retracted anteriorly. The muscular FHL may then be retracted medially. Detaching the lateral fibres of the FHL muscle from the distal tibia aids exposure further. This approach may be extended proximally between the lateral head of gastrocnemius and the peroneal muscles.

Hind-foot

Subtalar joint stability: the subtalar joint allows pronation and supination and consists of two separate joint cavities. Posteriorly the joint is formed between the inferior–posterior talar facet and the superior–posterior facet of the calcaneus. The anterior articulation is formed between the talar head, anterior–superior facets, sustentaculum tali and the concave surface of the navicular. This talocalcaneonavicular joint functions as a ball and socket. These two joints are separated by the sinus tarsi and have separate joint capsules although they share a similar axis of rotation.

There are three lateral groups of supporting structures. These are the deep ligaments, peripheral ligaments and retinaculae.

The cervical and interosseous ligaments are deep ligaments which lie between the two joint capsules. The cervical ligament runs from the cervical tubercle of the calcaneus anteriorly and medially to the talar neck. The interosseous ligament lies posterior to the cervical ligament and runs superiorly and medially. It takes its origin from the calcaneus just anterior to the posterior joint capsule and inserts into the talar neck just medial to the insertion of the cervical ligaments.

Lateral support comes in part from the inferior extensor retinaculum. These have three roots which are lateral, intermediate and medial although it is likely that only the lateral root confers stability.[7]

The three peripheral ligaments which stabilize the subtalar joint are the calcaneofibular ligament (CFL), which also spans the ankle joint, the lateral talocalcaneal ligament (LTCL) and the fibulotalocalcaneal ligament (FTCL).[8]

The talus: the anatomy of the talus requires particular mention for several reasons. Firstly it is the only bone in the foot not to receive significant muscular attachments and secondly it is at high risk of avascular necrosis after injury. The talus consists of a body, neck and head and articulates with the tibia, calcaneum and navicular, meaning that around 60% of its surface is covered with articular cartilage. It receives a blood supply from each of the three arteries supplying the foot (Table 1). There is some variability in this supply and an anastamosis usually exists between the artery of the tarsal sinus and the artery of the tarsal canal.[9]

The calcaneal tendon: is the combined tendon of the gastrocnemius and soleus muscles. It inserts into the inferior third of the posterior part of the calcaneum and transmits the force of the strongest ankle plantarflexors. The tendoachilles is able to withstand up to 17 times body-weight whilst only stressing the gastro–soleus complex to generate 13% of its maximum force.

The tendon consists of a spiral of fibres which undergo a 90° rotation during their course from the musculo-tendinous junction to insertion. Hence the medial fibres insert posteriorly and the lateral fibres insert anteriorly. Eighty percent of the tendon is type I collagen with a small proportion of type III collagen. Higher proportions of type III collagen predispose to injury.

The tendon is separated from the calcaneum by the retrocalcaneal bursa and from the skin by the subcutaneous calcaneal bursa. The paratenon surrounds the calcaneal tendon and is continuous proximally with the muscle fascia and distally with the periosteum. On the medial and dorsolateral aspects there are gliding membranes lubricated with polysaccharides which reduce friction and allow smooth tendon movement.

The blood supply to the tendon is derived from end to end via the paratenon. This creates a watershed area between the more proximal area supplied by the posterior tibial artery and the more distal

The arterial supply of the talus

Artery	Originating artery	Area supplied
Artery of the tarsal canal	Posterior tibial artery	Talar neck + almost all the body of the talus. Medial 1/3 of body supplied by deltoid branches
Artery of the sinus tarsi	Perforating peroneal artery	Inferomedial talar head
Dorsalis pedis	Anterior tibial artery	Superolateral talar head

Table 1

supply from the perforating peroneal artery.[10] Hence, between 2 cm and 6 cm proximal to the tendon insertion is the commonest area for tendon rupture to occur. Due to the low metabolic rate and poor blood supply in this region, healing is slow.

Applied anatomy and surgical approaches to the hind-foot: as described above, the anterolateral approach to the ankle may be extended to allow access to the talonavicular, calcaneocuboid and calocalcaneal joints. This approach may be used in conjunction with a medial approach for the fixation of talar fractures.

The posterior talocalcaneal joint may be approached from laterally during subtalar arthrodesis. The landmarks for this incision are the lateral malleolus and the peroneal tubercle of the calcaneum. This is found 1.5 cm distal and anterior to the tip of the lateral malleolus and acts to separate the peroneus longus and brevis tendons as their courses diverge. The incision should start posterior to the lateral malleolus and curve anteriorly to pass over the peroneal tubercle. The sural nerve and accompanying short saphenous vein should lie well posterior to the incision. The peroneal tendons may be released from their tendon sheaths, which by the level of the peroneal tubercle should be separate. These are both covered by the peroneal retinaculum, which should be repaired during closure to prevent tendon dislocation. The calcaneofibular ligament may be identified running postero-inferiorly from the lateral malleolus. Beneath this lies the capsule of the posterior talocalcaneal joint.

Olliers approach, a transverse approach to the mid-foot, is no longer current practice due to the unacceptably high risk of superficial peroneal nerve injury.

The lateral approach to the calcaneum as described by Eastwood and Atkins[11] is useful for open reduction and internal fixation of calcaneal fractures. Surgery to the calcaneum has proved challenging to surgeons due to the high risk of wound breakdown and nerve damage. This approach seeks to maintain a vascular full-thickness tissue flap using the blood supply from the perforating peroneal artery, whilst avoiding sural nerve damage. However, a thorough history and vascular assessment of the lower limb should be carried out and diabetes, smoking or previous surgery to the posterior aspect of the distal fibula should be considered relative contraindications.

The incision is formed of two limbs, a vertical limb and a horizontal limb. These should be separated by at least 90°. The vertical limb should be made 5 cm proximal to the lateral malleolus commencing almost in the midline. This allows the sural nerve to be elevated anteriorly in the flap. The vertical limb should extend downwards to meet the junction between the skin of the sole and the skin of the foot. The horizontal limb may then be made in the skin of the sole of the foot as far anterior as the base of the fifth metatarsal. The flap may then be elevated by subperiosteal dissection to expose the body of the calcaneum. Dividing the calcaneofibular ligament allows access to the subtalar joint whilst splitting abductor digiti minimi in the line of its fibres allows access to the calcaneocuboid joint.

Mid-foot

Approach to Lisfranc fracture-dislocations: one of the commonest indications for surgery to the mid-foot is for unstable fracture-dislocations of the mid-tarsal joints. There are strong intermetatarsal and intertarsal ligaments, although the plantar 'LisFranc's' ligament which runs from the medial cuneiform to the second metatarsal, is most often damaged. This commonly requires surgical repair to regain stability.

The surgical approach to this injury is generally made using a two-incision technique. The medial incision is sited between the first and second metatarsals and extends proximally and slightly towards the midline. This affords excellent exposure of the medial and intermediate cuneiforms as well as the medial two metatarsocuneiform joints. The dorsalis pedis artery with the accompanying deep peroneal nerve is found in the centre of the surgical field using this approach so great care must be taken during dissection to avoid damage to these.

The second incision is made laterally at the base of the 4th metatarsal and extending proximally. This allows direct visualization of the three lateral tarsometatarsal joints. Care should be taken to ensure the greatest possible width of the skin bridge between the two incisions to reduce the risk of skin necrosis at this site. The approaches should both involve full-thickness dissection with minimal undermining of the skin and gentle retraction.

Decompression of compartment syndrome in the foot: the presence of high-energy injury to the foot, such as that which sometimes accompanies LisFranc injuries, necessitates the early recognition and treatment of compartment syndrome. There are nine compartments in the foot. The contents of each are outlined in Table 2. These may all be decompressed using a three-incision technique: The first incision is placed medial to the second metatarsal shaft whilst the second is placed lateral to the fourth metatarsal shaft. These allow decompression of the intermetatarsal compartments. The third incision is sited on the medial side of the foot along the body of the abductor hallucis muscle. Dissection both dorsal and plantar to this muscle allows decompression of the central and calcaneal compartments.

Decompression of all foot compartments is desirable, although some surgeons opt to decompress the foot purely through a medial incision whilst accepting the likelihood of damage to the intrinsic muscles of the foot. Dorsal incisions for decompressing the intermetatarsal compartments have a relatively high morbidity with skin necrosis and poor wound healing.

Contents of each of the fascial compartments within the foot

Compartment	Muscle Contents
Medial	Abductor hallucis Flexor hallucis brevis
Lateral	Abductor digiti minimi Flexor digiti minimi brevis
Superficial Central	Flexor digitorum longus Flexor digitorum brevis
Deep central (Calcaneal)	Quadratus plantae
First to fourth intermetatarsal compartments	Plantar and dorsal interossei
Distal plantar	Oblique head of adductor hallucis

Table 2

The choice of which approach to use may be dictated by the type of injury and clinical findings. Despite surgical intervention this condition carries a poor prognosis with a high incidence of contractures, toe-deformities, sensory neuropathy and paralysis.

Forefoot

Applied surgical anatomy of approaches to the first metatarsophalangeal joint (1st MTPJ): the 1st MTPJ is approached via either a dorsal or medial approach. This allows for fusion, arthroscopy, arthroplasty or soft tissue procedures around the joint. The dorsomedial approach to the 1st MTPJ is no longer commonly used due to the high incidence of injury to the dorsal digital nerve.[12]

The medial approach starts from just proximal to the interphalangeal joint taking care to align with the long axis of the first metatarsal the proximal extent of the incision. The dorsal digital branch of the medial cutaneous nerve lies dorsally in close proximity to the incision. The capsule may then be incised.

The dorsal approach begins just proximal to the interphalangeal joint and should remain medial to the EHL tendon in a straight line. The fascia may then be divided in the line of the incision.

Deep surgical dissection in this area must avoid the FHL tendon, which lies within a fibro-osseous tunnel on the plantar surface of the joint, kept in place by the medial and lateral sesamoid bones.

Anatomy of surgical approaches to the lesser metatarsophalangeal joints: the lesser metatarsophalangeal joints may be approached by two different approaches. These are the dorsal approach and the transverse approach.

Dorsally the second and third MTPJ may be approached using an incision medial to the second metatarsal whilst the fourth and fifth MTPJ may be approached through an incision placed laterally to the fourth metatarsal. Care should be taken to avoid the dorsal cutaneous nerves which supply sensation to the toes. These lie on the dorsolateral and dorsomedial surfaces of each metatarsal.

If all the distal metatarsals require surgical intervention then a transverse approach may be used. This involves careful dissection to avoid damage to the dorsal veins of the foot but affords excellent access the metatarsophalangeal joints.

Gait

Restoring normal or near-normal gait is one of the primary goals of many lower-limb surgeries. Understanding the role that the different structures contribute to normal gait is important when considering gait dysfunction. Muscular activity during gait affords control of the foot such that the centre of gravity of the body progresses smoothly forward without excessive frontal plane motion. These muscle contractions are either concentric (muscle shortening) or eccentric (muscle lengthening).

Walking gait is divided into a swing and a stance phase. The stance phase occupies just over 60% of the gait cycle and culminates at the point of toe-off (TO). After this the swing phase occupies the remaining 40%. The gait cycle has been further divided into eight stages (Figure 3).[13]

During the normal walking gait cycle there are two discrete periods of double limb support; initial and terminal. Together these form around 20% of the gait cycle. Initial double limb support occurs at heel-strike through to the end of the loading response phase. During mid-stance there is purely single limb support. Terminal double limb support occurs from the start of terminal swing until the end of pre-swing at toe-off. During running the periods of double leg stance disappear and there is solely single leg stance with periods of float where neither leg contacts the ground.

Gait may also be specifically considered in relation to foot motion in the sagittal plane using the rocker theory which was described by Perry in 1992.[14] During the first rocker the ankle plantarflexes after heel-strike bringing the forefoot into contact with the ground. Ankle plantarflexion is brought under control by eccentric contraction of the extrinsic anterior compartment muscles. This prevents a foot slap during gait. The strongest of these is tibialis anterior which descends from the anterior compartment in the leg to insert into the medial cuneiform and the base of the first metatarsal (Figure 4).[15]

Next during the second rocker the ankle dorsiflexes as the centre-of-gravity of the body moves over the joint. The foot must be flexible here to adapt to uneven ground. Tibialis posterior is the most powerful invertor of the foot. This is active in mid-stance during the second rocker to invert the subtalar joint which creates rigidity in preparation for force transmission at toe-off. The most powerful foot evertors are the peroneus longus and brevis which antagonize the inverting force of tibialis posterior. The dorsiflexion which occurs during the second rocker is controlled eccentrically by both the extrinsic and intrinsic plantarflexors of the foot.

The final third rocker occurs as the metatarsophalangeal joints dorsiflex in preparation for toe-off. Here the windlass mechanism is activated, tensioning the plantar fascia under the

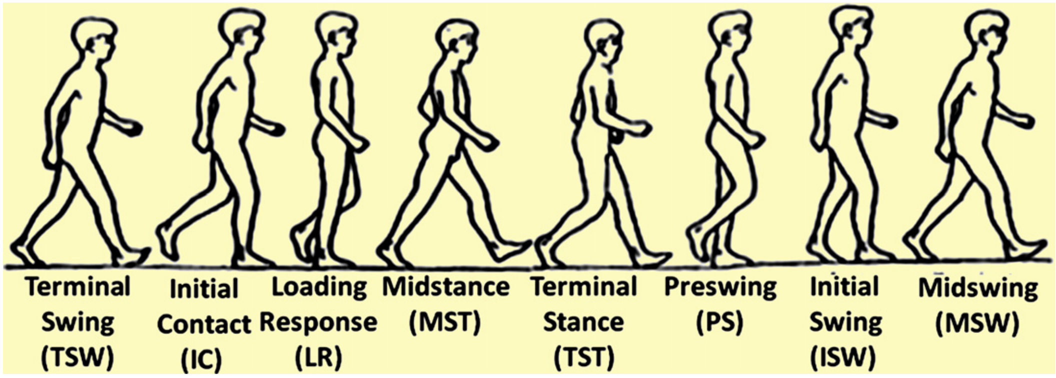

Figure 3 Descriptive phases of gait.[13]

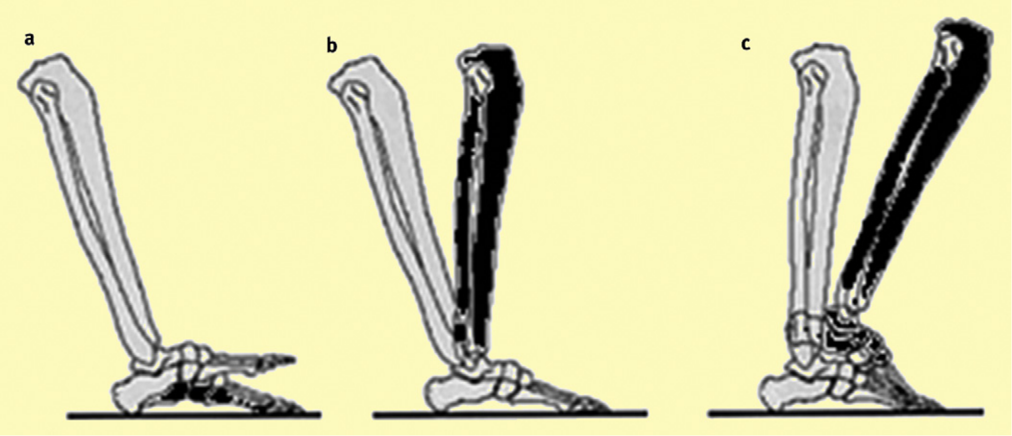

Figure 4 The three ‘rocker’ phases of foot motion during gait. **a** Depicts the first rocker, **b** depicts the second rocker, **c** depicts the third rocker.[15]

metatarsophalangeal joints and transforms into a rigid lever which can transmit a propulsive force to the ground. The extrinsic plantarflexors cease their eccentric activity in the terminal stages of the third rocker whilst the intrinsic plantarflexors contract concentrically to add further force and control to toe-off which occurs at the end of the third rocker.

During the swing phase the anterior compartment muscles contract concentrically to allow foot clearance and pre-positioning before the next heel-strike.

Biomechanics of the foot and ankle

Foot function during the phases of gait as described above is permitted to occur by the specific motion of the joints of the foot and ankle. These are described in the next section.

Motion of the ankle (tibiotalar) joint

The ankle functions almost purely as a uni-planar hinge joint. The talus is on average 2.4 mm wider anteriorly than posteriorly and this mortise shape provides bony stability during dorsiflexion. There is also a small degree of coronal plane rotation. As a result dorsiflexion causes the forefoot to point laterally whilst plantarflexion causes the forefoot to point medially.[16] The primary axis of rotation of the tibiotalar joint lies along a line between the tips of the two malleoli and this is angled at 10° to the frontal plane. Along this axis there is a normal range of movement of 10—20° dorsiflexion and 25—30° plantarflexion. Full ankle dorsiflexion provides only 11° of internal tibial rotation. Propulsion during toe-off requires 19° of internal tibial rotation. Hence some subtalar motion is required for normal gait.[17] Congenital fusion of the subtalar joint can result in remodelling of the tibiotalar joint to a ball and socket joint. This joint configuration affords sufficient internal tibial rotation to allow a propulsive gait.

Motion of the subtalar joint

The effect of tibiotalar motion on the subtalar joint is explained using the principle of the ‘mitred hinge’. This is the principle whereby tibial rotation is transformed into pronation and supination of the forefoot by the combined motion of the subtalar and transverse tarsal joints. External tibial rotation results in subtalar supination whilst internal tibial rotation results in foot pronation (Figure 5).[18]

The subtalar joint is able to invert by 20° and evert by 5° in the normal foot. This is reduced in patients with flat feet and may be reduced to around 12°.[19] In normal feet, 1° of tibial rotation results in 1° of subtalar motion. The presence of a flatfoot deformity increases this relationship so a single degree of tibial rotation results in greater than 1° of subtalar motion (Figure 6).[17]

Motion of the transverse tarsal (Chopart’s) joints

Transverse tarsal motion is key to movement between flexibility and rigidity of the mid-foot during gait. One explanation of this is that the axes of the talonavicular and calcaneocuboid lie in parallel in the frontal plane when the subtalar joint is everted. The talonavicular joint or *acetabulae pedis* behaves as a ball and socket with its axis running through the talar neck. The calcaneocuboid joint is saddle-shaped with its axis through the calcaneal body. These configurations allow flexion and extension of the mid-foot relative to the hind-foot. When the subtalar joint is inverted the axes diverge, increasing the rigidity of the foot and facilitating force transfer to the forefoot.[20]

During the swing phase the subtalar joint is held in slight supination but at heel-strike there is rapid pronation as the heel

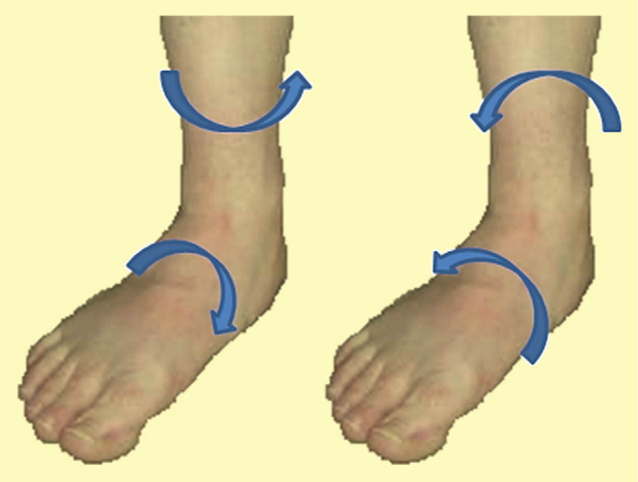

Figure 5 The subtalar joint acts as a mitred hinge; external tibial rotation causes subtalar inversion or supination. Internal tibial rotation causes subtalar eversion or pronation.

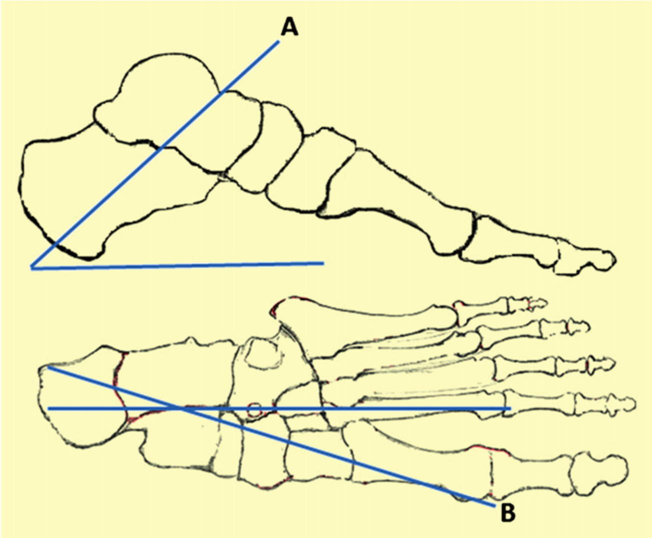

Figure 6 The axis of the subtalar joint lies 42° above the coronal plane (**A**) and 16° medial to the sagittal plane in the midline of the foot (**B**).

contacts the ground slightly lateral to the longitudinal axis of the lower limb. During the first 15% of the stance phase the lower limb internally rotates. This has the effect of pronating the foot, which allows it to become flexible. Here the foot is able to adapt to uneven ground. As the body-weight passes over the planted foot in late stance the heel inverts, supinating the forefoot and locking the mid-tarsal joints. This makes the mid-foot more rigid and allows effective transmission of force from the forefoot to the ground.[17]

Motion of the tarsometatarsal (Lisfranc's) joints and intertarsal joints

The tarsometatarsal joints (TMTJ) contribute little to mid-foot flexibility. What little movement there is results from a gliding motion. Joint stability results both from a high degree of congruency and also from strong ligamentous support. The second metatarsal base is 'keyed' into its metatarsocuneiform joint, as the intermediate cuneiform lies slightly more proximal than the medial and lateral cuneiforms. This confers further bony stability. Lisfranc's ligament runs from the medial cuneiform to the second metatarsal and is a major stabilizer. Movement at the first and second TMTJ is considerably less than that at the fourth and fifth. One study described first TMTJ motion as 3.5° flexion/extension and 1.5° pronation/supination. This compared to 9° flexion/extension and 9° pronation/supination at the fourth and fifth TMTJ.[21]

Motion of the metatarsophalangeal joints

The first metatarsophalangeal joint is highly specialized in order to adapt to the variety of functions it performs. The normal range of motion is from 30° plantarflexion to 90° dorsiflexion. Achieving full painless dorsiflexion is essential for a normal toe-off during gait. The first metatarsophalangeal joint is stabilized by strong collateral ligaments but its congruency depends greatly on position. In neutral there is 0.38 cm^2 joint surface area whilst in full dorsiflexion this reduces to 0.04 cm^2.[22] Whilst most of the joint motion is achieved through a tangential gliding motion, extreme dorsiflexion is achieved by joint compression. This predisposes to the formation of dorsal osteophytes which are common features of first metatarsophalangeal arthritis.

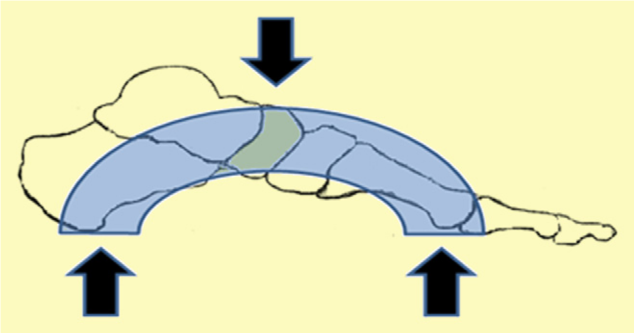

Figure 7 The beam model for stability of the medial longitudinal arch. This model assumes arch stability from bony contact and ligamentous support.

The plane from the first to fifth metatarsal heads which forms during toe-off is known as the metatarsal break. This is usually between 50° and 70° and represents the instant centres of rotation of each of the five metatarsophalangeal joints. The metatarsal break is usually visible on the soles of well-worn shoes as a transverse crease.

Metatarsophalangeal joint movement is essential during the third rocker of gait. As the proximal phalanx passes over the metatarsal head it depresses it. In hallux valgus deformity the ability of the proximal phalanx to depress the first metatarsal head is diminished. This results in transfer of weight to other metatarsal heads, which may result in callosities or 'transfer lesions'.

Arches of the foot

There are two longitudinal arches in the foot. These are the medial and lateral longitudinal arches. The medial longitudinal arch consists of the calcaneum, talus, navicular, medial, intermediate and lateral cuneiforms and the first three metatarsals. The talus sits at the apex of the arch and confers stability by acting as a wedge between the calcaneum and navicular. There

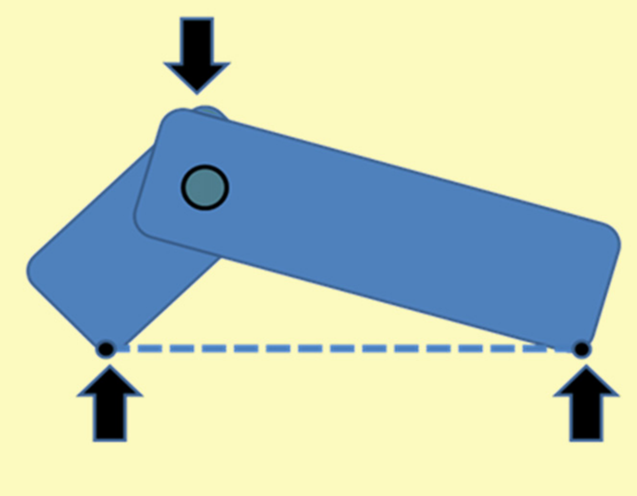

Figure 8 The truss model for medial longitudinal arch support. Half the body-weight passes through the apex of the arch whilst standing. The ends of the ach are unable to move apart due to the tight plantar fascia which connects them (dashed line). Hence arch height is maintained.

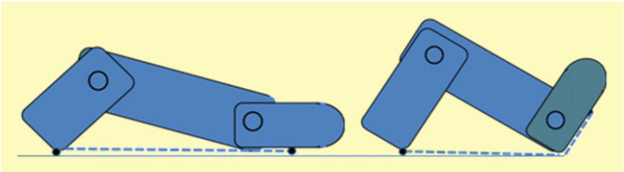

Figure 9 Schematic demonstration of the windlass mechanism for elevation of the medial longitudinal arch following metatarsophalangeal joint dorsiflexion.

are a number of important static stabilizers of the arch. These were studied by sequentially dividing structures in cadaveric feet to assess relative contributions to arch stability. The most important primary stabilizer is the plantar fascia, followed by the long and short plantar ligaments and then the spring ligament. Whilst tibialis posterior and other long flexors are important dynamic stabilizers, releasing these structures without releasing any static stabilizers has only a modest effect on arch height. One study found the result of releasing posterior tibial tension to be a reduction of 0.5 mm in arch height.[23]

There are two models for considering the stability of the medial longitudinal arch; the beam model and the truss model.

In the beam model, a load is applied to the apex of the arch generating compressive forces on the dorsal surface and tensile forces on the plantar surface. Stability in this model results from bony congruency and ligamentous attachments (Figure 7).

In the truss model, there is a triangular arrangement of structures. The bones of the arch are able to pivot about their apex whilst the tough plantar fascia forms the third side. This is firmly attached to the medial and lateral calcaneal tuberosities proximally and its slips insert into the plantar plate and the fibrous flexor sheathes distally (Figure 8).[24]

Hicks described the windlass effect whereby the medial longitudinal arch is raised on dorsiflexing the first metatarsophalangeal joint. The plantar fascia spans this joint and has minimal elasticity. When considering the truss model of arch stability, dorsiflexing the first MTPJ shortens the plantar side of the triangle which has to result in drawing the calcaneum closer to the metatarsal head. When this occurs arch height must increase (Figure 9).[25]

Conclusion

Understanding the complex anatomy and of the foot is an essential part of Orthopaedic practice. This article aims to provide a concise review of key concepts to aid in refreshing knowledge or exam preparation.

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