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# Normal Biomechanics of the Foot and Ankle

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*The biomechanics of the foot and ankle are important to the normal function of the lower extremity. The foot is the terminal joint in the lower kinetic chain that opposes external resistance. Proper arthrokinematic movement within the foot and ankle influences the ability of the lower limb to attenuate the forces of weightbearing. It is important for the lower extremity to distribute and dissipate compressive, tensile, shearing, and rotatory forces during the stance phase of gait. Inadequate distribution of these forces could lead to abnormal stress and the eventual breakdown of connective tissue and muscle. The combined effect of muscle, bone, ligaments, and normal foot biomechanics will result in the most efficient force attenuation in the lower limb. This article will look specifically at the normal biomechanics of the foot and ankle.*



Normal biomechanics of the foot and ankle can be divided into static and dynamic components. The static structures include the bones, joint surface congruity, ligaments, and fascia. The dynamic components include the arthrokinematics of the tarsal bones and muscle function.

## STATIC STRUCTURES

Muscle activity is not necessary to support the fully loaded foot at rest.[12,15] The maintenance of the arch in the static foot is attributed to passive ligamentous and osseous support.[15] Hicks[3,4] was the first to emphasize the importance of the beam action of the metatarsals and the tensile strength of the plantar aponeurosis. He indicated that in the static stance position the plantar aponeurosis takes up approximately 60% of the stress of weightbearing and the beam action of the metatarsals approximately 25%. The ability of the plantar aponeurosis to absorb stress increases as the aponeurosis becomes taut with toe extension. This mechanism has been described by several authors as the windlass effect (Fig. 1).[1,4,11,16] At maximum extension of the toes, during the push-off phase of gait, the aponeurosis winds around the metatarsophalangeal joints (MTP). This twisting effect increases the tension of the tissue, allowing the plantar aponeurosis to take on greater amounts of stress.[15] Tension within the plantar aponeurosis, in addition to absorbing more stress, assists in supination of the subtalar joint.[4] The short and long plantar ligaments and the calcaneonavicular ligament (spring ligament), also assist in the passive maintenance of the arch.[9] The beam action of the metatarsals, as described by Hicks, represents the supportive aspect of the long bones of the foot. Hicks[4] has not directly measured the amount of stress the metatarsals absorb. The bones, however, are major stabilizers of the foot. This is obvious when observing the trabecular patterns which indicate the direction of force transmission into the foot. The trabecular systems follow the alignment of the medial and lateral arch.[9] Root et al.[16] describe surface congruity as a stabilizing factor of the tarsal bones. Joint congruity has classically been described as a stabilizing influence in synovial joints.[18] The joint alignment and congruity of the metatarsal and tarsal bones are critical in establishing the medial and lateral arches. This joint relationship is also important for normal arthrokinematics of the foot and ankle.

In summary, the static mechanisms responsible for force attenuation within the foot include the windlass effect of the plantar aponeurosis, the tensile strength of the plantar ligaments, the beam effect of the metatarsals, and the joint congruity

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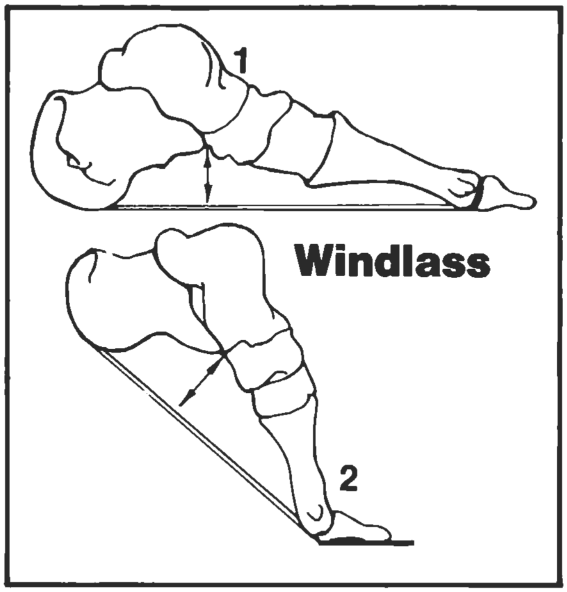


Fig. 1. *Windlass effect of toe extension. 1, Plantar aponeurosis in a slack position with the foot in neutral; 2, increased tension of the plantar aponeurosis as the toes extend, raising the medial arch facilitating supination.*

of the tarsal and metatarsal bones. The dynamic aspects of foot and ankle biomechanics work in conjunction with, and are dependent upon, the static mechanisms.

## DYNAMIC STRUCTURES

Movement of the foot and ankle is a complex action involving many joints. Functionally, the foot and ankle are similar to a closed kinetic chain. Steindler[17] defines a closed kinetic chain as ". . . a combination of several successively arranged joints constituting a complex motor unit, where the terminal joint of the chain meets with considerable resistance." The lower extremity is frequently described as a closed kinetic chain during the gait cycle. However, the foot, independent of the lower extremity, may also be considered as a unit so arranged that motion at one joint influences mechanisms of other joints within the chain. The complex motions of the foot and ankle which promote the interdependence of joint movement are called pronation and supination. Root et al.[16] describe pronation and supination as triplane motions. For example, pronation includes the body plane movements of abduction, dorsiflexion, and eversion (Fig. 2).[6,16] These three motions are derived from the transverse, sagittal, and frontal planes, respectively. However, because the axes of motion of the triplane joints are oblique, traversing all three body planes, the movement of

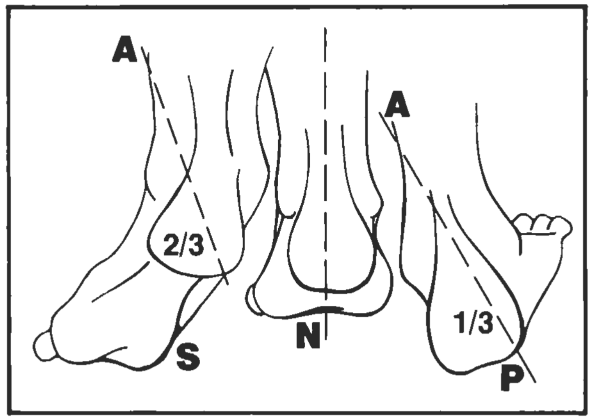


Fig. 2. *Open kinetic chain pronation and supination. S, Supination two third's from neutral; N, neutral; P, pronation one-third from neutral; A, oblique axis of motion of the subtalar joint (anterior, superior, and medial to posterior inferior and lateral).*

abduction, dorsiflexion, and eversion occur simultaneously. (Fig. 2, P).[3,6,16] Supination is the triplane motion including adduction, plantar flexion, and inversion (Fig. 2, S).[3,6,16] Supination and pronation as described above occur in an open kinetic chain. Root et al.[16] describe this open kinetic chain movement by observing the calcaneous in the nonweightbearing position. The functional biomechanics of the foot and ankle are important in the weightbearing position or the closed kinetic chain. Sixty percent of the gait cycle is weightbearing, better described as the stance phase of gait.[7,16] Supination and pronation occur at certain points in the stance phase to assist movement, stabilize joints, and reduce forces within the foot and lower limb. Root et al.[16] have identified five triplane joints within the foot that allow pronation and supination to occur. The triplane joints include the talocrural, the subtalar, the midtarsal, the first ray (first metatarsal/cuneiform), and the fifth ray (fifth metatarsal).

## PRONATION: HEEL STRIKE/TOE STRIKE

Pronation occurs in the stance phase of gait to allow for shock absorption, ground terrain changes, and equilibrium.[10,16] From heel strike to toe strike there are four basic forces acting on the foot and lower limb which need to be attenuated. Upon heel strike, 80% of body weight is directly over the calcaneous, producing a vertical force against the ground.[5,10] Bone is a specialized connective tissue designed to reduce compressive forces. The alignment of the tibia, talus, and calcaneous at heel strike (Fig. 6) are important to distribute the vertical compressive forces safely.

From heel strike to toe strike the compressive force of weightbearing is distributed between the calcaneous and the metatarsals.[5] The tarsals and the metatarsals at footflat are in a mutual compression, very similiar to a stone arch.[5] The midfoot carries virtually no weight during the stance phase.[5] There is also an anterior shearing force, within the foot, of the tibia on the talus.[10,16] This anterior movement is decelerated mainly by the gastroc/soleus muscle group.[7,16] Mann,[10] describes a medial shearing to the foot resulting from an internal rotation of the lower limb. The subtalar joint, consisting of the talus and the calcaneous, responds to the internal rotation and medial shear by allowing the calcaneous to move laterally or into valgus.[14,16] The talus rolls in a medial direction (plantarflexes and adducts) to fully articulate with the middle facet on the calcaneous.[14,16] This middle facet is formed by the medial process on the calcaneous called the sustentaculum tali. Therefore, as the posterior aspect of the calcaneous rolls laterally, the sustentaculum tali falls medially along with the talus (Fig. 3).[14,16] This rotation of the talus and the calcaneous has been described as the torque converter of the lower limb.[7,14,16]

Ambulation is a series of rotations, starting in the lumbar spine, that propel the body through space.[7] The transverse rotations of the tibia and the femur are transmitted and reduced at the subtalar joint.[7] During the stance phase of gait the foot does not rotate. The tibia rotates medially at heel strike and the talus follows resulting in pronation of the subtalar joint or a valgus heel (Fig. 3). The transverse rotations of the lower limb are converted into the triplane motions of pronation and supination. The midtarsal joint, which consists of the talonavicular and the calcaneal cuboid articulations, unlocks with subtalar joint pronation.[13,16] The cuboid and the navicular become more parallel allowing the forefoot to become a loose bag of bones.[16] The forefoot is now a more efficient mobile adaptor to changes in ground terrain, thus facilitating equilibrium. The midtarsal area is where we can observe the lowering and raising of the medial arch.[2]

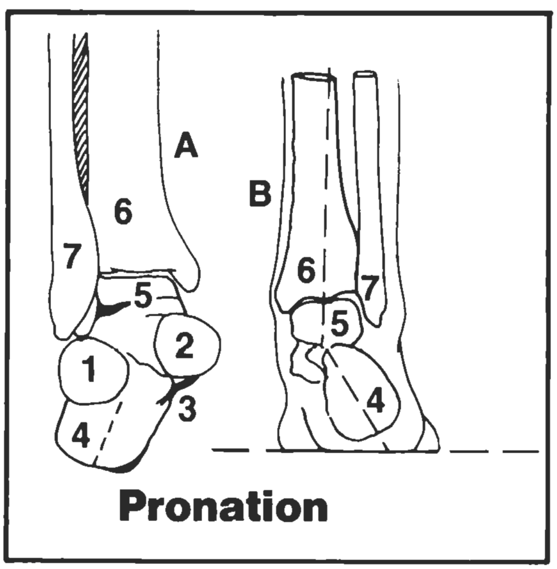


Fig. 3. *Closed kinetic chain pronation. A, Anterior view of the subtalar joint and the talocrual joint; B, posterior view of the subtalar joint and the talocural joint. 1, Calcaneal/cuboid articulation; 2, talo/navicular articulation; 3, sustentaculum tali; 4, calcaneous; 5, talus; 6, tibia; 7, fibula.*

In summary, there are many forces acting on the foot and lower limb from heel strike to toe strike. The four we have reviewed include compression, rotation, anterior shear, and medial shear. Normal pronation is important in attenuation of these forces. It is a passive activity, in the closed kinetic chain, that results from internal rotation of the lower limb and a medial shear to the foot. Pronation is initiated at heel strike and controlled by an eccentric contraction of the supinators. The three muscles that are active from heel strike to toe strike, include anterior tibialis, extensor digitorium longus, and extensor hallicus longus.[15] Root et al.[16] classify the above muscles as supinators of the foot.

## SUPINATION—TOE STRIKE/PUSH-OFF

Supination occurs at the end of the stance phase of gait. It enables the extrinsic muscles to function more efficiently and sets up a rigid lever from which to push off.[10,16] This rigid lever is established by a locking of the bones of the foot and ankle.[16] The fixed position of the tarsals and metatarsals allow for a muscle pulley system to be set up. Several of the extrinsic muscles are dependent upon bony levers for proper function. For example, the peroneus longus during push-off stabilizes the first ray.[16] The ability of the muscle to act in this manner is dependent upon the cuboid pulley. (Fig. 4).

Supination of the foot results from several mechanisms. First, from toe strike to push-off (midstance) the activity of the extrinsic muscles initiate supination.[10] EMG studies have shown during midstance the increase in activity of the gastroc/soleus, posterior tibialis, flexor digitorium longus, and the flexor hallicus longus.[15] Mann and

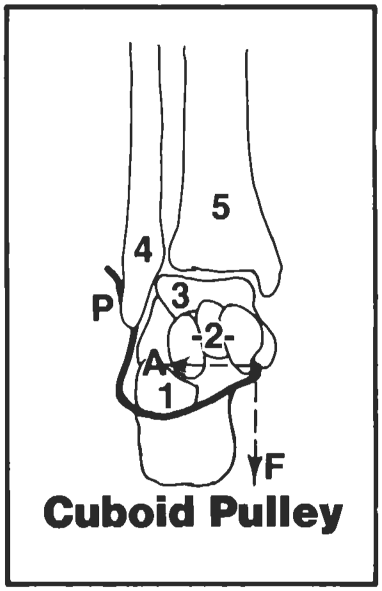


Fig. 4. *Cuboid pulley. A and F represent the vectors of the peroneus longus action. A, Abduction vector; F, plantarflexion vector; P, peroneus longus tendon. 1, Cuboid; 2, cuneiforms; 3, talus; 4, fibula; 5, tibia.*

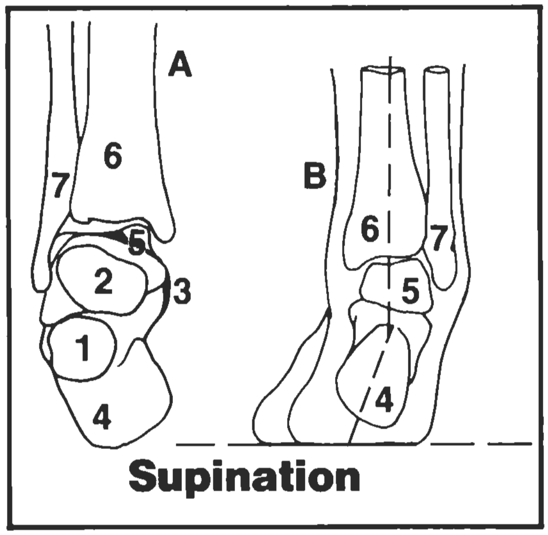


Fig. 5. *Closed kinetic chain supination. A, Anterior view of the subtalar joint and the talocrural joint; B, posterior view of the subtalar joint and the talocrural joint. 1, Calcaneal/cuboid articulation; 2, talo/navicular articulation; 3, sustentaculum tali; 4, calcaneous; 5, talus; 6, tibia; 7, fibula.*

Inman[12] have demonstrated with EMG studies the significance of the intrinsic muscles from toe strike to push-off. The abductor digiti quinti, flexor digitorium brevis, flexor hallicus brevis, abductor hallicus brevis, dorsal interossei, and the extensor digitorium brevis are all important in stabilization of the midtarsal joint during the final 50% of the stance phase.[12] The second factor influencing supination of the foot is the external rotation of the lower limb.[10] The contralateral limb swings forward past the weightbearing limb initiating an external rotation force.[10] This external rotation causes a lateral shearing force within the foot promoting supination.[10] The subtalar joint initiates supination by inversion of the calcaneous. The talus is pushed into a lateral position (abduction and dorsiflexion) by the sustentaculum tali (Fig. 5).[16] The midtarsal joint locks upon supination of the subtalar joint.[13,16] This locking mechanism occurs when the cuboid and the navicular are perpendicular to each other. (Fig. 5). The bones now act as rigid levers for more efficient pull of peroneus longus and the posterior tibialis, respectively. Thus, a synergistic contraction of these two muscle groups stabilize the midfoot and first ray. First ray stabilization affords good alignment of the first MTP joint and a rigid lever for push-off. The third factor influencing supination is the mobility of the first MTP joint. Dorsiflexion of the MTP produces increased tension of the plantar aponeurosis assisting subtalar joint supination.[4,11] This mechanism was described previously as the windlass effect (Fig. 1). The normal amount of joint range of motion needed to facilitate this mechanism is 60–70° of passive MTP dorsiflexion.[1,11,16]

In summary, supination of the foot is dependent upon a combination of dynamic and static mechanisms. The activity of the intrinsic and extrinsic muscles, in conjunction with external rotation and MTP extension produce a supination movement.

## NEUTRAL

Root et al.[16] describe a neutral position of the subtalar joint which is two-thirds from inversion and one-third from eversion of the calcaneous (Fig. 2). The normal foot needs to pronate and supinate 6–8° from the neutral position.[10] The amount of supination and pronation that is available can be measured by lining up the longitudinal axis of the lower limb and the vertical axis of the calcaneous (Fig. 6).[8,16] Passive movement of the calcaneous into inversion is normally 20°.[16] This represents the amount of supination available at the subtalar joint. Conversely, the amount of eversion is normally 10°.[16] This represents the amount of pronation available. Another method of determining neutral is described by James.[8] According to James,[8] the talar head in a pronated foot can be palpated as a medial bulge. Conversely, in a supinated foot the talar head bulges

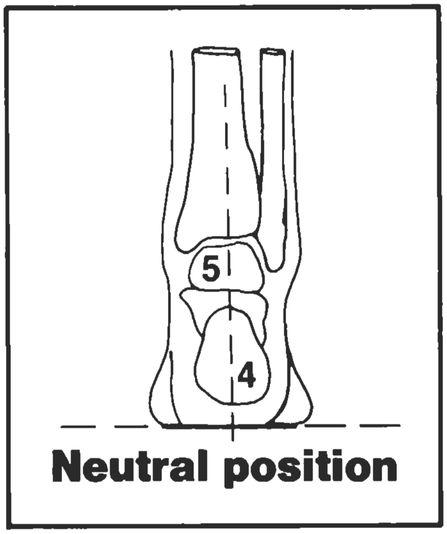


Fig. 6. *Neutral position of the subtalar joint showing the longitudinal axis of the lower limb and the vertical axis of the calcaneous. 5, Talus; 4, calcaneous.*

laterally.[8] In the neutral position, the talar head can be palpated equally on the medial and lateral aspect of the ankle.[8] The neutral position described above, is usually present when the longitudinal axis of the lower limb and the vertical axis of the calcaneous are parallel (Fig. 6).[8]

## CONCLUSION

Understanding the functional biomechanics of the foot and ankle has profound clinic applications. For example, the inability of the lower limb to convert transverse rotations at the subtalar joint could have detrimental effects on other joints in the chain such as the knee, the midtarsal, and the forefoot. The pelvis and the lumbar spine are influenced by functional leg length discrepancies which could be related to abnormal pronation and supination. Evaluation of the foot and ankle takes on a different meaning when considering the neutral position of the subtalar joint. Physical therapists need to understand the normal biomechanics of the foot and ankle and it's relationship to the normal function of the lower kinetic chain. Pronation and supination are dynamic terms. The foot is pronating at heel strike and passes through neutral and starts to supinate at midstance. The triplane motions act as shock absorbers, assist in maintaining balance, improve the efficiency of muscle contraction, assist in distribution of normal forces through the lower kinetic chain, and help establish a stable structure at push off, enabling us to propel ourselves through space very efficiently.

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