Biomechanics of the Ankle

Patricia K. Wellborn, Joshua N. Tennant,
and Trapper A. J. Lalli

1 Introduction

The biomechanics and function of the human foot and ankle are the product of its unique anatomy and structure. The ankle joint complex consists of three primary joints: tibiotalar (or talocrural), subtalar (or talocalcaneal), and the transverse tarsal joint. These joints work synergistically to conduct ankle motion and provide stability to the complex, which is fundamental in the ability to ambulate and efficiently manage weight-bearing forces. This chapter will explore the biomechanical properties of the ankle joint complex and its role in ambulation, as well as some examples of abnormal gait and force distribution.

2 Anatomical Contributions to Biomechanics

2.1 Tibiotalar Joint

The tibiotalar joint is the articulation between the distal tibia and the talar body. It is less commonly referred to as the talocrural joint, but the two terminologies are interchangeable. This joint serves as the primary dorsiflexor and plantarflexor of the ankle joint complex. It is also the primary weight-bearing joint of the ankle joint complex.

The tibiotalar joint is most stable in dorsiflexion [1, 2]. In dorsiflexion, as well as the stance phase of gait, the primary contributor to stability is the bony anatomy [1]. As the tibiotalar joint plantarflexes, the joint becomes more heavily reliant on the surrounding soft tissues for stability [1]. Three ligamentous groups are key for stabilization of the tibiotalar joint. From medial to lateral, these consist of the medial deltoid ligaments, the syndesmosis, and the lateral ankle ligaments. The deltoid ligament stabilizes the medial portion of the joint and resists eversion and valgus stress. The deltoid ligament is composed of a combination of six individual ligaments that are variably present amongst individuals. The tibionavicular, tibiospring, and deep posterior tibiotalar ligaments are present in all individuals. The tibiocalcaneal, superficial posterior tibiotalar, and deep anterior tibiotalar ligaments have a variable presence [3].

The syndesmotic ligaments lie between the tibia and the fibula. The syndesmosis consists of the anterior inferior tibiofibular ligament (AITFL), the posterior tibiofibular ligament (PTFL), and the interosseous tibiofibular ligament. These syndesmotic ligaments help stabilize the distal part of the fibula. The lateral ligamentous complex consists of the anterior talofibular, posterior talofibular, and calcaneofib-

P. K. Wellborn (✉) · J. N. Tennant · T. A. J. Lalli
Department of Orthopaedics, University of North Carolina, Chapel Hill, NC, USA
e-mail: Patricia.Wellborn@unchealth.unc.edu; josh_tennant@med.unc.edu; trapper_lalli@med.unc.edu

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ular ligaments. These lateral ligaments resist inversion and varus stress [1].

As the tibiotalar joint progresses from plantarflexion to dorsiflexion, there is both rotational and translational motion. Leardini et al. defined the articular contact point as the area of maximal contact and greatest pressure on the articular surface of either the distal tibia or talus. They discovered that that the articular contact point in the distal tibia shifts in relation to the amount of ankle dorsiflexion. At maximum plantarflexion, the articular contact point is on the posterior half of the tibial articular surface. As the ankle dorsiflexes, this contact point shifts to the anterior half of the tibial articular surface [4]. The center of contact behaves similarly in the talus. As the tibiotalar joint moves from dorsiflexion to plantarflexion, the center of contact on the talus moves from anterior to posterior [5]. In dorsiflexion, the talus is translated posteriorly and flexes forward. Conversely, in plantarflexion, the talus is translated anteriorly and extends backward [4].

In addition to the articular contact point shifting on the distal tibia and talus, there are varying degrees of contact area depending on ankle position. Numerous studies have attempted to identify the contact area between the tibia and the talus and the degree to which the area changes with tibiotalar motion [5–7]. Castro reported the contact area at the tibiotalar joint varies between 1.5 and 9.4 cm². In his meta-analysis, it was inconclusive whether contact area increases with dorsiflexion or whether the variations seen in studies were due more to differences in technique amongst the studies themselves [6]. Kimizuka et al. performed a cadaveric study and found that the weight-bearing contact area is localized to the anterior and lateral portion of the joint (Fig. 1). They found that the average articular contact area between the tibia and talus was 4.8 cm² with a maximal intra-articular pressure of 9.9 MPa. Intra-articular pressure is defined as the pressure within the tibiotalar joint. With increasing force applied to the joint, the articular contact area increased in size. With traction applied to the tibiotalar joint (diastasis), contact area decreased and intra-articular peak pressures increased [7]. Similar to Kimizuka et al., Calhoun et al. [5] performed a cadaveric study exploring the relationship between motion, contact area, and pressure. They found that contact surface area increased from a plantarflexed to dorsiflexed position. They also found that force per unit area (amount of force in a given articular area) decreased proportionately. Similar findings were found with both

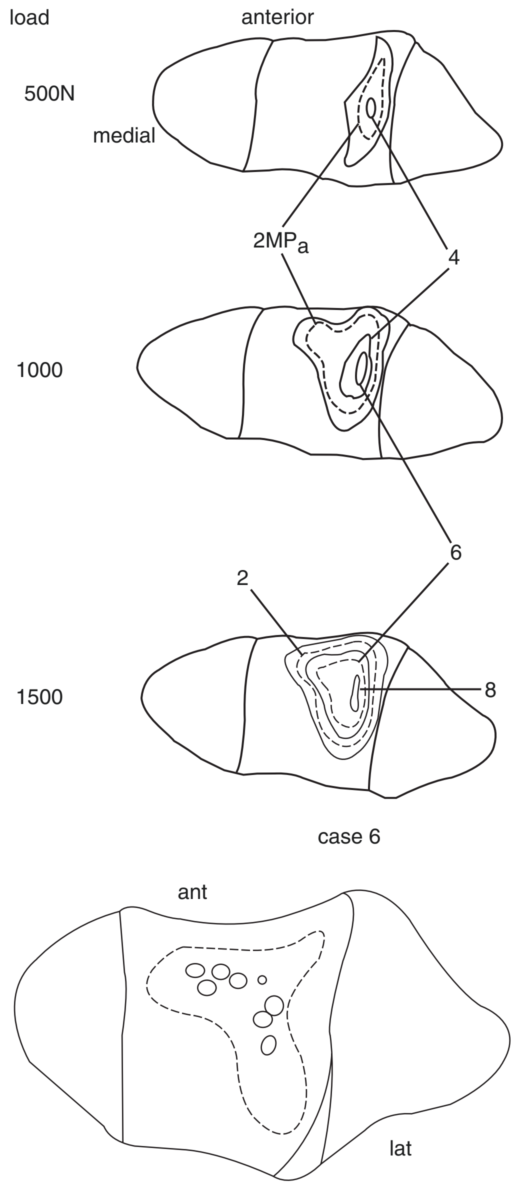

Fig. 1 The results of the force study are shown. Contact was localized to antero-lateral portion of joint, and contact area increased with increasing forces. (Reproduced from Kimizuka with permission [7])

inversion and eversion in both neutral and dorsiflexed positions. This study also explored the impact of increasing forces across the tibiotalar joint. As applied force increased, contact area increased but articular pressure remained relatively the same [5, 6].

2.2 Talofibular/Distal Tibiofibular Joint

The talofibular and distal tibiofibular joints are the articulation between the distal fibula (lateral malleolus) and the distal tibia and talus. The fibula plays an important role in bony stability for the tibiotalar joint during weight-bearing. It is estimated that the fibula supports around 15–20% of the weight-bearing forces [6]. As the tibiotalar joint dorsiflexes, the fibula translates laterally and distally as well as externally rotates [6]. Conversely, the fibula translates medially and proximally, and internally rotates, as the tibiotalar joint plantarflexes. This complex three dimensional movement contributes to both static and dynamic stability of the ankle joint complex.

2.3 Subtalar Joint

The subtalar joint is the articulation between the talus and the calcaneus. It is less commonly referred to as the talocalcaneal joint. It is a triplanar, uniaxial joint and serves as the primary inverter and evertor of the ankle joint complex. Its complicated motion is a manifestation of its complex anatomy. At the anterior portion of the joint, the inferior talus is convex and the superior calcaneus is concave. Conversely, in the posterior portion of the joint, the inferior talus is concave and the superior calcaneus is convex. The subtalar ligamentous complex includes the interosseous talocalcaneal, lateral talocalcaneal, and anterior talocalcaneal ligaments as well as the calcaneofibular portion of the lateral ligamentous complex and the tibiocalcaneal portion of the deltoid ligament [1]. When the foot is dorsiflexed, the subtalar joint extends (dorsiflexes), abducts, and pronates [8]. This places the heel in valgus. As the foot is plantarflexed, the subtalar joint flexes (plantarflexes), adducts, and supinates which places the heel in varus [8].

2.4 Transverse Tarsal Joint

The transverse tarsal joint is the articulation between the talus, calcaneus, cuboid, and navicular bones. It is also commonly referred to as the Chopart joint. This joint contributes to inversion and eversion but serves its greatest role in gait biomechanics. It can be "locked" and "unlocked" throughout gait. This allows for control of either a rigid or flexible foot. This concept will be expanded on later in the chapter in Sect. 5.

3 Motion of the Ankle Joint Complex

The motion of the ankle joint complex involves various joints with different axes. It is the combination of motion in multiple joints that create familiar ankle movements.

3.1 Range of Motion

Sagittal ankle motion (plantarflexion and dorsiflexion) is the principal movement of the ankle joint complex. The vast majority of this motion occurs at the tibiotalar joint, with an average 60° of sagittal motion [9]. This is comprised of approximately 10–30° of dorsiflexion and 40–55° of plantarflexion [1, 6]. Range of motion of the ankle is best measured in a weight-bearing stance rather than passively, as this is the most accurate representation of functional range of motion [6]. The required range of sagittal motion for walking is around 30° [1, 10], around 37° is needed for ascending stairs, and around 56° is needed for descending stairs [1]. With increasing age, there is a loss of sagittal motion, primarily plantarflexion [6].

Coronal motion refers to inversion and eversion of the ankle joint complex. The average motion is 23° of inversion and 12° of eversion [1, 9]. It is controversial what percentage of this motion originates in the subtalar joint versus the tibiotalar joint [1, 9]. There is likely variation among individuals regarding the contribution from each joint [9].

Translational motion of the tibiotalar joint describes anterior or posterior motion of the talus relative to the plafond. This motion is most relevant when the tibiotalar joint undergoes destabilizing forces, such as ligamentous instability or fractures. The greatest amount of translational motion (and therefore, laxity of the ankle joint) is seen at a neutral position of the tibiotalar joint. As the tibiotalar joint approaches the extremes of both plantarflexion and dorsiflexion, translational motion is decreased. Flexion angle of the tibiotalar joint remains the most important parameter in determining laxity [4].

3.2 Tibiotalar Axis of Rotation

The tibiotalar joint has the greatest motion of the joints within the ankle joint complex. It is controversial whether the tibiotalar joint is uniaxial or multiaxial, or whether the axis moves with different positions. Lundberg et al. studied the tibiotalar rotational axis and found that the axis shifts throughout the course of motion from plantarflexion to dorsiflexion. In plantarflexion, the axis is angled from inferomedial to superolateral. In dorsiflexion, the axis is angled from inferolateral to superomedial (Fig. 2). The transition of the axis was found to be abrupt in some subjects and a more gradual transition in others [11]. Throughout motion, the midpoint of the axis remained near the midpoint of a line between the tips of the two malleoli at a central point in the talus, suggesting that this point represents a center of rotation and movement of the tibiotalar joint [2, 10]. Overall, this continues to be explored and further studies are needed to fully understand the axis of rotation [6].

3.3 Subtalar Motion

Subtalar motion is crucial for inversion and eversion of the ankle joint complex. It also contributes to motion in the sagittal plane as well as

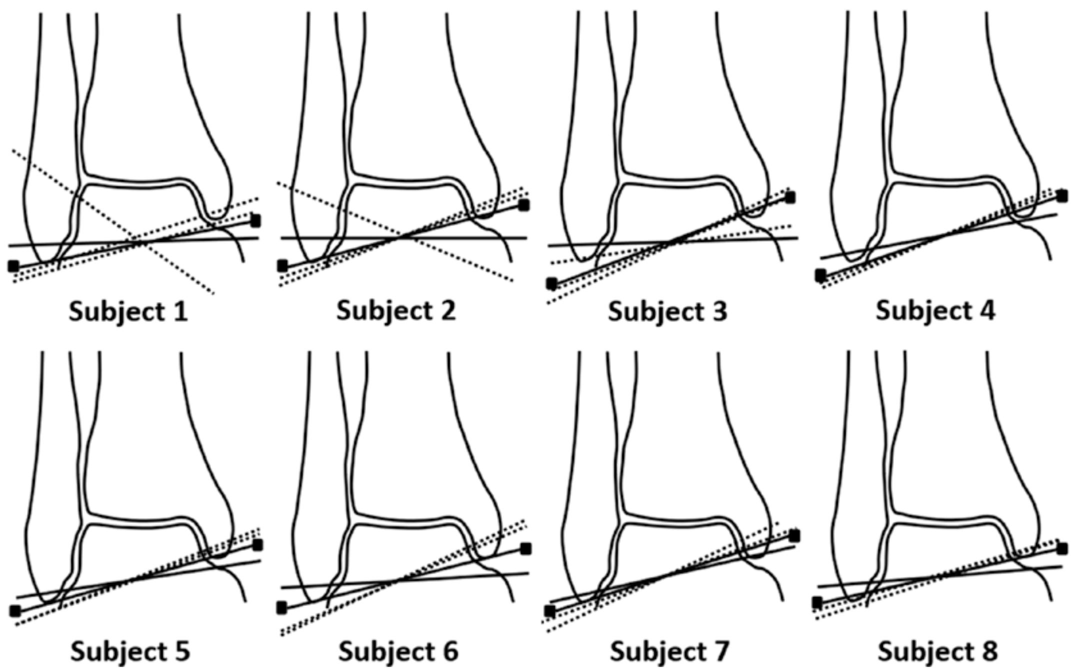

Fig. 2 Results from Lundberg's study demonstrating the tibiotalar axis of rotation. Lines represent the variation in the axis with varying degrees of dorsiflexion. (Reproduced from Lundberg with permission [11])

some rotation. During ambulation, there is approximately 10° of combined sagittal and rotational motion produced at the subtalar joint [10]. This motion is often described as triplanar. The subtalar joint has two different centers of rotation, due to having both an anterior and a posterior aspect to the joint. Contributing to the complexity of subtalar motion is the rotational nature of the calcaneus. Both the talus and calcaneus can rotate and translate during motion, which produces a screw-like motion of the joint [2, 10]. Even small degrees of motion in the subtalar joint create powerful movements in the ankle joint complex.

3.4 Four-Bar Linkage Model

The four-bar linkage model is a popular method for describing the motion of the ankle joint complex. In this model, there are four bars connecting the tibia, fibula, talus, and calcaneus (Fig. 3, line segments representing the calcaneofibular and tibiocalcaneal ligaments). The talus-calcaneus and tibia-fibula then rotate around each other on these line segments. The talus has two radii representing the varying center of rotation. The advantage of this model is its ability to account for the irregular shape of the talus, as well as the translational motion of the talus under the tibia. Using this model accounts for the combination of the "rolling" and "sliding" motions of the ankle joint complex [4, 6, 12, 13].

3.5 Pronation/Supination

A combination of all aspects of motion described above creates the motions of pronation and supination. Pronation and supination are described relative to the plantar aspect of the foot. Pronation results in the plantar foot pointing laterally, while supination results in the plantar foot pointing medially. Pronation is a combination of ankle joint complex dorsiflexion, eversion, and abduction. Conversely, supination is a combination of

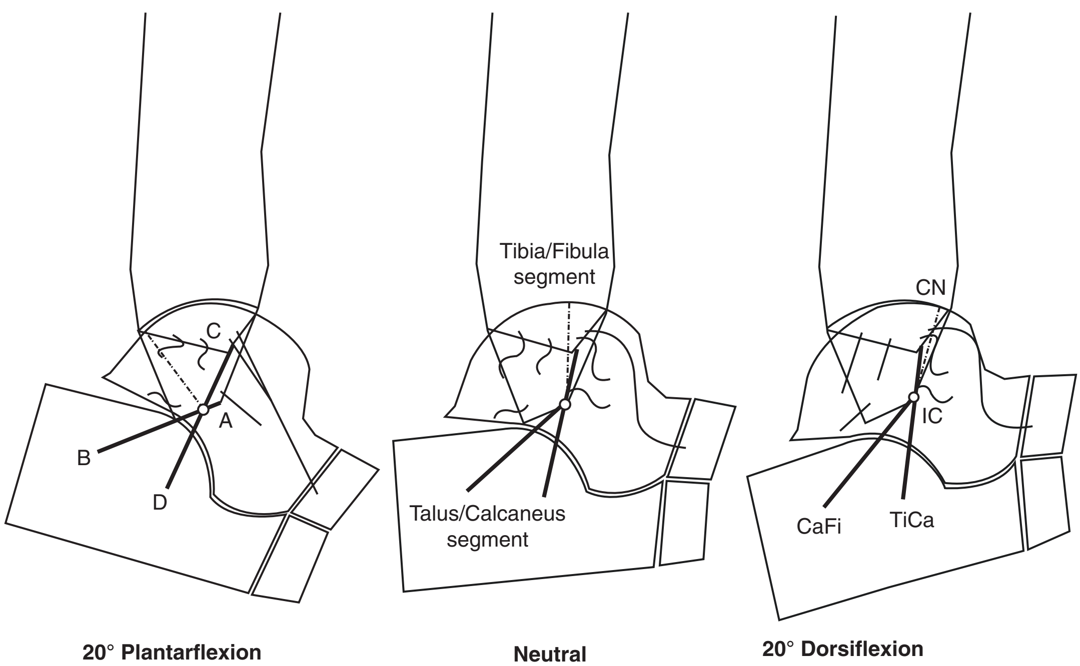

Fig. 3 The four-bar linkage model. The solid lines represent the calcaneofibular (CaFi) and tibiocalcaneal (TiCa) ligaments. The center of rotation (IC) is the location where the two ligament fibers cross. CN represents the common normal articular contact point. (Reproduced from Leardini with permission [4])

plantarflexion, inversion, and adduction, combining motions of multiple ankle and hindfoot joints [1, 14]. Five triplane joints contribute to the motion: the tibiotalar joint, subtalar joint, Chopart joint, first metatarsal-cuneiform joint, and the fifth metatarsal-navicular joint [14]. The complex motions of pronation and supination are critical to the ankle joint complex's ability to handle uneven ground and other varying forces.

4 Static and Dynamic Stabilizers of the Ankle

The ankle joint complex requires stability from both static and dynamic forces to manage the significant ground reaction forces and uneven ground surfaces during ambulation. Static stabilizers include: the tibia, talus, fibula, calcaneus, along with their joint congruity and associated ligaments and fascia. Dynamic stabilizers include: the surrounding muscles, tendons, and the dynamic nature of tarsal bone motion. At different stages of ambulation, there is a variable impact between the static and dynamic stabilizers.

4.1 Static Stabilizers

A vast majority of the stability of the ankle joint complex is attributed to the bony structures and their articular congruity. Calhoun et al. found articular congruity to be responsible for 70% of the anterior to posterior stability, 50% of stability in inversion/eversion, and 30% of internal/external rotational stability [13]. In weight-bearing conditions, articular congruity provides 100% of the stability in eversion and inversion [2, 6, 9]. However, this only provides around 30% of rotational stability [2, 6, 9]. When the ability for bony structures to provide stability has been maximized, the ankle joint complex relies on ligamentous structures for the remainder of stability.

The ankle joint complex has numerous ligaments on both the medial and lateral aspects. These ligaments tend to be relaxed during functional range of motion, i.e., the motion needed to perform routine daily tasks. However, the ligaments are tensioned as the ankle increases towards the maximal range of motion [9]. The ligamentous structures are the primary determinant of the maximal range of motion [9].

The lateral ligament complex consists of the anterior talofibular (ATFL), calcaneofibular (CFL), and posterior talofibular (PTFL) ligaments. The ATFL prevents internal rotation and anterior translation of the talus. The CFL provides subtalar stability and prevents adduction. The PTFL prevents external rotation of the talus [2, 9]. These three ligaments play a key role in resisting inversion of the ankle joint complex and are also the primary restraint to anterior translation of the talus [6]. Anatomically, the CFL is parallel to the axis of motion of the subtalar joint, which allows it to stabilize the subtalar joint while not restricting motion [6]. The ATFL and CFL are in 90-degree orientation to each other and work in perpendicular planes [6]. The ATFL is the primary restraint in plantarflexion while the CFL is primary in dorsiflexion [6].

Hinterman et al. performed a cadaveric study examining the role of the lateral ligamentous complex. The lateral ligaments were sequentially transected under varying loads. Under a true axial load, there was stable internal tibial rotation and calcaneal eversion regardless of the competency of lateral or medial ligaments. This further demonstrated the role of articular congruity in the ankle joint complex. When the ATFL was released, there was a significant increase in tibial internal rotation. However, there was no further change in rotation with the transection of the remaining ligaments. On the other hand, a release of the final subtalar interosseous ligaments significantly increased the internal rotation of the tibia. There was a greater loss of stability in plantarflexion than dorsiflexion with the release of all ligaments. Although there were similar findings for calcaneal eversion, the calcaneus was always stable in dorsiflexion regardless of ligamentous integrity [15]. This study demonstrated key findings of the importance of articular congruity, greater ankle stability in dorsiflexion, and that the ATFL is the most important component of the lateral ligamentous complex.

The medial ligamentous structures are collectively known as the deltoid ligament. The deltoid ligament resists valgus tilt of the talus, anterior translation, lateral translation, and eversion of the ankle [2, 9]. It has both superficial and deep components [3, 6] and, as previously discussed, can be composed of up to six ligamentous bands [3]. An anatomic study by Campbell et al. identified the tibionavicular, tibiospring, and deep posterior tibiotalar ligaments to be present in all cadaveric specimens with the deep posterior tibiotalar ligament being the largest [3]. The other three bands (tibiocalcaneal, superficial posterior tibiotalar, and deep anterior tibiotalar) were variably present amongst specimens [3]. In the cadaveric study by Harper et al., they identified the deltoid ligament to be the primary restraint against valgus tilt with both the superficial and deep components contributing equally. They also found that the deep deltoid ligament is a secondary restraint to both anterior and lateral translation of the talus (lateral malleolus and lateral ligamentous complex are primary restraints) [6, 16]. When the deltoid ligament was transected, the articular contact area of the tibiotalar joint decreased and intra-articular pressure increased [13].

Additional static stabilizers of the ankle joint complex include the plantar aponeurosis and the stabilizers of the arch. The plantar aponeurosis bears up to 60% of the stress forces during weight-bearing [14]. With toe extension, the aponeurosis becomes tighter, and therefore, is able to handle more force. This is known as the "windlass effect" [14] (Fig. 4). Other static stabilizers of the arch include the short and long plantar ligaments and the calcaneonavicular ligament (spring ligament) [6].

4.2 Dynamic Stabilizers

The dynamic stabilizers of the ankle joint complex are the surrounding muscles and tendons that pass around the ankle joint complex. This includes the peroneus brevis, peroneus longus, peroneus tertius (if present), tibialis anterior, posterior tibialis, extensor digitorum, extensor hallucis longus, flexor hallucis longus, flexor digitorum, and the gastrocnemius/soleus complex [8]. The role of dynamic stabilizers will be expanded upon in Sect. 5.

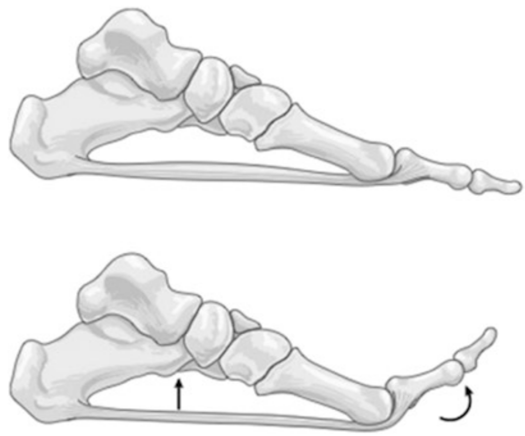

Fig. 4 The windlass effect. Extension of the toes tightens the plantar fascia. (Reproduced from Rosenbaum with permission [17])

5 Gait

The ankle joint complex's primary purpose is to provide a stable weight-bearing platform that supports the forces of ambulation in an energy-efficient manner. Weight-bearing forces reach as high as 5.5 times body weight during normal ambulation [6]. This is in addition to the destabilizing stresses that occur when walking on uneven ground or making lateral movements.

5.1 Phases of Gait

In normal gait, there are two distinct phases: stance and swing (Fig. 5). Stance phase occurs when any portion of the foot is in contact with the ground. Swing phase occurs when that foot is not in contact with the ground. A complete cycle occurs when the ipsilateral foot makes contact with the ground again after a full cycle of gait. A "double support period" occurs when both feet are in contact with the ground simultaneously. This occurs at two separate instances during the gait cycle, with each instance comprising around 10% of the total

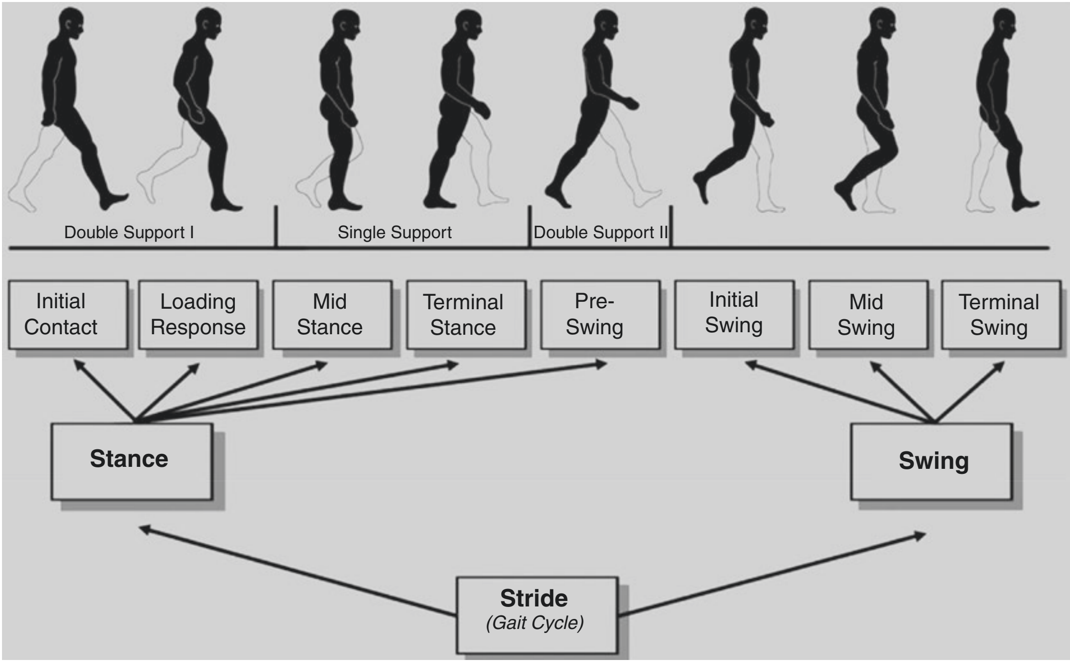

Fig. 5 This depicts normal gait. One cycle is composed of both stance and swing phases. These are further subdivided as shown. One complete cycle is referred to as a stride. (Reproduced from Shah with permission [18])

gait cycle (total 20%). These double support periods are replaced in running with "floating periods", which are defined as times when neither foot is touching the ground [18].

5.1.1 Stance Phase

During normal ambulation, approximately 60% of the gait cycle is spent in the stance phase [14, 18, 19]. The stance phase is further subdivided into five subphases [18].

Initial Contact

Initial contact occurs when the heel of the first foot makes initial contact with the ground. This also initiates the first double support period [18]. At this subphase, around 80% of the body weight is directly over the ipsilateral calcaneus. Body weight provides for a vertical compressive force and is the first period of increased forces [14].

Loading Response

The loading response subphase occurs when the entire first foot is in contact with the ground [18]. This is a period of controlled plantarflexion of the ankle and foot through eccentric contraction (lengthening of a muscle during contraction) of tibialis anterior (TA), extensor hallucis longus (EHL), and extensor digitorum longus (EDL). The knee passively flexes to maintain a center of gravity directly over the ankle [20]. This subphase is a shock absorption period and to accommodate the encountered forces, the foot pronates [14]. The hindfoot swings into valgus, the talus plantarflexes and adducts, and there is eccentric contraction of the supinators (TA, EHL, EDL). This is referred to as the "torque converter of the lower limb" [14]. During this subphase, the contralateral foot leaves the ground and enters its own swing phase, which ends the double support period [18].

Mid-Stance

The mid-stance subphase occurs as the body continues to move forward due to momentum. The entire foot remains in contact with the ground. There is passive dorsiflexion of the ankle and the knee becomes locked in extension. Minimal energy is needed in this phase as momentum provides forward movement. Ground reaction forces are anterior to the knee and ankle joint complex at this subphase [18].

Terminal Stance

The terminal stance subphase starts as the heel begins to lift off of the floor. Body weight shifts towards the metatarsal heads. The gastrocnemius/soleus complex fires concentrically to generate the power needed for propulsion [18]. As the weight continues to shift towards the metatarsal heads, the foot begins to supinate [14]. There is contraction of the gastrocnemius/soleus as well as posterior tibialis, flexor digitorum longus, and flexor hallucis longus. The intrinsic foot muscles also contract to allow for stabilization of the midtarsal joint. With supination of the subtalar joint and intrinsic muscle contraction, the midtarsal joint becomes locked. This creates the rigid lever needed to generate the force for foot push off in the next subphase [14].

Pre-swing

The pre-swing subphase begins at the "toe off" period as the foot begins to leave the ground. There is concentric tibialis anterior contraction and EHL contraction producing dorsiflexion of the ankle, foot, and hallux [18, 21]. During this subphase, the knee and hip also flex to prepare for foot clearance in the swing phase [18].

5.1.2 Swing Phase

The swing phase of the gait cycle occurs when the foot is no longer in contact with the ground. It is subdivided into the initial, mid, and terminal subphases. Minimal energy is needed for the foot in swing phase as it is being driven forward by momentum. Adequate dorsiflexion of the foot is critical to a successful swing phase in order to clear the ground. The tibialis anterior continues to contract concentrically throughout the swing phase. In addition, there is hip and knee flexion, which assist with clearing the foot from the ground [18].

5.2 Three Rocker Model

The "three rocker model" is another model for describing the subphases of the stance phase (Fig. 6). It was developed to describe the shifting of the fulcrum as the stance phase progressed. Each rocker (or point of rotation) has a primary purpose of either stiffening the foot to allow for propulsion and power or flexing the foot to allow for force absorption [4, 18, 19].

5.2.1 First Rocker

The first rocker begins with the foot's initial contact with the floor and comprises 10% of the gait cycle [22]. As the heel makes contact, there is a controlled lowering of the foot to the floor through eccentric tibialis anterior contraction. The heel is the fulcrum in this stage which produces ankle plantarflexion and knee flexion. As the heel makes contact with the ground, the ankle is pushed into valgus. This unlocks the Chopart joint which causes the foot to become flexible and allows it to act as a shock absorber for the increasing forces generated in this phase of gait [4, 18, 19].

5.2.2 Second Rocker

The second rocker occurs during midstance and comprises 20% of the gait cycle [22]. In this subphase, the foot is entirely in contact with the ground. The ankle is now the fulcrum. The goal of this subphase is to control forward motion. This is achieved through passive dorsiflexion of the ankle with eccentric contraction of the gastrocnemius/soleus complex [4, 18, 19].

5.2.3 Third Rocker

The third rocker is the final stance subphase and comprises 30% of the gait cycle [22]. As momentum continues to shift forward, the ankle reaches its limit of passive dorsiflexion. The gastrocnemius/soleus complex then starts to concentrically contract. This shifts the fulcrum to the metatarsal heads. As this occurs, concentric contraction of the posterior tibialis shifts the hindfoot into varus [4, 18, 19]. As the metatarsophalangeal joints dorsiflex during toe off, the plantar fascia is ten-

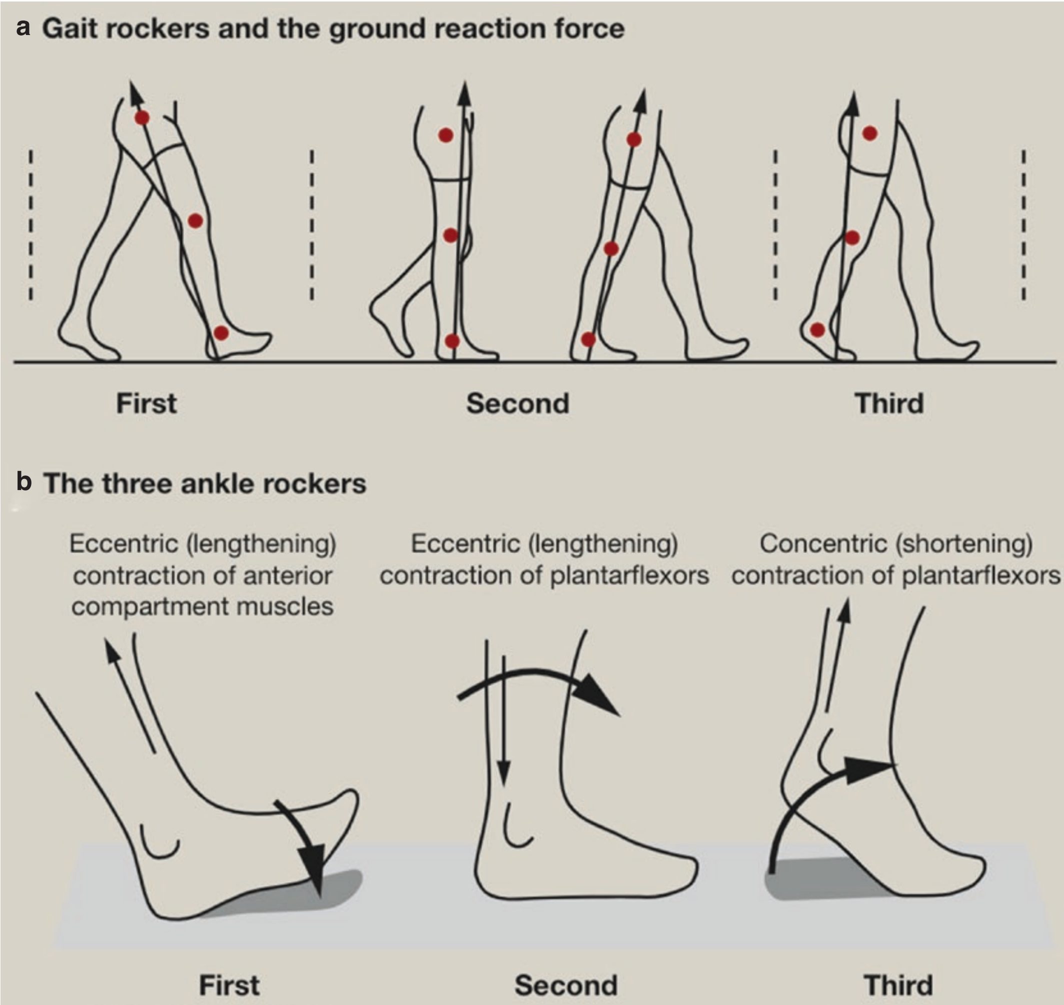

Fig. 6 The three rocker model. (**a**) Red dots represent the center of rotation at each joint. The line represents the ground reaction force direction. (**b**) The three rocker model with respect to foot position and the necessary muscle contractions. (Reproduced from Shah with permission [18])

sioned through the windlass effect. This creates the rigid lever arm that allows for the production of power needed for push off [4, 18, 19].

5.3 Pre-requisites for Normal Gait

Perry originally described the five prerequisites for normal gait [19]. First, there must be stability during the stance phase. This requires a stable foot position. Second, there must be adequate clearance during the swing phase, i.e., the foot needs to be able to clear the ground. Third, there must be adequate step length. This requires balance, a stable stance side, and sufficient hip and knee flexion on the swing side. Fourth, there must be appropriate pre-positioning during swing phase. Lastly, normal gait requires energy conservation and efficient use of energy in the gait cycle [18, 19].

5.4 Motion During Gait

Normal, energy-efficient gait requires around 30° of sagittal motion in the tibiotalar joint [4]. Typically, around 20° of plantarflexion is needed at toe off phase [21]. Ankle dorsiflexion needs are more variable but the typical motion is around 10–30° of dorsiflexion during ambulation [21]. In addition to sagittal motion, the triplanar motion of normal gait also includes approximately 14° of coronal motion and 22° of axial motion [4].

5.5 Energy Needs During Gait

Normal gait is an energy-efficient process. The body maximizes passive movements and utilizes forward momentum to achieve extreme efficiency. Normal gait requires around 2.5 kcal/min. These energy needs are just slightly greater than those required for sitting and standing (both around 1.5 kcal/min) [19]. Any modification to gait that affects the normal gait cycle will increase energy needs. The most common needs for increased energy are due to faster pace, antalgic gait, or use of an assistive device. Additionally, energy needs may increase with a lower leg amputation at any level, the use of a brace, or the presence of a knee flexion contracture [19]. As discussed above, the body frequently relies on eccentric contraction of various muscles for control during the gait cycle. Eccentric muscle contraction is the most energy-efficient form of muscle contraction [20]. Disruptions to this process have a profound effect on biomechanics and function.

5.6 Forces During Gait

The ankle joint complex and foot experience tremendous forces throughout normal gait which increase even more during running and destabilizing activities. There is substantial variability in different studies about the amount of force seen in gait. It is estimated that these forces are around 120% of body weight at heel strike [2]. During stance phase, the tibiotalar joint endures forces around 4 times body weight (BW), with averages between 3 and 5 × BW [1, 9]. The subtalar joint experiences forces around 2.4 × BW and the Chopart joint around 2.8 × BW [9]. At heel rise, tibiotalar forces increase to around 4.5–5.5 × BW [6]. These forces may increase up to 13 × BW during running [1].

5.7 Dynamic Changes in Intra-articular Pressure

During normal gait, there are significant changes that occur to the intra-articular pressure of the tibiotalar joint. This is important due to the potential for accelerated wear and arthritis formation with variable loading. Suckel et al. performed a cadaveric study and found that the major area of stress and greatest torque changes were seen in the anterolateral portion of the tibiotalar joint [23]. The medial talus had significantly lower pressures compared to the lateral aspect of the talus. This is consistent with the typical anterior tibial osteophytes seen in tibiotalar osteoarthritis. During heel strike, there was a rapid increase in intra-articular pressure throughout the tibiotalar joint. This reached a plateau after around 20% of stance phase occurred. During push off, the intra-articular pressure continued to increase. Intra-articular pressure reached a maximum at around 70% through the push off phase [23].

5.8 Running/Sprinting

The body makes several changes to the gait cycle when running, and even more when sprinting. The primary difference is the change from double support periods to floating periods, where neither foot is in contact with the ground. The time spent in stance phase also decreases significantly. As speed increases, stance time decreases from around 60% when walking, to 31% while running, to 22% while sprinting [24]. As speed increases, sagittal plane motion of the ankle increases. This enables a lower center of gravity. Similarly, hip and knee flexion also increase. To achieve greater dorsiflexion, tibialis anterior contraction changes from eccentric while walking to concentric during running and sprinting [24]. It is important to note that while this allows greater speed, the change to concentric contraction comes at the cost of increased energy expenditure.

6 Abnormal/Altered Biomechanics

Given the complexity of gait and normal ambulation, the process is easily altered by ankle joint complex pathology. Any alteration to the typical gait cycle results in a less efficient process and, therefore, requires increased energy. Various accommodative strategies occur either consciously or, more typically, subconsciously.

6.1 Antalgic Gait

An antalgic gait, or limp, occurs as a result of increased pain or other symptoms in one affected leg. This may arise from several sources of pain ranging from the hip/pelvis down to the toes. An antalgic gait arises to limit the amount of weight-bearing time spent on the affected side. This results in increased stance time on the contralateral side and greater total time spent in double support periods [18].

6.2 Planovalgus Foot

A planovalgus foot, or flatfoot, is defined as the hindfoot in increased valgus and a loss of the normal arch of the midfoot. This produces an increase in ankle plantarflexion, a contracture of the triceps surae, and an overall reduction in the normal ankle range of motion. The loss of ankle motion is accommodated by increased dorsiflexion and flexibility through the transverse tarsal (Chopart) joint. With increased motion at the transverse tarsal joint, the hindfoot is driven into more valgus through the subtalar joint. In sum, these changes lead to a shift towards pronation of the foot during all phases of gait [25].

6.3 Foot Drop

Foot drop results from either a weakness or a complete loss of ankle dorsiflexion. This may have several different etiologies including peripheral neuropathy, peroneal nerve injury, tibialis anterior muscle/tendon injury, or lumbar pathology. Ultimately, this results in an equinus (plantarflexed) position of the ankle and an inability to fully dorsiflex the ankle. Using the rocker model to describe foot drop, during the first rocker phase, there is loss of the controlled plantarflexion, and instead, there is a "slap" type impact of the foot [18]. There are several accommodative strategies for gait that patients with foot drop may do either consciously or subconsciously. Since the ankle is plantarflexed, the affected extremity is functionally longer than it should be. To compensate, the body enacts strategies to "shorten" this limb [20]. In order for the foot to clear the ground, the ipsilateral hip and knee will increase the amount of flexion [18, 20]. Similarly, pelvic obliquity may develop to accommodate foot clearance [18, 20]. A steppage (or marching) type gait, circumduction of the affected limb, and abduction of the affected limb are other maneuvers to help shorten the functionally long leg [20].

6.4 Ankle Joint Complex Osteoarthritis

One of the most common sources of altered biomechanics is the development of ankle osteoarthritis. This may be present in any of the three joints of the ankle joint complex independently or in combination. In contrast with the hip and knee, ankle osteoarthritis is primarily post-traumatic rather than idiopathic [21, 26]. Therefore, it is much easier to identify those patients at risk of developing arthritis in the future. As arthritis progresses, there is loss of both active and passive sagittal motion of around 10° [21]. With the loss of plantarflexion, there is also a decrease in peak plantarflexion moment and ankle power [4, 21]. Similarly, there is a loss of the standard motion coupling between the tibiotalar and subtalar joints [21]. To accommodate for these motion losses, the body spends less time in stance phase on the affected leg [21]. This also limits the maximum force that can be loaded on the affected leg [21]. These changes result in a shorter stride length and slower walking speed [4, 18, 21].

There are several conservative and surgical treatment options utilized in the management of ankle osteoarthritis and these will be discussed in other chapters.

7 Conclusion

The ankle joint complex is a uniquely formed structure where the combination of articular anatomy, ligamentous support, and muscular force through tendon attachments is essential for gait and managing weight-bearing forces. An energy-efficient gait cycle requires coordination from the hip through the ankle, with the ankle joint complex serving the greatest role. Biomechanics of the foot and ankle thus form a foundation from which to build our understanding of diagnosis and treatment of foot and ankle pathology.

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