Foot Biomechanics During Walking and Running

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• *Objective*: **To describe the anatomy and biomechanics of the foot and to explain how movement and gait are integrated in the foot during walking and running.**

• *Design*: **We review the anatomy and the biomechanical adaptations of the foot during walking and running.**

• *Material and Methods*: **Illustrations are presented to depict these biomechanics.**

• *Results*: **The human foot is an intricate mechanism that cushions the body and adapts to uneven surfaces. It provides traction for movement, awareness of joint and body position for balance, and leverage for propulsion.**

• *Conclusion*: **With an understanding of the factors discussed herein, clinicians will have more knowledge to evaluate foot problems.**

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The foot is the "root" between the body and the earth. During gait, movement of the foot is synonymous with movement of all the bones of the lower extremity. An intricate mechanism that cushions the body and adapts to uneven surfaces, the foot provides traction for movement, awareness of joint and body position for balance, and leverage for propulsion. Not only does the foot provide a base of support that allows adjustment to uneven surfaces but also its motion decreases energy expenditure by contributing to the swing phase and stance phase of the gait cycle with dorsiflexion. In addition, the subtalar joint has the largest surface area of all the joints.

This ability of the foot to accommodate to the surface and yet maintain stability of support is accomplished by many complex features. Herein we (1) describe the general anatomic features, (2) correlate the biomechanics with movement, and (3) integrate movement and gait.

ANATOMY OF THE LOWER EXTREMITIES

Before one examines the biomechanics of walking and running, a thorough understanding of the anatomy of the lower extremities is important. Each foot has 26 bones; between the ankle and the hip are 4 more bones—tibia, fibula, patella, and femur. These 30 bones on each side (60 in all) form the skeleton of the lower extremities.[1,2]

The two bones in the hindfoot (greater tarsus) are the heel bone (calcaneus) and the ankle bone (talus). The subtalar joint, between the talus and the calcaneus, contributes to the complex motions of pronation and supination. The remaining bones of the foot are the lesser tarsus (part of the midfoot) and the metatarsus and the phalanges (the forefoot). The midfoot begins at the midtarsal joint, which is between the talus in conjunction with the navicular and the calcaneus with the cuboid. The three wedge-shaped cuneiform bones are in front of the navicular.

In front of the lesser tarsus are the five metatarsal bones, attached to the tarsus proximally at their bases; they form the weight-bearing area distally at their heads. The thickest and most medial of these bones is the first metatarsal; these bones are numbered laterally to the fifth metatarsal (Fig. 1).

The first and fifth metatarsals have a range of motion (up and down) to adapt to uneven surfaces. Additionally, as the foot pronates and supinates, they can move out of the way of stress. The other metatarsals normally do not move because they are firmly fixed at their bases. The sesamoids are two other bones under the first metatarsal head in each foot. They are enveloped within the tendons of the flexor hallucis brevis muscle on the plantar aspect of the foot. During the propulsive, or toe-off, portion of the gait cycle, these bones help redistribute and attenuate force over the first metatarsal head.

The bones of the foot are held together by ligaments such that in the normal foot, none of the bones between the calcaneus and the heads of the metatarsals transmits weight directly to the ground. Thus, the weight on the talus is transmitted to the calcaneus in the rear and to the heads of the metatarsals in the front. The unusual shape of the bones, combined with ligamentous and, to a lesser extent, muscular support, forms two longitudinal arches (medial and lateral) and a less obvious transverse arch.[1,3,4] The arches protect the foot by redistributing pressure and by creating a foot that is

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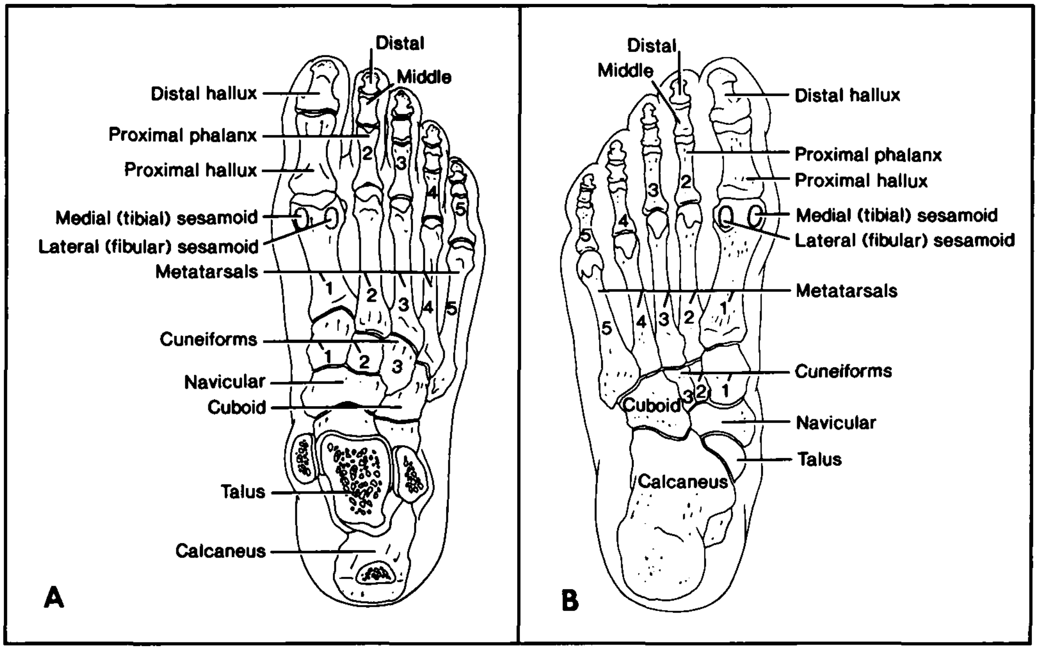

Fig. 1. Dorsal (*A*) and plantar (*B*) views of bones of foot. (Drawings from Cull P, editor. The Sourcebook of Medical Illustration. Carnforth, Lancs [England]: Parthenon Publishing Group, 1989: 58-61.)

both rigid and mobile. Of particular interest is the plantar aponeurosis, which originates from the calcaneal tuberosity and courses distally to blend with skin, flexor tendon sheaths, and transverse metatarsal ligaments.[5] By virtue of its distal insertions, the plantar aponeurosis becomes tight with flexion of the metatarsophalangeal joints; it lends support to the longitudinal arches because of a "windlass" effect and stabilizes the metatarsophalangeal joints.[5-8]

BASIC BIOMECHANICS OF THE FOOT

In any discussion of the motion of the lower extremities, three cardinal planes are important. By virtue of the unusual anatomy, movement of the foot has special definitions. Thus, motions within the *sagittal plane* are dorsiflexion (upward) and plantar flexion (downward), the *frontal plane* are inversion (adduction) and eversion (abduction), and the *transverse plane* are adduction, or internal rotation, of the foot (when the distal part of the foot moves toward the midline of the leg on its vertical axis) and abduction, or external rotation (when the end of the foot moves away from the midline of the body). Furthermore, because the mechanical axes of the foot and the ankle are not perpendicular to any of the cardinal planes, all motion is essentially triplanar, although in some cases, uniaxial. Thus, the terms "supination of the foot," a simple rotation resulting in inversion, adduction, and plantar flexion, and "pronation of the foot," resulting in eversion, abduction, and dorsiflexion, have been established. Pronation and supination, however, have also been used to describe eversion and inversion.[3,4,9,10]

In the subsequent paragraphs, we discuss the special qualities of the foot that allow it to be rigid or equally flexible when necessary.[3,6,11] When the foot first touches the ground, it is unlocked; thus, it has more freedom of motion to adapt to various terrains. Later, when the foot is about to leave the ground, it locks to become a rigid lever that propels the leg forward with body weight. Although the foot has inherent structural stability, the rigidity is achieved as a result of the external rotation of the entire lower extremity.

The ankle joint is a synovial articulation between the inferior aspects of the tibia and fibula and the superior surface of the talus.[1] Because no muscles attach directly to the talus, no pure dorsiflexors or plantar flexors are present in the foot.[5] Although the ankle joint is uniaxial and is often described as a pure plantar flexor and dorsiflexor,[1] its axis is oblique, a factor that results in pronation and supination; movements in the other planes are less important.[12] Dorsiflexion of the ankle while the foot is fixed causes internal rotation of the tibia and pronation of the foot.[9]

The subtalar joint consists of a gliding articulation between the talus superiorly and the calcaneus inferiorly. A closely associated joint is the talocalcaneonavicular, which is a complex of synovial joints between the talus superiorly and the navicular, calcaneus, and spring ligament inferiorly. A major portion of eversion and inversion occurs at that articulation.[1,2] The axis of the subtalar joint runs downward, posteriorly and laterally, at a mean angle of 41° from the horizontal plane and is 23° rotated from the long axis of the foot[7] (Fig. 2); thus, its motion is more equally triplanar than that of the ankle joint. A pronounced variation in this orientation exists, however, with large interindividual ranges of motion of 21 to 69° from the horizontal and 4 to 47° from the long axis of the foot (Fig. 2). As the axis becomes more horizontal, the joint contributes more to eversion and inversion than to abduction and adduction. Similarly, the closer the axis is to the sagittal plane, the less the joint contributes to plantar flexion or dorsiflexion.[12]

Thus, as previously discussed, the axis of the subtalar joint is analogous to an oblique hinge. When rotation is imparted to the superior aspect of the talus, it causes rotation of the calcaneus in the opposite direction.[9] External rotation of the leg produces inversion, and internal rotation causes eversion of the calcaneus[3,4,6,7,11] (Fig. 2 and 3).

Inversion occurs in the subtalar joint when the calcaneus is brought toward the midline, and eversion of the hindfoot occurs throughout the first 15% of the stance phase, at which time inversion begins. This motion at the subtalar joint is passed through the talus and calcaneus to the navicular and cuboid bones (Fig. 3 and 4).

The transverse tarsal joint is a combination of the calcaneocuboid and talonavicular synovial gliding joints.[1] The motion in this joint can be described by a pair of functional axes. The longitudinal axis parallels the subtalar joint axis and provides eversion-abduction and inversion-adduction. The oblique axis is close to the ankle joint axis and provides primarily plantar flexion and dorsiflexion. The subtalar and transverse tarsal joints are closely related; as one joint supinates, the other follows. With eversion of the calcaneus—that is, pronation of the subtalar joint—the axes of the calcaneocuboid and talonavicular joints become parallel; this alignment allows increased motion in the transverse tarsal joint and thus leads to the flexible foot (Fig. 5). With supination, the axes are no longer parallel; thus, the foot becomes rigid.[13] This fact becomes important with the action of the foot during walking and running, particularly in allowing one to adapt easily to uneven ground.

In the previous description of joint motion, the foot was considered free (that is, in an open kinematic chain). When the foot is fixed (in a closed kinematic chain), such as during walking or running in the stance phase, the motion of the foot and ankle is translated proximally to the tibia, fibula, and femur.[12] When the periods of external and internal rotation of the lower limb are correlated with the positions of the hindfoot, the lower limb is in internal rotation at heel strike, an outcome that causes eversion of the hindfoot and therefore a relatively flexible longitudinal arch of the foot. As the lower leg externally rotates during the stance phase, the hindfoot is inverted, and stability along the longitudinal arch of the foot is increased (Fig. 6). The joint motions previously described for external and internal rotation of the lower limb may thus be both propagated from above and induced from below.

The tarsometatarsal joints are divided functionally into five rays. The first ray (first metatarsal and medial cuneiform) is primarily a combination of dorsiflexion-inversion or

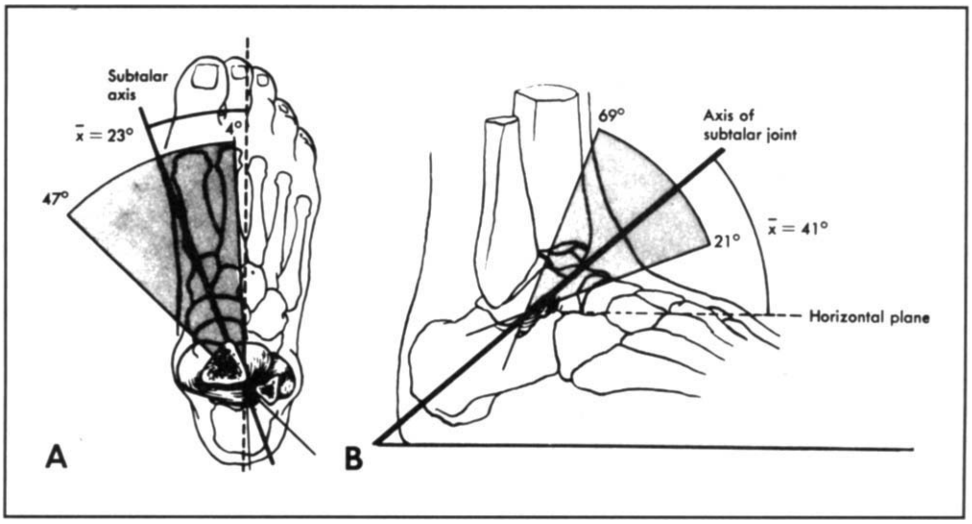

Fig. 2. Subtalar axes in transverse plane (*A*) and in horizontal plane (*B*). (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

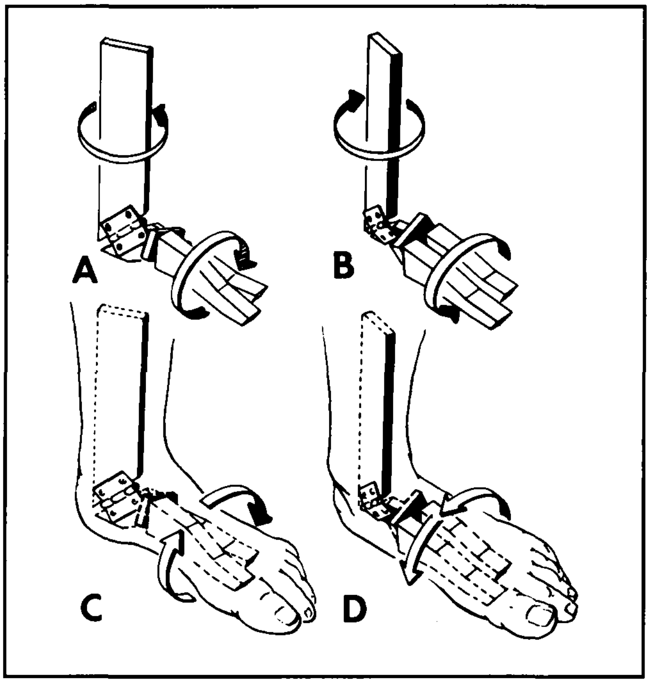

Fig. 3. Schema of mechanism by which rotation of tibia is transmitted through subtalar joint into foot. *A*, Outward rotation of upper stick results in inward rotation of lower stick; thus, outward rotation of tibia causes inward rotation of calcaneus and subsequent elevation of medial border of foot and depression of lateral border of foot as seen in *C*. *B*, Inward rotation of upper stick results in outward rotation of lower stick; thus, inward rotation of tibia causes outward rotation of calcaneus and depression of medial side of border of foot and elevation of lateral border of foot as seen in *D*. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

plantar flexion-eversion, with minimal contributions to abduction-adduction. The second through fourth rays (second metatarsal-intermediate cuneiform, third metatarsal-lateral cuneiform, and fourth metatarsal) allow essentially pure plantar flexion and dorsiflexion. The fifth ray (fifth metatarsal) results in pronation-supination between the fifth metatarsal and the cuboid.[12] The metatarsophalangeal joints are biaxial; they allow plantar flexion-dorsiflexion and abduction-adduction.[12] The metatarsal break is an axis represented by a line drawn obliquely across the metatarsal heads,[9] around which dorsiflexion of the toes occurs. The interphalangeal joints are hinge joints and thus result in simple flexion-extension.[12]

In light of the fact that the navicular articulates with the three cuneiforms and the three medial rays and that the cuboid articulates with the two lateral rays, external rotation of the leg causes inversion of the heel and consequent elevation on the medial side of the foot and depression on the lateral aspect. Internal rotation of the leg produces the opposite effect on the foot.[3]

The axes of rotation between any two bones or groups of bones within the midfoot are difficult to determine. Because excursion for any two bones is small, motion may be considered parallel motion of one surface across another. In the midfoot, total motion ranges from just a few degrees of dorsiflexion to about 15° of plantar flexion. Motion of all the tarsal and tarsometatarsal joints affects the shape of the arch. If the first ray is moved upward or downward, the second through the fifth rays move successively less. Conversely, moving the fourth and fifth rays upward or downward imparts more stability to the medial rays.[3,4]

The second tarsometatarsal joint is recessed into the midfoot and forms a "keylike" configuration with the second cuneiform.[4] This situation restricts motion at the second ray; thus, it is more stable than the first ray and the lateral three rays. Biomechanically, this effect is important during the latter stages of the stance phase when load is transferred into the forefoot for toe-off, because it allows an increased load to be transmitted through the stable second metatarsal (which forms the cornerstone of the arch)[4,14] (Fig. 7).

During the latter part of the stance phase, when the weight is transferred to the forefoot, an oblique axis through which all toes extend at the metatarsophalangeal joints passes from the head of the second metatarsal (which is the most distal) to that of the fifth metatarsal (which is the most proximal). This axis varies in orientation to the long axis of the foot (from 50 to 70°). This phenomenon of the metatarsal break facilitates external rotation of the leg at toe-off, and this in turn facilitates supination and hence rigidity of the foot[3,4,6] (Fig. 8).

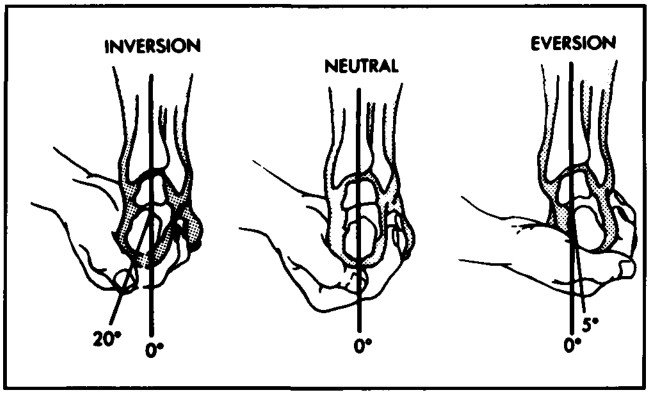

Fig. 4. Types of motion in subtalar joint. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

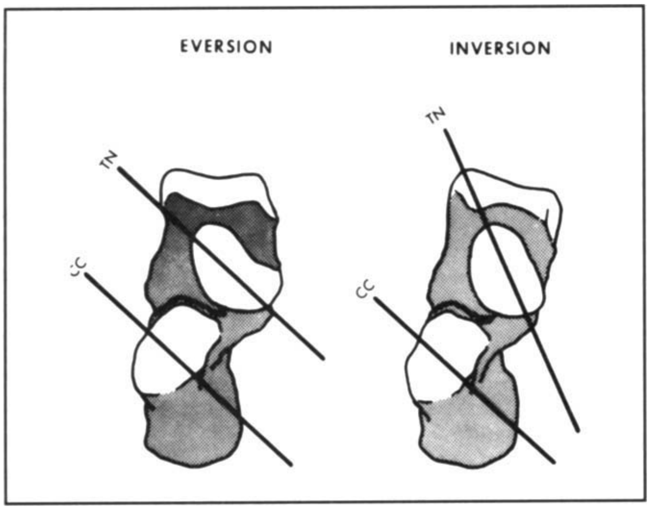

Fig. 5. Axes of rotation in talonavicular (*TN*) and calcaneocuboid (*CC*) joints. When hindfoot is everted, these axes are parallel; thus, relatively free motion in transverse tarsal joint is allowed. When hindfoot is inverted, axes are divergent; thus, motion in transverse tarsal joint is restricted and stability is greater. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

In summary, the rotations that occur in the lower segment act on the talus. The translation of this rotation through the oblique hinge at the subtalar joint transmits the rotation to the foot. The changes of the axes of the transverse tarsal joint and those that occur distal to this joint convert the flexible foot into a rigid arch system. Any abnormal rotation in one of these segments can alter the entire gait pattern.

GAIT BIOMECHANICS

The hypothetical normal foot position during the stance phase occurs when (1) the heel bone is in line with the leg and perpendicular to the ground, (2) the plane of the forefoot (metatarsal heads) is perpendicular to the rearfoot and parallel to the ground, (3) the ankle joint can dorsiflex 10°, and (4) no forces are on the foot from the leg in any of the three body planes (sagittal, frontal, or transverse) causing it to invert or evert, abduct or adduct, dorsiflex or plantar flex.[3,4,6,14,15]

The major joints of the lower extremity are the hip, knee, ankle, and those of the foot (subtalar, midtarsal, first and fifth metatarsals, and toes). The hip joint is a ball-and-socket design and has free rotational movement in all directions (flexion, extension, abduction, adduction, internal rotation, external rotation, and circumduction). For normal foot motion, sagittal and frontal planes of motion must be smooth, but smoothness is not as important as rotation, which controls the angle of gait and supination and pronation of the foot.[4,6,8,11]

The knee joint is a hinge type, primarily allowing flexion and extension, with small amounts of rotation and gliding motions possible.[4,6,8,11] The ankle joint, also a hinge type, allows gliding and angulation.[4,6,8,11] Angulation consists of

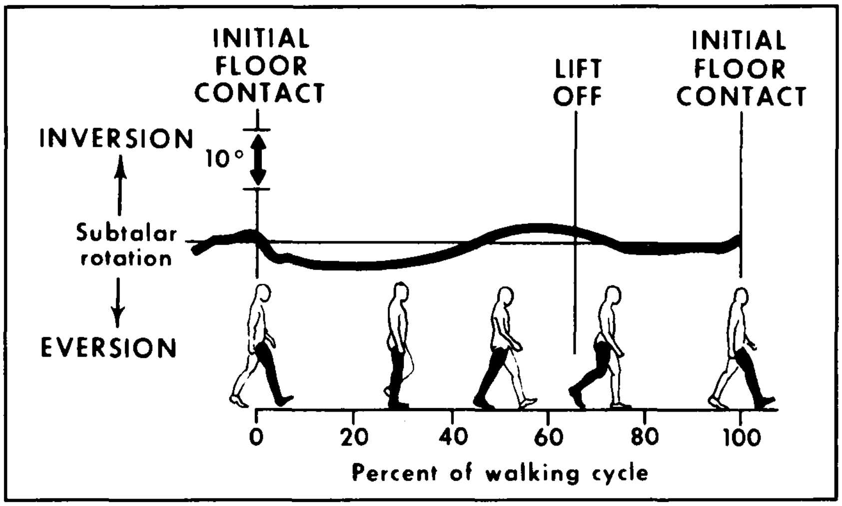

Fig. 6. Motion in subtalar joint during normal walking cycle. At initial floor contact, rapid eversion is followed by progressive inversion until lift-off, after which eversion recurs. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266, as adapted from Wright DG, Desai SM, Henderson WH. J Bone Joint Surg [Am] 1965; 46:361-382. By permission of Mosby-Year Book.)

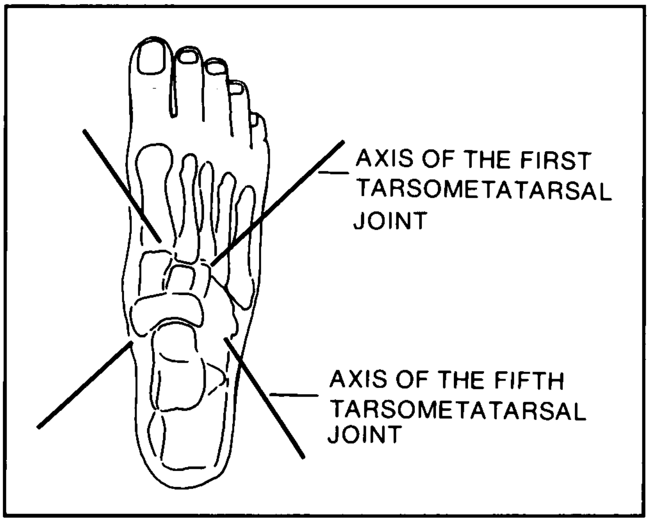

Fig. 7. Tarsometatarsal axes of rotation. (From Sammarco GJ. Biomechanics of the foot. In: Frankel VH, Nordin M, editors. Basic Biomechanics of the Skeletal System. Philadelphia: Lea & Febiger, 1980: 193-220. By permission.)

dorsiflexion and plantar flexion. For weight bearing, the gliding motion compensates for forward and backward displacements of the body's center of gravity.

The bones of the foot and leg work together. During stance, as the foot pronates, the leg must internally rotate on the foot; as the foot supinates, the leg must externally rotate, and concurrent stress extends up the limb.

Of importance, many of the preceding descriptions of joint motion are based mainly on original reports, which are primarily observations rather than complete investigations, and the application of these studies to gait analysis is, of necessity, hypothetical.

The speed of normal walking is between 3.6 and 4.5 km/h. At that speed, a person averages approximately 60 cycles/min and spends 60% of each cycle in the stance phase and 40% in the swing phase.[3,6,11,15] The cycle from heel strike on one leg to the next heel strike on the same leg equals 100% of the total gait cycle. The period from 0 to 15% is the heel strike phase, from 15 to 30% is midstance, from 30 to 45% is push-off, and from 45 to 60% is acceleration of the swinging leg. The swing phase is subdivided into swing-through and deceleration of the swinging leg.

At the end of the stance phase of one leg and the beginning of the stance phase of the other, a time of double-limb support continues for approximately 11% of the gait cycle (Fig. 9 and 10).

During gait, each lower segment of the skeleton rotates in the transverse plane. The degree of rotation progressively increases from the more proximal segments to the more distal segments. During walking on level ground, the pelvis rotates a mean of 6°; the femur, 13°; and the tibia, 18°. The lower limb rotates internally from the beginning of toe-off through the swing phase and the first 15% of the stance phase. During the middle of the stance phase and at push-off, the direction is reversed, and external rotation culminates just after toe-off, when internal rotation recurs. This transverse rotation is passed to the talus through its articulation with the tibia and fibula. As external rotation occurs, a degree of increased stability is attained along the medial aspect of the hip, knee, ankle, and foot. Muscle contraction and ligaments also aid in stabilizing the foot until it is lifted off the ground.[3,4,6,11]

Plantar flexion at heel strike continues until the onset of midstance, and progressive dorsiflexion occurs from heel-off until the 40% point of the cycle, when plantar flexion begins again. During the swing phase, dorsiflexion of the ankle joint occurs until heel strike (Fig. 10).

The muscles in the lower segment of the skeleton assist with control of the foot, and they have three primary functions: to stabilize, to accelerate, and to decelerate. All three functions must occur during normal gait. The major muscle function within the foot, however, is to provide joint stability

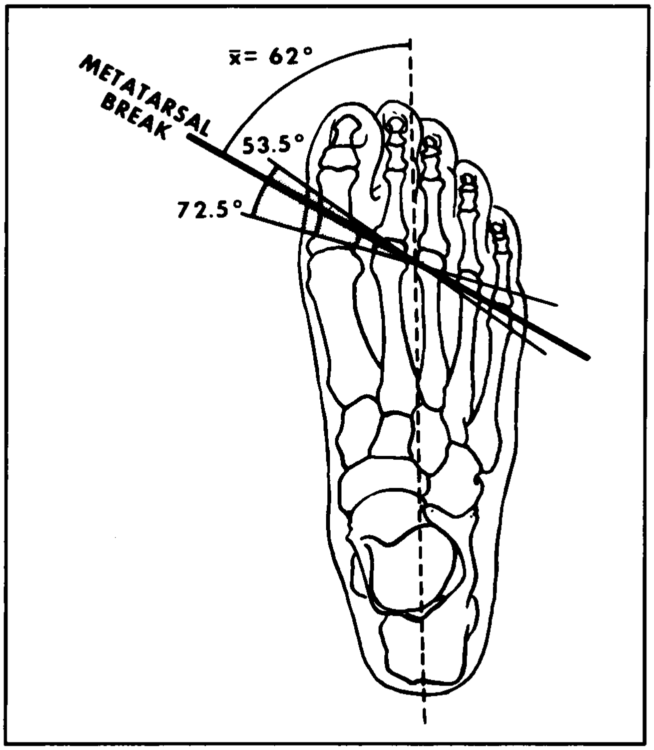

Fig. 8. Metatarsal break in relationship to longitudinal axes of foot. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

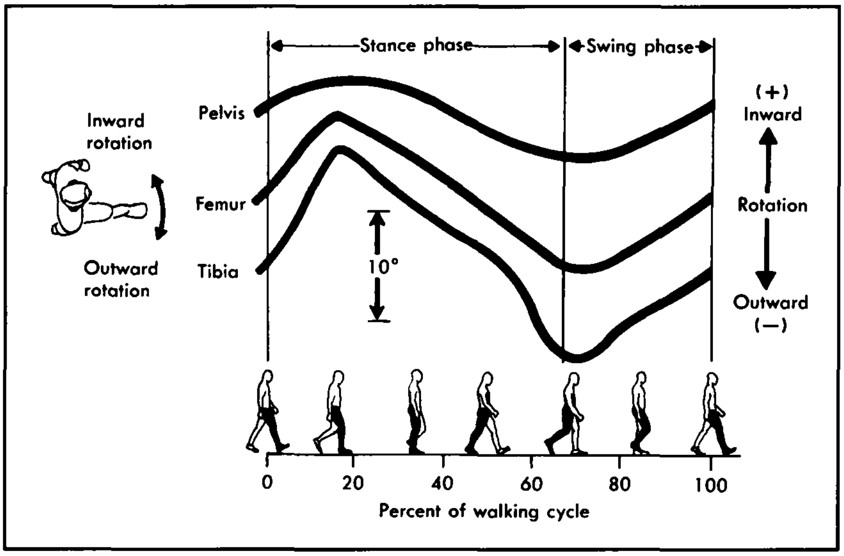

Fig. 9. Transverse rotation of pelvis, femur, and tibia during normal walking cycle. Rotation is inward until foot is flat at 20% of cycle, after which progressive outward rotation is noted until toe-off, when inward rotation recurs. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

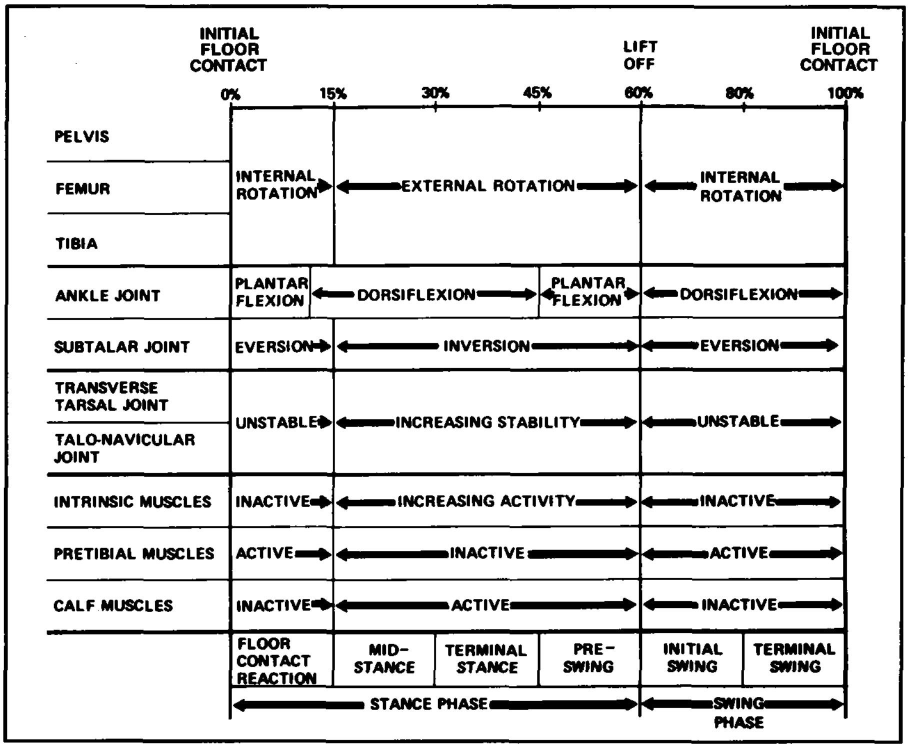

Fig. 10. Schema of complete walking cycle, showing rotations in various segments and joints and activity in foot and leg musculature. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

during gait. The extrinsic muscles of the lower extremity posterior to the ankle axis are the plantar flexors, and those anterior to the ankle axis are the dorsiflexors. Those medial to the subtalar axis are invertors, and those lateral to the subtalar axis are evertors[3,6,16,17] (Fig. 11).

The activity of the dorsiflexors (anterior compartment) occurs during the swing phase and early stance phase. The dorsiflexors help clear the foot during swing and decelerate the foot as it strikes the ground (prevent foot slapping at heel strike). The plantar flexors generally function during midstance and terminal stance phases until toe-off. The intrinsic muscles of the foot are also active during the midstance until toe-off.[3,6,16,17]

The other mechanism that helps stabilize the foot is the plantar fascia. It arises from the inferior tubercle of the calcaneus and passes forward, dividing into bands that circle the flexor tendons and insert into the base of each proximal phalanx.[1] Thus, the plantar fascia acts as a cable between the heel and the toes. A combined truss and Spanish windlass[4,5,8,13] mechanism is formed at the metatarsophalangeal attachment of the fascia. As the metatarsophalangeal joints extend passively when one stands on the ball of the foot, the plantar fascia is pulled distally, and the distance from the calcaneus to the metatarsal heads is shortened. Thus, the base of the truss becomes shorter. As the distance between the heel and the ball of the foot is shortened and the height of the arch is increased, the tarsal bones are locked into a forced flexion position in order to create a solid structure of support. The passive function of the fascia complements the active function of the muscles during standing, walking, running, and squatting[4,5,8,13] (Fig. 12).

In summary, during the gait cycle at heel strike, the lower segment of the skeleton internally rotates until foot flatness is achieved at 15% of the cycle. The heel is everted, the forefoot is flexible and adapting to the ground, and the pretibial muscle is active during the first 15% of the stance phase. When midstance begins, the lower segment reverses into external rotation and the heel inverts, with progressive stabilization of the longitudinal arch until toe-off. Active contraction of the posterior calf muscles and the intrinsic muscles of the foot is present. As the foot is "loaded," the convex head of the talus is firmly seated in the concave navicular, and the plantar fascia exerts its forces on the arch (as weight passes over the foot and the toes are extended). The lower segment achieves maximal external rotation, the heel is maximally inverted, intrinsic muscle and plantar flexor activity is at its maximum, and the axes of the transverse tarsal joint are divergent just before toe-off; at this time, stabilization of the longitudinal arch is maximized. All these events reverse as soon as lift-off begins; internal rotation of the lower segment, heel eversion, and unlocking of the transverse tarsal joint result in a relatively flexible structure until foot flatness is achieved at 15% of the new walking cycle (Fig. 13).

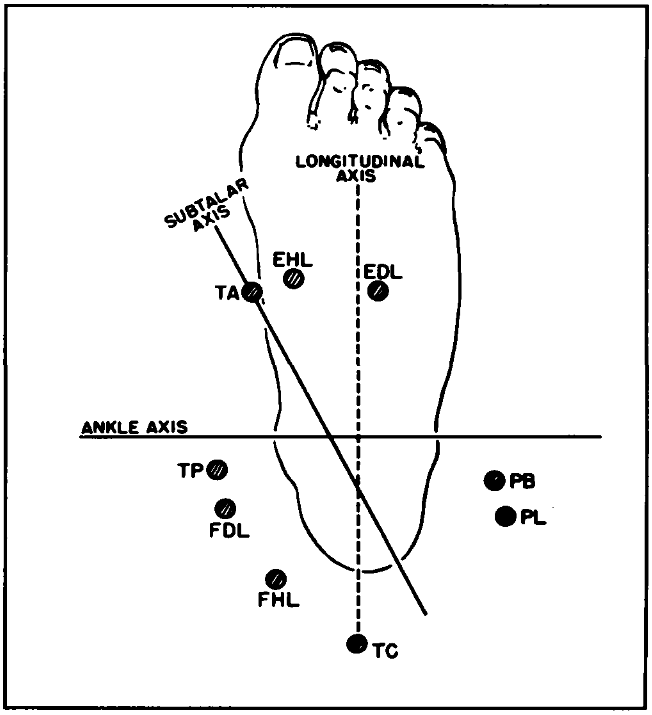

Fig. 11. Subtalar and ankle axes in relationship to extrinsic muscles. *EDL* = extensor digitorum longus; *EHL* = extensor hallucis longus; *FDL* = flexor digitorum longus; *FHL* = flexor hallucis longus; *PB* = peroneus brevis; *PL* = peroneus longus; *TA* = tibialis anticus; *TC* = tendocalcaneus; *TP* = tibialis posterior. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

RUNNING BIOMECHANICS

Running is one of the most common athletic activities for both the athlete and the nonathlete. Especially during the past decade, interest in physical fitness has grown rapidly because of an increasing participation in many athletic endeavors, the most popular of which has been recreational running. Whether the purpose of running is to catch a bus or to win a race, the biomechanics are similar. Although the subsequent description of the biomechanics of running is presented as fact, speed, anatomic variations, state of training, fatigue, footwear, and running surfaces all can appreciably influence biomechanical variables.[18] A good basic understanding of the biomechanics of running, however, is important in dealing with a wide variety of lower extremity injuries.

The biomechanics of running differ substantially from those of walking. During running, joint range of motion,

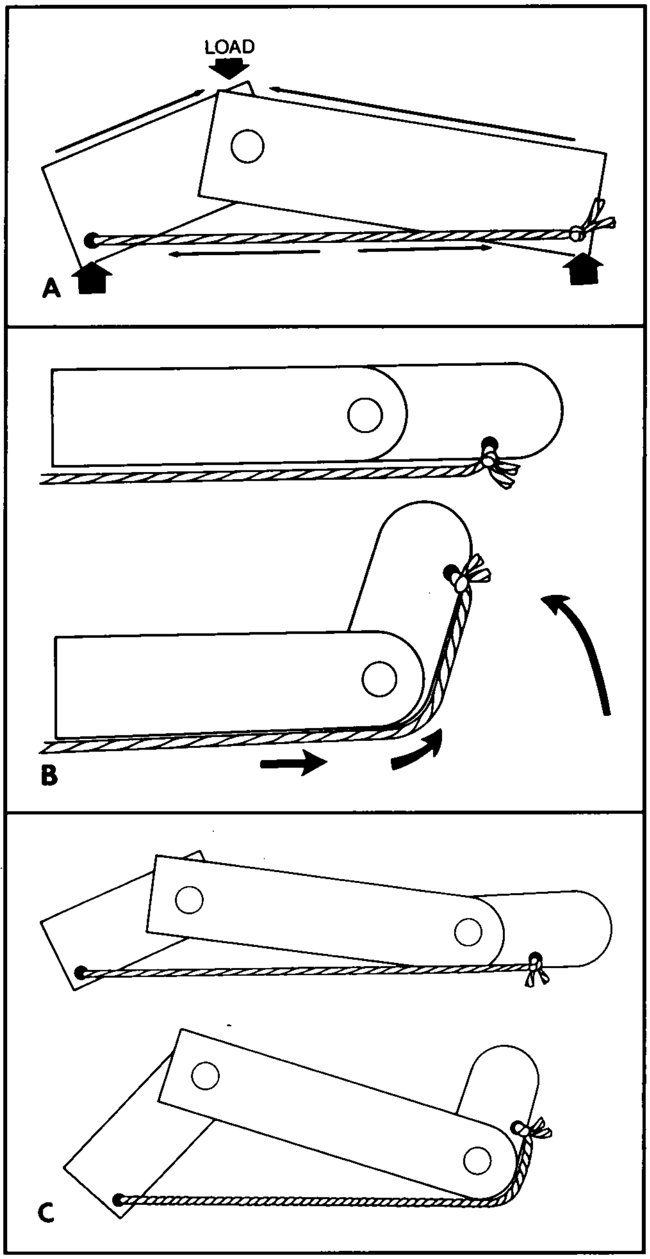

Fig. 12. *A*, Truss. Wooden structure is analogous to bony structures of foot. Plantar fascia is represented by tether between ends of bone. The shorter the tether, the higher the truss is raised. *B*, Spanish windlass. *Upper drawing*, Metatarsal is represented by fixed wooden structure, and proximal phalanx is represented by moving one. Rope attached to moving structure represents attachment of plantar fascia to proximal phalanx. *Lower drawing*, As moving structure turns, rope advances. *C*, Combined truss and Spanish windlass. As plantar fascia raises arch of foot (*upper drawing*), it concurrently locks joints and makes a single unit from multiple individual bones and joints (*lower drawing*). (From Sammarco GJ. Biomechanics of the foot. In: Frankel VH, Nordin M, editors. Basic Biomechanics of the Skeletal System. Philadelphia: Lea & Febiger, 1980: 193-220. By permission.)

muscle activity, and joint reaction forces all vary primarily on the basis of speed and often from one step to the next.[7] The speed of gait can generally be classified into jogging, 3.31 m/s (8 min/mile); running, 4.77 m/s (6 min/mile); and sprinting, 10.8 m/s (9.21 s/100 m). In contrast, walking is defined as 1.32 m/s (20 min/mile).[17] Gait can be categorized into a stance phase (60%), which consists of two periods of double-limb support (each 12%) and one period of single-limb support (35%), and a swing phase (40%).[13] As the speed of gait increases, a third phase—the nonsupportive float phase—develops (Fig. 14). This phase distinguishes running from walking by increasing speed, from a slow jog, to a run, to a sprint. (The stance phase decreases, and the swing and especially the float phases increase.[15]) From walking to sprinting, the period of the stance phase decreases from 0.62 to 0.14 second.[17] As during walking, the center of gravity of the body resembles a sinusoidal curve in space, with the peak during the float phase and the bottom during the stance phase before the onset of knee extension and ankle plantar flexion.[13] This vertical oscillation of the center of gravity decreases with increased running speed.[18] In addition, the body maintains a forward lean throughout the running cycle.[18] During running, each foot lands in the midline; thus, the leg is in a functional varus of 8 to 14°. The feet are generally neutral or slightly internally rotated and land under the knee below the center of gravity.[19] At a running pace of 6 min/mile, initial ground contact is usually made along the posterior 60% of the lateral border of the foot. Usually, contact occurs in the posterior third of the foot (rearfoot or heel strikers).[20] During the stance phase, range of motion of the lower extremity joints and periods of muscle activity increase with higher speeds.[7] Rotation of the pelvis, femur, and tibia has been well quantified during walking but less so during running. Apparently, the general direction of transverse rotation is similar during running, with maximal internal rotation achieved by the first one-third of the stance phase and maximal external rotation at toe-off. During running, most of the forward force is provided by the swinging arm and leg rather than by the stance limb.[13]

The running cycle is a dynamic combination of multiple joints and muscles acting in concert in order to produce fluid locomotion. One of the most basic actions is pronation-supination of the foot. During running at a 6 min/mile pace, pronation is completed in 30 ms, or about 5 times faster than during walking. At foot strike, the lower leg is internally rotating; as the foot is loaded, the calcaneus simultaneously everts, a relationship that results in pronation and flexibility of the foot and increased motion in the transverse tarsal joint.[7] The foot of the average runner strikes the ground with the calcaneus in approximately 4° (range, 4 to 12°) of inversion, and pronation occurs at approximately 12° (range, 4 to 25°) of eversion, although substantial variation exists from

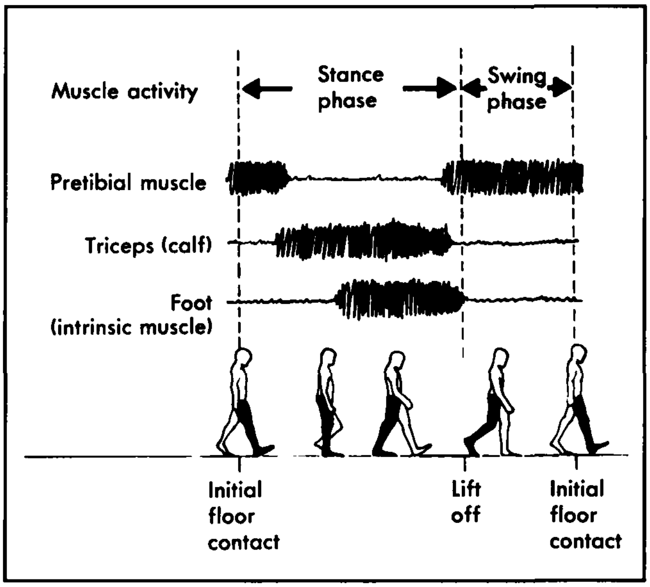

Fig. 13. Schematic phasic activity of leg and foot muscles during normal gait. (From Mann RA. Biomechanics of the foot. In: American Academy of Orthopaedic Surgeons, editor. Atlas of Orthotics: Biomechanical Principles and Application. St. Louis: Mosby, 1975: 257-266. By permission.)

the "normal."[18,21] This pronation is one of the mechanisms of absorbing shocks; thus, runners with cavus (high-arched) feet generally absorb forces more poorly than do those with lower arches. Rearfoot motion does not seem to vary consistently in relationship to speed; however, it seems to be influenced by shoe wear.[21] Running barefoot normally results in increased pronation, probably from changes in biomechanics, because the musculoskeletal system must absorb some of the force that otherwise would be dissipated by the shoe.[18] Nevertheless, some runners with excessive pronation in their shoes have neutral motion when running barefoot. This difference may be attributed to the cushioning properties of the shoe, which tend to amplify rearfoot motion, to other biomechanical changes, or to the possibility that measurement of the motion of the shoe does not accurately reflect movement of the foot.[21]

After maximal pronation, the foot begins to supinate. After the foot is on the ground and fully loaded and the center of gravity has passed the base of support, external rotation of the lower extremity causes inversion of the calcaneus and creates a rigid foot on which the muscles can act.[7,13] The obliquity of the metatarsal break also helps to supinate the foot by enhancing external rotation of the tibia as the toes are dorsiflexed.[13] Stability of the foot is enhanced by the plantar aponeurosis and the intrinsic foot muscles.[7] The external rotation that produces supination is initiated by the forward swing of the opposite leg that brings the pelvis forward. Because the femur of the stance leg is fixed to the pelvis by the adductors, the femur rotates externally.[13] This rotation is passed through the knee joint, which is stabilized by ligaments and the popliteal muscle, to the tibia and then to the ankle and the foot.

Other actions occur around the ankle as well. Typically, long-distance runners initially contact the ground heel first or with the foot flat, whereas sprinters commonly land on the midfoot.[7] In a study of 753 distance runners, 80% were rearfoot strikers and the others midfoot. Faster runners were often midfoot strikers.[22] At the time of heel strike, rapid dorsiflexion at the ankle joint, along with hip and knee flexion, helps absorb the force of impact.[7] In contrast, during walking, plantar flexion occurs at heel strike. Some studies, however, have confirmed some degree of plantar flexion during running, although it often depends on the type of foot strike of the runner.[18] Even during sprinting, dorsiflexion generally occurs, although insufficient for the heel to touch the ground.[7] During sprinting, unlike at slower speeds, the foot is in mild plantar flexion at impact because foot strike typically occurs on the more distal part of the foot.[23] Dorsiflexion peaks at midstance, after which plantar flexion rapidly occurs in the foot until toe-off.[24] Just after toe-off, progressive dorsiflexion occurs until foot strike, except that during sprinting, plantar flexion begins during the terminal part of the swing phase just before contact.

Two active groups of muscles around the ankle are important during running. The anterior compartment muscles are active just before toe-off, throughout the swing phase, and during the first half of the stance phase to the point of maximal dorsiflexion.[7] In contrast to walking, in which the anterior muscles act eccentrically to control plantar flexion, during running they contract concentrically and thus stabilize the ankle, assist dorsiflexion, and most likely accelerate the tibia over the fixed foot; this contraction may be one of the mechanisms for maintaining or increasing speed.[7,17] For sprinters, a period of inactivity during late swing is associated with plantar flexion of the foot.[17] The posterior calf muscles become active at the end of a swing phase; at foot strike, they undergo an eccentric contraction, which helps to control forward movement of the tibia and thus lends stability to the ankle.[7] Therefore, cocontraction between the anterior and the posterior muscles occurs at impact and creates a stable foot.[18] The posterior muscles then continue to function for approximately 60% of stance, or until half of plantar flexion has occurred.[7] The rest of plantar flexion seems to be produced by poorly understood passive mechanisms.[13] Although the posterior calf muscles cause push-off during the acceleration phase of running, they seem to function minimally in this capacity during steady-state running; they may instead be functioning to restrain the forward movement of the tibia.[13] During jogging and running, this stabilization

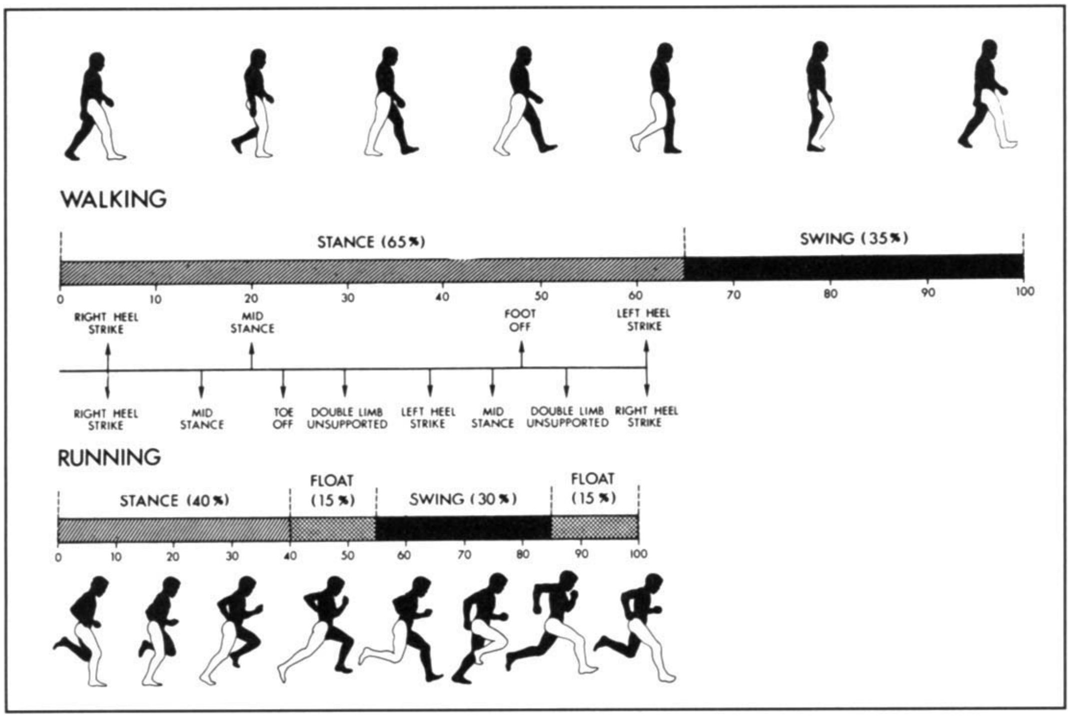

Fig. 14. Comparison of phases of walking and running cycles. Running gait cycle differs from walking because of increase in double-limb unsupported time, or float phase, decrease in stance phase, and increase in swing phase. (From Adelaar RS. The practical biomechanics of running. Am J Sports Med 1986; 14:497-500. By permission of American Orthopaedic Society for Sports Medicine.)

combined with the forward movement of the trunk allows the knee to extend during toe-off.

During running, pronounced forces—the vertical force, fore and aft shear, medial and lateral shear, and torque—develop between the foot and the ground (Fig. 15).[13] The vertical force rarely exceeds 120% of body weight during walking, whereas during running, it approaches 275%.[7] These impact forces are even higher in children, approximately 3.4 times body weight for 6-year-olds and 4 times for 4-year-olds.[18] Localized forces may be as high as 13 times body weight at the ankle and 10 times at the Achilles tendon.[22] Furthermore, vertical force plate analysis generally shows a brief impact spike followed by two peaks during walking but only a single peak after the impact spike during running. The probable explanation is that two periods of double-limb support occur during walking.[13] The impact peak is actually smaller than the second peak, which is associated with propulsion,[21] because more force is generated with propulsion than with impact. With midfoot or forefoot strikers, the initial impact peak generally flattens out and dissipates.[18]

Shear forces are similar during walking and running, although again the magnitude is greater during running. Mediolateral shear forces vary substantially, most likely because of wide variations in anatomic alignments and foot placements among runners.[21] During running, a second period of medial shear seems to occur that has questionable importance.[13] The anteroposterior shear forces peak at approximately half the body weight during the first part of stance and contribute to a braking force; a second, similar force, associated with forward propulsion, then develops in the opposite direction.[21] At impact, the foot (or shoe) has a horizontal velocity component of approximately 17% of the runner's forward velocity. The resulting shear force (rather than high vertical forces) contributes to shoe wear; thus, increased areas of shoe wear reflect initial ground contact rather than peak force.[21] Minimizing the horizontal component of the ground reaction force (that is, the braking force) is apparently important in optimizing performance. Although the magnitude of this force seems to be related to foot speed at impact and the distance between the foot and the body's center of gravity, foot speed and position at impact cannot always be relied on for an estimation of the braking force. Torque measurements correlate with the transverse rotation curve because an internal torque is generated against the ground with internal rotation of the lower extremity. Similarly, external rotation leads to an external torque.[7]

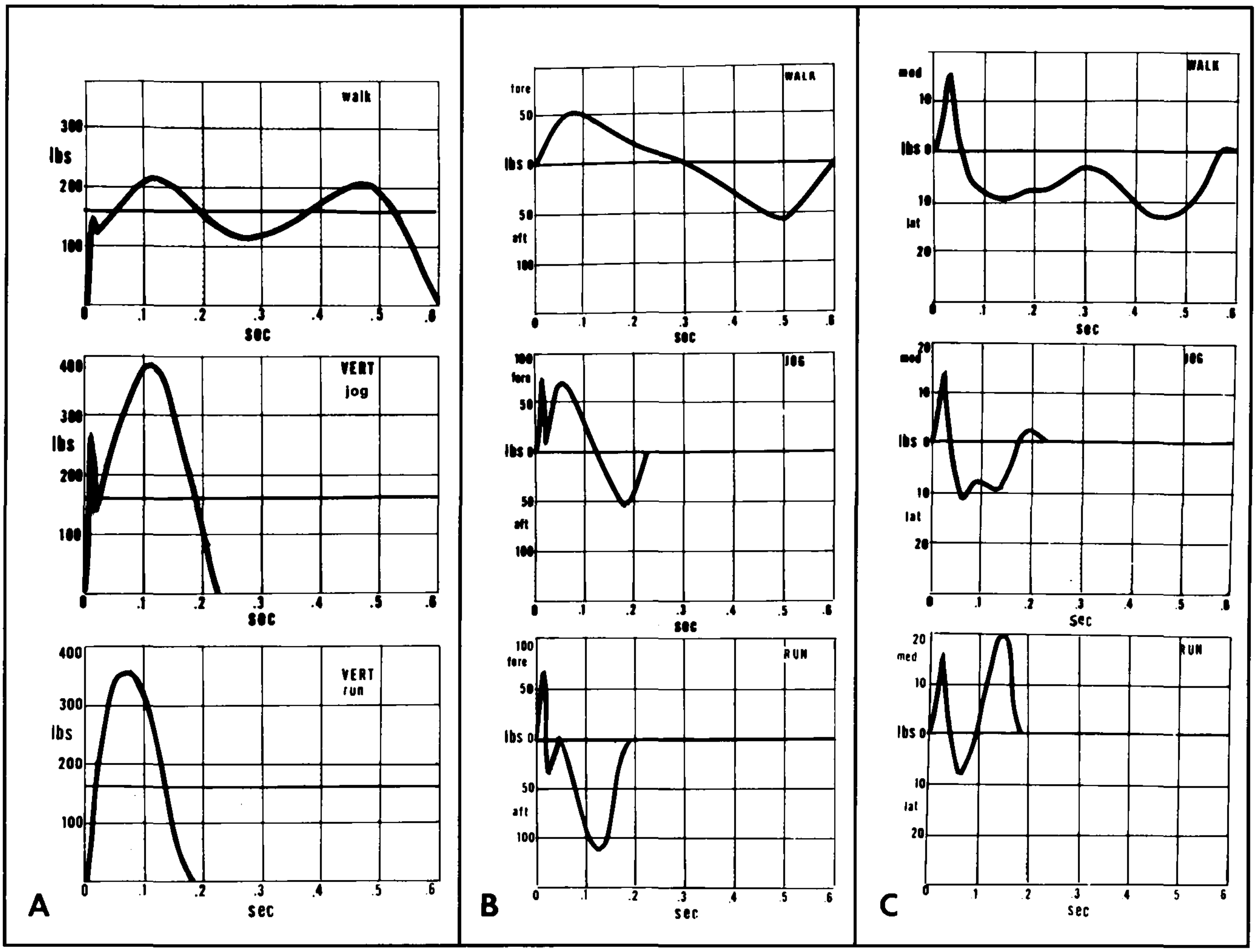

Fig. 15. *A*, Vertical ground reaction forces. *B*, Fore and aft shear forces. *C*, Medial and lateral shear forces. (From Mann RA, Hagy JL. Running, jogging, and walking: a comparative electromyographic and biomechanical study. In: Bateman JE, Trott AW, editors. The Foot and Ankle: A Selection of Papers From the American Orthopaedic Foot Society Meetings. New York: Thieme-Stratton, 1980: 167-175. By permission.)

The distribution of the forces acting on the sole can be averaged, and a measurement known as the center of pressure is obtained.[21] (Force is a unit of measure of strength or energy brought to bear on a surface or object, and pressure is the application of force to some object by another object in direct contact with it that is extended over an area.) Because this measurement is an average, the center of pressure may not reflect the maximal areas of pressure and may even potentially be in an area without pressure.[25] Maximal pressures have been measured at the heel, the metatarsal heads, and the great toe.[20] The center of pressure measurement reflects the gait pattern of the runner. A typical heel striker generates the pressure shown in Figure 16 (11%). The center of pressure actually begins outside the outline of the shoe because of the shear forces that result in lateral displacement.[21] Measurements in the proximal portion of the foot are high in density because the forces are concentrated in this region during more than two-thirds of the stance phase.[21] The center of pressure varies among people, with speed, and even between right and left feet.[21]

Stride length and rate during running have also been studied. The stride length is defined as the distance from the point of initial contact of one leg to the point of initial contact of the other. Stride rate and length both increase at higher velocities. At higher speeds, stride rate increases to a greater extent than does length (Fig. 17).[26] A study of a world-class sprinter at speeds up to 9.5 m/s showed that stride length increased to a larger extent at higher speeds and that stride rate decreased concurrently.[24] No consistent relationship seems to exist between stride characteristics and runner size

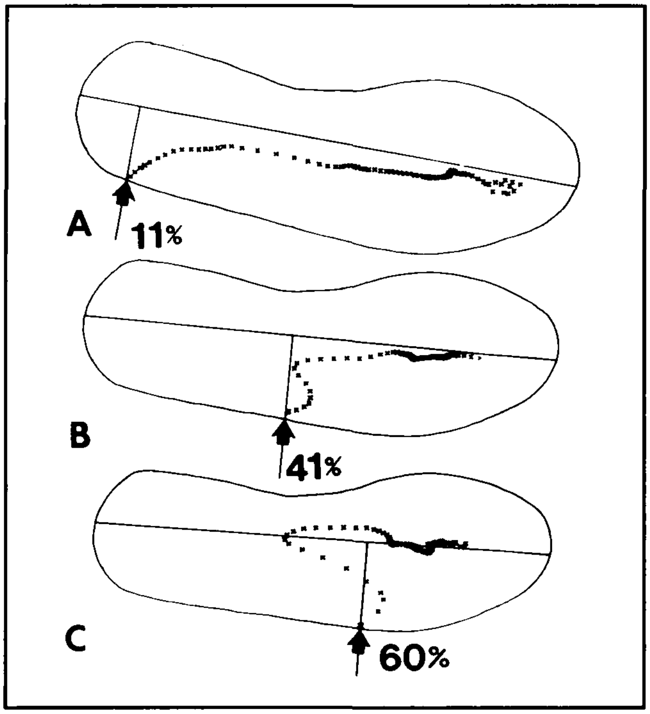

Fig. 16. Center of pressure patterns of three subjects all running at same speed. Note great differences among subjects despite matched running speeds. *A*, Rearfoot striker. *B*, Midfoot striker. *C*, Forefoot striker. (From Cavanagh.[21] By permission of Mosby.)

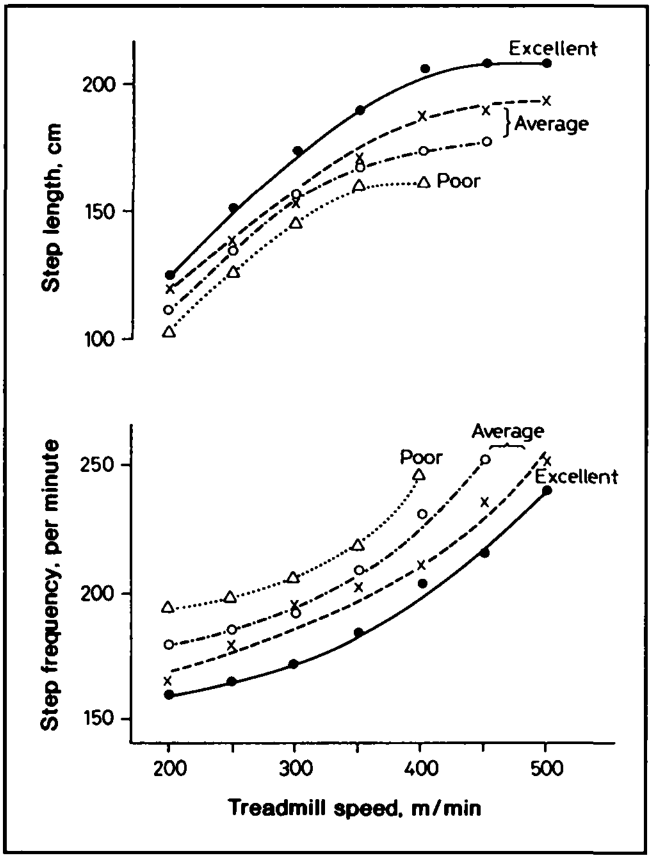

Fig. 17. Variability of stride length (step length) and stride rate (step frequency) with velocity. (From Hoshikawa T, Matsui H, Miyashita M. Analysis of running pattern in relation to speed. Med Sports 1973; 8:342-348. By permission of S. Karger.)

or leg length, although stride length apparently increases in parallel with leg length; however, individual variations are substantial. In general, trained runners seem to have a longer stride at a specific speed, although some studies have shown the opposite.[18]

Efficiency contributes to running styles. No definitive studies have been done, however, to determine whether runners naturally adopt efficient styles or what constitutes an efficient style. Training has been reported to increase running economy, and, in fact, biomechanics may be more closely related to the economy of running, which is defined as the metabolic cost of performing a particular task and is not necessarily related to efficiency. Runners tend to have a stride length that is within 4.2 cm of the most economic length; the importance of this finding is questionable because fairly large differences in stride length result in small changes in energy consumption.[23] Furthermore, the specific criteria that dictate optimal stride length have not been definitively ascertained. In fact, the length may be related to the efficiency and velocity of the muscle contractions themselves (this hypothesis is strengthened by the observation that when runners are fatigued, they tend to adopt a longer stride).[23] In addition, economic runners have less vertical motion of the center of gravity,[18] generally small anteroposterior and vertical ground reaction forces, a low impact peak in the vertical force, and a rearfoot striking pattern.[27]

CONCLUSION

We have described the anatomy and biomechanics of the foot and have explained how movement and gait are integrated in the foot during walking and running. With an understanding of these factors, the clinician should be better able to evaluate foot problems.

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