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REVIEW ARTICLE

Foot Biomechanics and Relation to the Gait Cycle

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ABSTRACT

The foot and ankle are fundamental to all upright locomotion performed by the human, accommodating itself to the external environment and providing a harmonious relationship between body and the external environment by propagation. The evaluation of the mechanical behavior of different structural foot elements can be used to understand the foot behavior during different phases of the gait cycle. Understanding the foot biomechanics during gait helps in the design of the orthotics and prosthetics. These data are essential for identifying abnormal patterns and characterizing impairments, disabilities, and handicaps. In this article, we will explain the basic biomechanics of the foot during the normal gait cycle.

Keywords: Ankle joint, Pelvis, Subtalar joint, Transverse tarsal joint, Windlass effect.

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BACKGROUND

Gait is a series of rhythmic and coordinated movements of the upper limb, trunk and the lower limb to bring about forward propulsive movements of the body with minimum energy expenditure. Each segment of this arc should function appropriately so that excessive stresses are not placed over the other segments. The ankle and the foot being the terminal part of this lever arm hold an essential place in the gait cycle. Loss of joint motion, weakness of musculature, sensory imperceptions, abnormal soft tissues, and bony misalignment, each can produce gait abnormalities. For a satisfactory gait, we need a pliant foot so that it can adjust to the uneven ground and a semi-rigid foot which helps in push-off phase and a rigid foot which aids in weight bearing.

The Gait Cycle

The gait cycle is classified into stance phase (62%) and swing phase (28%). The normal smooth functioning of foot and ankle is of paramount importance, especially in the stance phase. The stance phase, in which the foot receives the weight of the body and propels it forward, is further divided into five stages: heel strike, flat foot, midstance, heel off and toe off. The swing phase, when the foot is not in contact with the ground, is divided into early, intermediate and late stages. It consists of an early acceleration phase and late deceleration phase (Fig. 1).[1] The momentum generated by the gastro-soleus and hip flexors at terminal stance carries the leg forward.[1] The articulated skeleton of foot acts as a rigid lever during push off, allowing muscular contraction to propel the body forward, and at heel strike, it becomes a flexible shock absorber to accommodate the impact of body weight and hence allows maximal contact of sole with the ground. For the stance phase to pass smoothly without much stress in the foot and other parts of the body, one needs:

- Normal functioning of joints
- Adequate strength in the muscles
- Good sensory perception
- Normal arches of the foot
- Healthy soft tissues in the sole.

Pelvic and Tibial Rotation in Combination with Foot Biomechanics

Generally, during the gait cycle, the pelvis rotates internally of about 6^{o}.[2] The femur and tibia rotate internally of about 18^{o} in all stages of swing phase and during heel strike and flat foot.[2,3] During the midstance and late stance phase, the tibia starts rotating laterally till the toe off occurs (Fig 2).[3]

Internal Foot Biomechanics

At heel strike, the tibia is rotated internally, and the ankle joint is in a slight plantar flexed position. Heel strike stretches the attachments of calcaneum as it causes compression of the heel pad, prominent in the terminal

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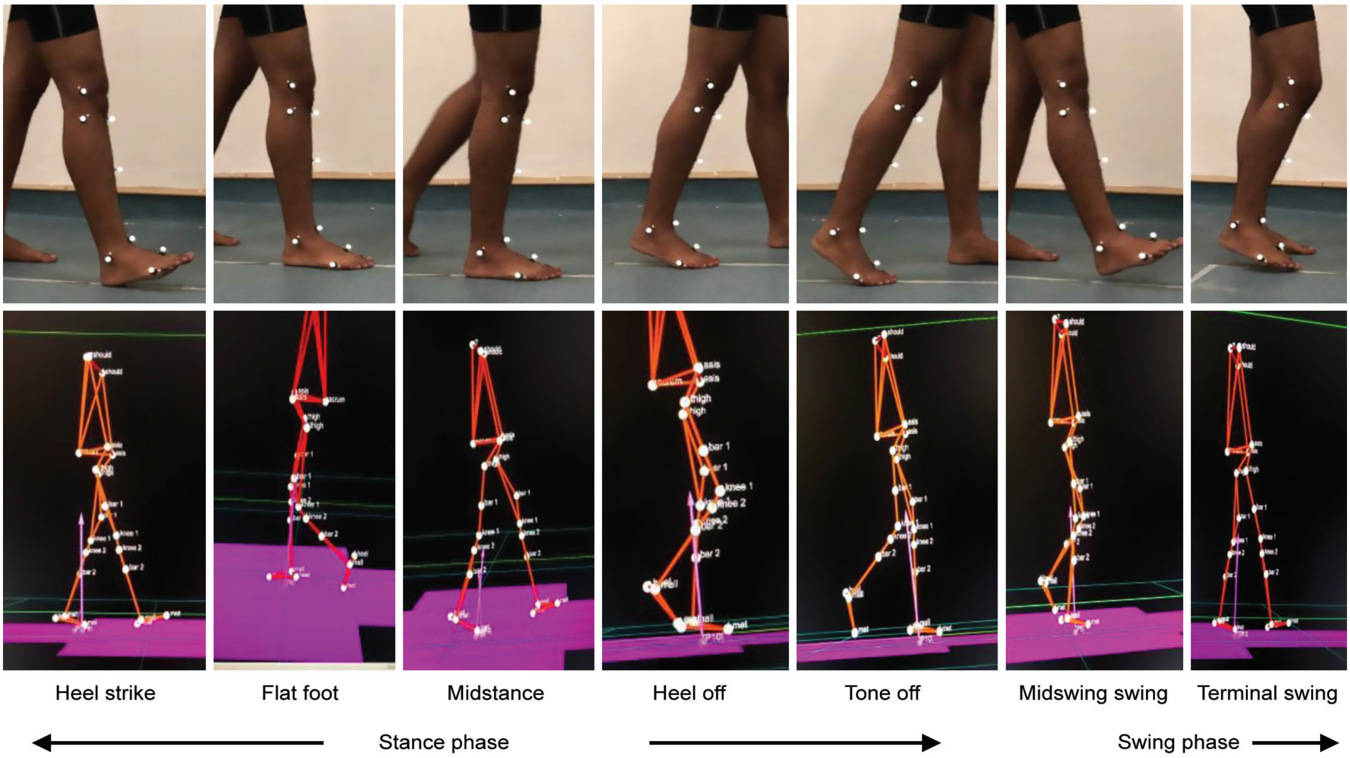
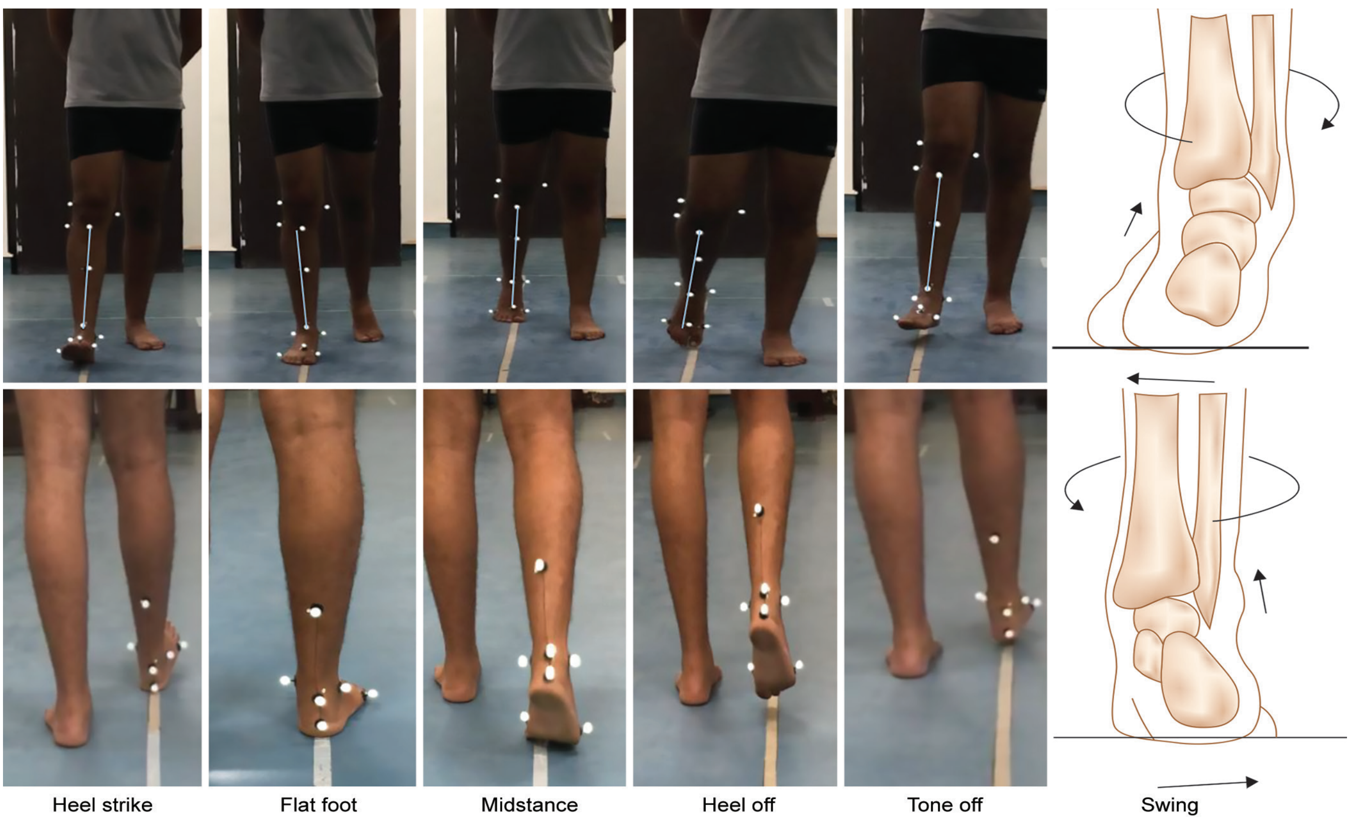


Fig. 1: Stages of gait cycle



Tibia internally rotating	Tibia externally rotating
Calcaneus everts and subtalar joint pronation	Calcaneus inverts and subtalar joint supination
Midtarsal joint unlocks	Midtarsal joint locks
Midfoot pliability increases	Midfoot stability increases

Fig. 2: The movements occurring in the tibia, calcaneus and subtalar joint during various phase of gait cycle

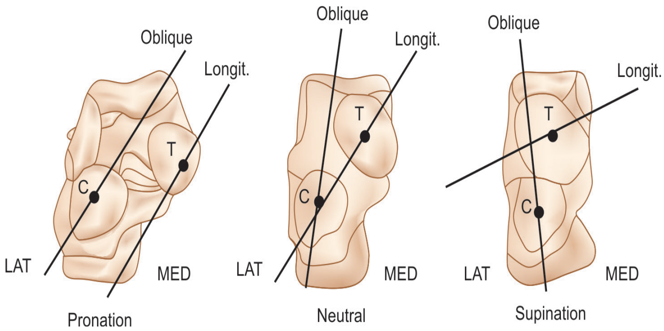


Fig. 3: The axes of the calcaneocuboid and talanavicular joint axes during supination and pronation

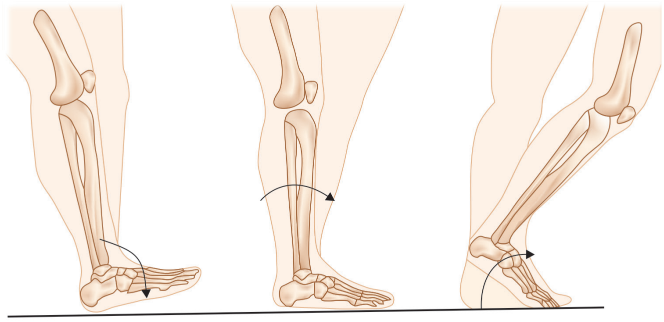


Fig 4: The three rockers of the foot during the gait cycle

stance phase. The foot plantar flexes to flat foot. The dorsiflexors of ankle control this motion to prevent the foot from slapping down. From heel strike to just before flat foot, the tibia rotates medially. This causes internal rotation of the mortise in the plantar flexed position. As the mortise rotates the forefoot shifts medially from the toe-out position. Internal rotation of mortise causes pronation at the subtalar joint and pronation of calcaneum. This is because the body weight is transmitted laterally to the ankle joint axis. The talus rotates medially on the calcaneus to form a highly stable talonavicular joint. The forefoot is now more flexible, and it can accommodate the uneven supporting structures. During pronation, the axis of the calcaneocuboid and talonavicular are parallel which unlocks the joint to create a hyper-mobile forefoot[4,5] (Figs 2 and 3).

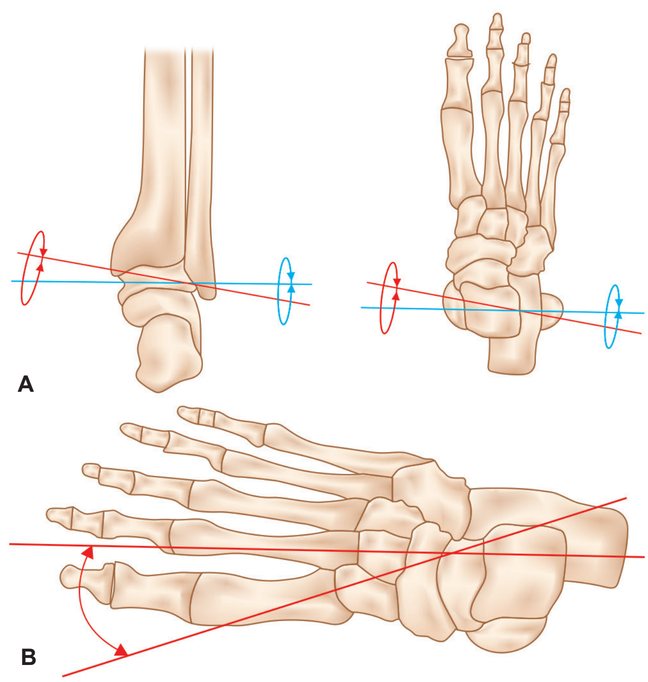
During the flat-foot position, the tibia rotates externally. These rotatory forces cause supination of the foot and increase stability at the transverse tarsal joint and along the longitudinal arch of the foot. The supination causes both joint axes to converge which locks the joint and increases the transverse tarsal joint stability. This allows the efficient transformation of forces and prepares the foot for the next phase.[6]

The ankle joint undergoes plantar flexion after heel rise causing the metatarsophalangeal joint to dorsiflexion. The plantar aponeurosis contracts and elevates the longitudinal arches by its windlass effect on metatarsal heads which increases the stability of the foot. The foot is highly stable at this point and is ready for toe-off. This stability is due to pronation of the hindfoot and windlass effect and weight bearing. After toe-off, the tibia rotates medially which causes pronation of hindfoot, and the foot becomes flexible for the swing phase to follow.[6]

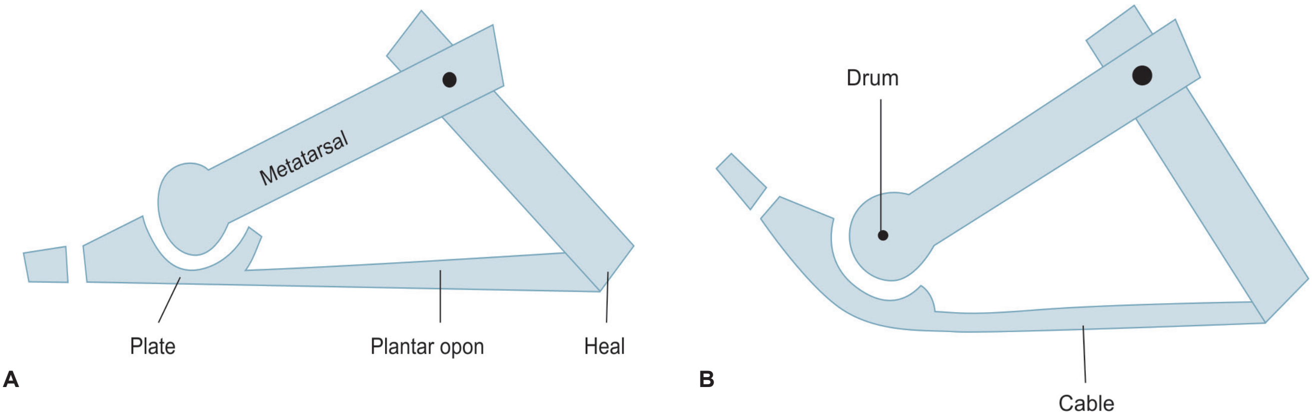
Movements occurring at the ankle joint are plantar flexion (0^{o} to 50^{o}) and dorsiflexion(0^{o} to 20^{o}). Movements at subtalar joint include inversion (0–35) and eversion (0–15). Abduction and adduction movements occur at the midtarsal joints. Pronation comprises eversion, abduction, and dorsiflexion; supination comprises inversion, adduction, and plantar flexion.[7,8]

The Ankle Joint

During the stance phase, the ankle joint progressively undergoes plantar flexion (heel strike-1st rocker); then dorsiflexion (foot flat–2nd rocker) and plantar flexion (push off-3rd rocker) (Fig. 4). The normal range of motion at the ankle joint is 20^{o} dorsiflexion, 50^{o} plantar flexion, which adequately allows smooth rollover of the body while the foot is fixed to the ground. Limitation of this range of motion impairs progression of normal gait. Ankle joint has an oblique axis (Fig. 5). In the frontal plane, the ankle joint is angled 82^{o}, directed laterally; in the transverse plane, the axis is directed laterally and posteriorly about 20^{o} to 30^{o}; as a consequence of this oblique ankle joint axis, dorsiflexion causes external rotation of the mortise and vice-versa. Also due to the diagonal axis, the tibia rotates internally during ankle dorsiflexion and externally during plantar flexion. The foot externally rotates when the ankle is in maximal dorsiflexion; when the foot plantar flexes, it internally rotates; foot fixed on ground as in stance phase of gait;



Figs 5A and B: The axes of ankle (A) and subtalar joint (B)



Figs 6A and B: The windlass mechanism

forward tibial progression (ankle dorsiflexion) results in tibial internal rotation; when tibia is behind foot (ankle plantar flexion), it is externally rotated.[7,8]

The Subtalar Joint

The subtalar joint forms one of the most important articulations of the foot and it has 40 degrees range of motion through an axis that passes diagonally from posterior, lateral plantar surface of the calcaneum to the anterior, medial dorsal surface of the navicular. Inversion and eversion movements occur at this joint along a straight axis passing down the posterior aspect of leg bisecting the calcaneus. The subtalar motion is essential in walking not only on plain surfaces but also in uneven grounds.[9,10]

During regular walking, the subtalar motion alternatively locks and unlocks the midtarsal joints, which allows the foot to become a rigid lever during push off, and as a shock absorber during heel strike and foot flat phases.

Similarly, at heel strike on uneven grounds the subtalar joint can move, to allow the talus to be aligned correctly in the ankle mortise facilitating ankle motion. If the heel contacts the ground off center, either medially or laterally, the subtalar joint can accommodate this offset and allow normal ankle motion and thus the normal progression of gait. If the subtalar joint is fixed, the malaligned talus creates shear stresses in the ankle during the stance phase leading to decreased gait efficiency and ankle arthritis.

After discussing the intricate relation of subtalar and ankle motion in normal gait, we will now analyze the relationship between subtalar and midtarsal joints, which is even more crucial. The midtarsal joint is the confluence of talonavicular and calcaneocuboid joints. Although limited motion occurs at these joints, their suppleness during heel strike and rigidity during push-off phase is of paramount importance. When the calcaneus everts, the axis of the talonavicular and the calcaneocuboid joints are parallel, and motion can occur at the midtarsal joint (Fig. 6).

Conversely, when the heel is in inversion, the axes are no longer parallel, and midtarsal motion is restricted. If you observe a person from the back while toe walking, you can notice that his heels are inverts. This unlocks the midtarsal joint allowing the foot to become a rigid lever to propel the body forward. Similarly, during heel strike, the heel pronates, allowing the entire sole to contact the ground and the midtarsal joint in an unlocked state acts as a shock absorber to receive the body weight as well as counter act the ground reaction force.[9,10]

To summarize, the subtalar joint will be in pronation during the early phase of the stance phase and shifts into supination during the later stage of the stance phase. It assumes the pronated position during the swing phase.[9,10]

Transverse Tarsal Joints

They will be free movements during the early phase whereas the movements will be restricted during the late stance phase. There is no movement restriction during swing phase. Inversion of subtalar joint locks the transverse tarsal joints and vice versa.[11]

The Longitudinal Arches

During gait, from about midstance to push off, elevation of the longitudinal arch of the foot occurs. This is achieved by a combination of factors, contraction of the extrinsic muscle, i.e., posterior tibial muscle, intrinsic muscle contraction, i.e., flexor brevis and passive dorsiflexion of the metacarpophalangeal joints. The passive dorsiflexion of metacarpophalangeal joint places tension of plantar fascia (which originates from calcaneus and inserts into the bones of proximal phalanges) creating a windlass effect to elevate the longitudinal arch. Elevation of this arch creates a stable lever arm, particularly when combined with locking of the midtarsal joint for push off. The windlass in the foot refers to the plantar aponeurosis which winds around the metatarsal head[12] (Fig. 6).

The Heel Pad

The heel pad acts as a shock absorber during heel strike and helps to accommodate ankle motion. The intricate arrangement of fat surrounded by firm fibrous septa that arise from the dermis and insert into the calcaneus buffers the impact of heel strike in a very efficient function. Damage to this hydraulic action cannot be repaired and can lead to impaired gait mechanics with significant pain on weight bearing.[13]

Body Weight Distribution

The body weight is distributed 50% of each foot, and again in either foot, as 50% on hindfoot and 50% on forefoot in proportion of six units on calcaneum, two units on head of the first metatarsal, and one each on the head of other metatarsals which constitute the respective ground contact points.

Between the heel strike and push-off, the ankle joint dorsiflexes allowing the body to move forward, the weight is transferred from the heel to the toes as this forward motion occurs. During regular walking, the vertical load applied to the foot is roughly equal to body weight, while during running the vertical load increased to two and a half times the body weight. The weight is borne for a longer time on the metatarsal head area during heel strike to toe-off; more so the highest concentration of pressure is on the second and third metatarsal heads.

Sensory Proprioception

The foot has a wider sensorial representation in the brain than the hand. It is the foot from where various proprioceptive stimuli start. The foot performs its specific function through a very complicated and subtle system of proprioceptive reflexes. In the pursuit of understanding the intricate biomechanics of the foot, the anatomists and podologists have compared the foot to various objects like a stool with three legs, tripod dome, and one binder, a screw, a bridge, self-balancing sailing boat. Foot acts as a stable base during standing and as a rigid lever during locomotion. While standing the stability is offered by the interlocking of the joints under influence of the compression from the opposing forces of body weight from above, and the equal and opposite ground reaction from below ("the structural stability" of Marton (1935). From the stable base provided by two feet, the body is held erect and balanced by the postural tone of muscles with the center of gravity within the confines of the base ("the postural stability").[14]

SUMMARY

The foot is the most dynamic, reactive and adaptive organs of the body. During the stance phase, the subtalar joint undergoes eversion in the early phase and vice versa. The ankle joint undergoes plantar flexion (first rocker) in the initial stance phase followed by dorsiflexion (2nd rocker) and plantar flexion (third rocker). These movements coupled with the internal and external rotation of tibia increases the stability of midfoot leading to take off. The combination of tibial internal rotation subtalar joint eversion leads to flexible midfoot which helps in the swing phase.

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