Anatomy and Biomechanics of the Normal Ankle and Pathology of the Arthritic Ankle
2.1 Ankle Anatomy

The ankle or talocrural joint is the junction between the foot and lower leg. Its gross osseous anatomy is relatively simple, as it consists of the ankle mortise, formed by the distal aspects of the tibia and fibula, which articulates with the talus, the uppermost tarsal bone. The ankle mortise encloses the superior aspect of the talus tightly (Fig. 1). The fibula and tibia are strongly connected to each other by the interosseous membrane and by the anterior and posterior tibiofibular ligaments, which together form the tibiofibular syndesmosis. The superior aspect of the talus consists of the talar dome, having a superior articular surface which is wider anteriorly than posteriorly. The radius of the talar dome is smaller medially than laterally, thus the talar dome can be seen as the segment of a cone with its base at the lateral side. The upper surface of the talar dome articulates with the tibial plafond. The medial and lateral articular facets of the talar dome articulate with the medial and lateral malleolus respectively. The lateral malleolus lies more posteriorly than the medial malleolus, and it also extends more distally. On the medial side the talus is connected to the medial malleolus by the strong deep and superficial medial or deltoid ligaments. They are the most important passive stabilizing structures of the ankle joint, from a clinical perspective comparable to the posterior cruciate ligament of the knee. On the lateral side the talus is connected to the lateral malleolus by the anterior and posterior talofibular ligaments. These latter two ligaments form, together with the calcaneofibular ligament, the lateral ligament complex. They are the passive elements controlling the rotation in the ankle joint, comparable to the function of the anterior cruciate ligament in the knee. Mechanoreceptors have been identified in both the medial and lateral ankle ligaments, and are important proprioceptive elements.

Fig. 1-A

Fig. 1-B
The soft tissues around the ankle joint consist of tendons and neurovascular structures. The tendons are located in 3 compartments, all covered by fascial layers having retinacular reinforcements:

1) the anterior compartment, where the tendons of the anterior tibial, extensor hallucis longus, extensor digitorum longus and peroneus tertius muscles are located (Fig. 2), together with the deep peroneal nerve and the anterior tibial vessels. Somewhat proximal to the ankle joint medial and lateral malleolar branches branch off the anterior tibial vessels. These branches supply blood to the anterior, medial and lateral aspects of the ankle joint. The anterior tibial vessels and deep peroneal nerve are at risk during an anterior approach of the ankle joint, and should be protected by opening the ankle joint at the medial side, thus creating a laterally based soft tissue flap.

Figs. 1-A through 1-C Osseous anatomy of the ankle and foot. Fig. 1-A Schematic osseous anatomy of the ankle and foot. Fig. 1-B Cross-section in the sagittal plane of the lower leg, ankle and foot through the tibia and talus. Fig. 1-C Drawing of the osseous and ligamentous structures of the ankle and hindfoot, as seen from anteriorly.

Fig. 1-C
Figs. 2-A through 2-D The anterior compartment with a demonstration of the anterior approach to the ankle joint. Fig. 2-A The anterior tibial tendon, the long extensor tendons, and the peroneus tertius tendon, after removal of the extensor retinaculum. Fig. 2-B Approach between the anterior tibial and extensor hallucis longus tendons, showing the neurovascular bundle overlying the joint capsule. Figs. 2-C and 2-D Anteromedial arthrotomy to the ankle joint, medial from the neurovascular bundle.

2) the posteromedial compartment, where the tendons of the tibialis posterior, flexor digitorum longus and flexor hallucis longus muscles are located, together with the tibial nerve and the posterior tibial vessels (Fig. 3). The flexor hallucis longus tendon and the posterior tibial artery are at risk for injury during preparation in the posterior part of the ankle joint when the posterior capsule is released from the distal tibia.

Figs. 3-A and 3-B The soft tissues of the posteromedial compartment. Fig. 3-A The tendon of the flexor digitorum longus muscle overlying the posterior tibial tendon, together with the posterior tibial artery and veins, and the superficial (tibiocalcaneal) medial collateral ligament. Fig. 3-B After reflection of the superficial medial collateral ligament, the deep (tibiotalar) medial collateral ligament is seen.
3) the lateral, or peroneal compartment, where the tendons of the peroneus brevis and longus muscles are located (Fig. 4), together with the peroneal vessels and sural nerve.

**Fig. 4** Lateral view of the ankle, after removal of the superficial fasciae and retinaculae. The peroneus brevis and longus tendons are seen, running in the peroneal compartment. Posterior to these tendons the short saphenous vein is visible, and anterior to the lateral malleolus are the anterior lateral malleolar vessels. The origin anterior talofibular ligament is clearly visible, the posterior talofibular and the calcaneofibular ligaments are lying under the peroneal tendons.

The following structures are encountered during the anterior surgical approach to the ankle joint (from superficial to deep): the superficial peroneal nerve in the subcutaneous fat, the superior and inferior extensor retinaculum, the interval between the anterior tibial and extensor hallucis tendons, the medial malleolar vessels and the anterior capsule of the ankle joint. The medial dorsal nerve to the foot (a branch of the superficial peroneal nerve) is at risk to be injured during the anterior approach. This branch has a variable course. It normally runs in the vicinity of the wound in the most distal part of the anterior incision, but can have a more medial course, thereby requiring extensile preparation and mobilization (Fig. 5). In order to avoid injury to the anterior tibial vessels the ankle joint should be opened medially. The medial malleolar vessels should be ligated or cauterized in order to prevent bleeding.
2.2 Biomechanics and Kinematics of the Normal Ankle and Hindfoot

The ankle joint is highly loaded during walking, up to five times body weight\(^4\), although it has a relatively small surface contact area of about 350 square mm\(^5\). Most of the load is distributed through the superior articular surface of the talus\(^6\), while the remaining load is transmitted through the talar facets, with the medial facet accepting twice the load of the lateral. The contact area is the largest with the talus in neutral position and in dorsiflexion, the position of the ankle joint during about half of the stance phase\(^6\). These forces are transmitted further downwards to the foot, and the medial tarsal bones (navicular, cuneiform bones) play an important role in this force transmission.

Although the range of motion of the tarsal joints is less compared to the ankle, its range of motion is higher than was previously thought. The motion patterns of the individual tarsal joints (talocalcaneal, talonavicular and calcaneocuboid) are coupled, leading to a constraint motion pattern of the hindfoot when it moves from eversion to inversion. This constraint motion pattern is defined by the articular structures (both by the geometry of the joint surfaces and by the articular ligaments). Detailed
cadaver experiments of the tarsal kinematics have been done by Van Langelaan\textsuperscript{7} with use of roentgen stereophotogrammetry. He found that a motion pattern around helical axes existed of both the talocrural and the individual tarsal joints. Benink\textsuperscript{8} confirmed these findings in a continuous motion setup study in vitro and in vivo. Lundberg et al\textsuperscript{9,10,11,12} carried out in-vivo kinematic studies of the ankle and hindfoot in healthy volunteers by roentgen stereophotogrammetry. They described that the dorsiflexion-plantarflexion motion at the ankle joint occurs around a horizontal axis in dorsiflexion and that, with increasing plantarflexion, this axis rotates into varus. Furthermore, they found that a large inter-individual variance exists in the inclination of the vertical rotation axis of the ankle joint. Their studies confirmed the cadaver findings by Van Langelaan\textsuperscript{7} and Benink\textsuperscript{8}. An excellent overview of the functional anatomy of the ankle and foot was written by Huson\textsuperscript{13}. He showed that the subtalar joint has a close-packed condition in the neutral position, and that with movement into inversion a loose-packed condition develops. The inversion movement in the subtalar joint is combined with an external rotation movement of the lower leg with respect to the foot. This means that in the loaded situation the talus shifts laterally and the calcaneus medially, so that axial loading remains in the axis of the lower leg. The ankle joint has a close-packed position in dorsiflexion, and rotation around the longitudinal axis becomes possible with plantarflexion.

To summarize, it can be stated that the kinematics of the loaded ankle and hindfoot joints are linked. This means that a rotation of the lower leg will result in motion at the tarsal joints, and furthermore, that a reduced motion of the ankle joint will produce an abnormal kinematic pattern at the hindfoot and vice-versa. Therefore, any disturbance in the normal function of the ankle could have its influence on the foot.

### 2.3 Pathology of the Arthritic Ankle

Aging has a limited effect on the quality of the articular cartilage of the ankle, in which it differs from the cartilage of the knee and hip\textsuperscript{14}. This might explain the low incidence of primary (idiopathic) osteoarthritis of the ankle joint in the elderly, as was seen in epidemiologic studies\textsuperscript{15,16}. Compared to other joints, ankle arthritis mostly develops as a late result of either trauma or of inflammatory joint disease. This explains that patients developing ankle arthritis in general are younger than those developing degenerative arthritis of the hip or knee\textsuperscript{5}.

Post-fracture arthritis can be the result of either a malleolar fracture, a tibial plafond fracture, a talar fracture or a lower leg fracture. If such fractures have healed with correct alignment, arthritis is probably due to cartilage damage at the time of
the initial injury. High-energy injury is expected to have a higher risk of such cartilage damage, but ankle arthritis can also occur after low-energy injury. However, symptoms caused by posttraumatic arthritis in well-aligned ankles can remain at a tolerable level for many years until, finally, surgical reconstruction may become necessary. Fractures that have healed with either limited or gross malalignment are of course more prone to develop post-fracture arthritis\textsuperscript{17}. If the ankle mortise is abnormal, either due to a shortened and/or externally rotated fibula\textsuperscript{18}, due to a malunited posterior malleolus\textsuperscript{19}, or due to a medial ligament injury\textsuperscript{20}, the joint contact area will be reduced significantly, leading to localized cartilage overload. This cartilage overload could then result in early and rapidly progressive ankle arthritis. A non-anatomically healed tibial plafond fracture will frequently cause the same phenomenon of early and progressive ankle arthritis. Extra-articular malalignment after, for example a lower leg fracture, in general has a less severe impact on the ankle joint, and will mostly not lead to rapidly progressive disease.

Posttraumatic arthritis due to chronic ligament laxity might be the result of cartilage damage at the time of the initial injury, or, more likely, due to recurrent ankle sprains. Inversion injuries frequently lead to symptomatic arthritis. Schaap et al\textsuperscript{21} reported that 30 per cent experienced residual symptoms after 9 months of follow-up. At 6.5 years 39 per cent of a subgroup treated non-operatively remained symptomatic\textsuperscript{22}. Lateral ligament insufficiency results in a rotatory instability of the ankle joint, giving rise to shear forces on the cartilage, and thereby to a slowly progressive cartilage damage and to ankle arthritis. Thus, if not healed properly, chronic instability may result in arthritis: \textit{instability arthritis}. The typical late result of instability arthritis is an ankle with moderate to severe varus deformity, whereby the talus lies tilted in the ankle mortise and cartilage loss at the medial part of the ankle joint exists. Not uncommon, this pathology can occur bilaterally, and thereby might result in substantial functional impairments for the patient (Fig. 6).

\textbf{Fig. 6} Anteroposterior weightbearing radiograph of the ankles of a 50-year old man, a former soccer player, suffering from bilateral instability arthritis. Asymmetric joint space narrowing exits at the medial aspect of both talocrural joints, together with a concomitant varus deformity of 15 degrees.
With inflammatory joint disease, arthritis can occur both at the ankle and the foot, however with a changing and not always predictable expression and disease pattern. Over time, most patients suffering from RA will develop symptoms both in the foot and the ankle. Vainio reported a 91 per cent prevalence of foot and ankle symptoms in female rheumatoid patients and 85 per cent in male rheumatoid patients in an in-patient setting\textsuperscript{23}. Another study noted a 94 per cent prevalence of foot and ankle symptoms in an outpatient setting\textsuperscript{24}. They also reported that at a mean 13.5 years of disease duration 42 per cent of patients thought their ankle and/or hindfoot symptoms were worse than their forefoot symptoms, while 28 per cent thought their forefoot symptoms were worse. Forefoot involvement has been reported to occur more often early in the disease, while hindfoot involvement would be more prevalent with longer disease duration. In the rheumatoid hindfoot, the typical deformity is valgus deformation, as a result of tenosynovitis and insufficiency of the posterior tibial tendon and muscle, and of synovitis of the tarsal joints (the talonavicular joint in particular). Rheumatoid valgus deformity is a relatively early phenomenon and can affect gait significantly\textsuperscript{25}. Valgus deformity of the hindfoot can eventually result in eccentric overload of the ankle joint and, especially in combination of synovitis of the ankle joint, in destructive changes of the ankle joint with a limited to moderate degree of valgus deformity at the level of the ankle joint itself. Sometimes valgus deformity of the ankle-hindfoot complex can, in the event of a coexisting osteopenia, result in a spontaneous fracture of the distal fibula, and thereby to a progressive deformity (Fig. 7).

\textbf{Fig. 7} Anteroposterior radiograph of the ankle joint of a female patient suffering from longstanding rheumatoid arthritis and severe arthritic changes of the ankle joint. She developed a spontaneous distal fibular fracture, aggravating a pre-existing valgus deformity of the ankle and hindfoot.
Inflammatory joint disease of the ankle without concurrent hindfoot disease occurs infrequently, and, if so, in general has a slowly progressive disease pattern. In such a situation, due to ankle synovitis, the lateral ligaments can become attenuated, and this could then also result in a secondary varus deformation, similar to instability arthritis. Varus deformity in inflammatory joint disease was seen in our two-center study in eight ankles out of ninety-three, and apparently is not a rare phenomenon. Inflammatory joint disease is furthermore characterized by the relatively high incidence of osteopenia and of cystic lesions in the juxta-articular osseous structures (Fig. 8). These rheumatoid comorbidities could compromise both the surgical procedure as expressed by a higher rate of intraoperative fractures, and the result at follow-up, as expressed by a higher rate of aseptic loosening and edge-loading due to persistent deformity in the frontal plane.

**Figs. 8-A and 8-B** Computer tomography scan with reconstructions in the frontal (**Fig. 8-A**) and sagittal (**Fig. 8-B**) plane of the right ankle of a 67-year old female patient with rheumatoid arthritis. There is severe cartilage loss at the ankle joint and large intra-osseous cysts have developed in the talus, together with smaller cysts in the distal tibia and superior part of the calcaneus.

**Note:** **Fig. 1-C** has been obtained from Primal Pictures Ltd, **Fig. 1-B** has been obtained from the Department of Anatomy, Leiden University, and **Figs. 2 through to 4** have been made at the Department of Anatomy, Leiden University.
References

1. Inman VT. The joints of the ankle. Baltimore, Williams & Wilkins, 1976.