Human feet have most often been described in the medical literature as semirigid bases functioning to provide an attitude of stable static support for the entire erect body. This theoretical concept, however, does not correlate with what we evaluate clinically.

When adults stand for prolonged periods at a time, common subjective symptoms can result in a feeling of overall fatigue or produce actual intrinsic foot discomfort. When intrinsic foot discomfort is associated with prolonged standing, many theoretical models can be attributed to explain the etiology of the symptoms. The model we favor is the one in which the unremitting tension from relaxed standing will eventually result in tension deformity of the plantar structures. The plantar structures most commonly symptomatic are the plantar fascia, spring ligament, and, less frequently, the posterior tibial tendon.

Another model, which has been suggested, is vascular congestion, theoretically due to prolonged standing. This model is based on the concept that the venous system is inhibited from proper function when not walking. Therefore, the muscular pump, which aids the deep veins to return blood up to the body, is not active. The veins become engorged and transudate leaks out into the interstitial spaces increasing the pressures within the foot and leg. The increased volume of interstitial fluid inhibits normal arterial blood flow into the foot, and the entire leg/foot vascular system becomes inefficient. This changes the properties of the fluid environment, which bathes the nerves, fascia, ligaments and tendons. Whichever model is correct, it is far less tiring to walk, run, jump, or dance on normally functioning feet than it is to stand.

It is apparent that the human foot has evolved as a dynamic functional structure in which it participates as the adapter, compensator, and regulator of gait in respect to the ground. The foot should be evaluated clinically as an integral part of the locomotor system, and not as a static support structure.

Human gait is unique, evolving a characteristic bipedal, orthograde, habitual type of locomotion. This method of locomotion imposes gross similarities in the manner in which all of us walk. However, each of us exhibits minor individual differences that allow us to be recognized by a friend or relative even from a distance. The causes of these
individual characteristics of locomotion are many. We all differ somewhat in the length and distribution of mass of the various segments of the body, which must be moved by muscles of varying fiber length.

Furthermore, individual differences occur in the position of joint axes, with resultant minor variations in lever arms. These and many other such factors combine to establish in each of us an individual walking pattern. Efficient gait results from the integration of many components. Mean values of one single morphological observation are of little clinical value. The clinician should be alert to the morphological variations that occur within the population, but it is more important to understand the functional interrelationships among the various components.

This is particularly true when observing the foot, where anatomic variations are extensive. If mean values are the only bases of comparison, it becomes difficult to explain why some feet function adequately and asymptotically, even though their measurements deviate significantly from the mean, whereas others function symptomatically, even though their measurements fall well within the mean. It seems clinically reasonable to use mean values only to provide a mathematical reference for estimating the extent of deviations from these means. Therefore the major emphasis should be placed on functional interrelationships and not on descriptive anatomy.

Human locomotion is a learned process; it does not develop as the result of an inborn reflex. The result of this learning process is the integration of numerous neuromusculoskeletal mechanisms, with gross similarities and individual variations into an efficiently functioning manner of walking. Once a person has learned to walk and has attained maximum growth, a built-in physiologic regulatory mechanism compensates for varying activities, terrain, and shoe style.

**KINEMATICS OF HUMAN LOCOMOTION**

Kinematics is concerned only with motion, and does not consider muscle function and forces. Walking is more than merely placing one foot in front of the other. During the walking cycle all major segments of the body are in motion with displacements that can be accurately described.

**Vertical Body Displacements**

The normal rhythmic upward and downward displacement of the body during walking is familiar to everyone, and is observed from a side view by seeing an individual's head bobbing up and down. These displacements with in the vertical plane are a necessary concomitant of bipedal locomotion. When the legs are separated, as during transmission of the body weight from one leg to the other (double weight support), the distance between the trunk and the floor must be less than when it passes over a relatively extended leg, as during midstance. Since the nature of bipedal locomotion demands these vertical oscillations of the body, they should occur in a smooth sinusoidal manner for the conservation of energy.
The center of gravity of the body should move in a smooth sinusoidal path, with the amplitude of displacement being approximately 4 to 5 cm. Although movements of the pelvis and hip modify the amplitude of the sinusoidal curve, the knee, ankle, and foot are particularly involved in converting what would be a series of intersecting arcs into a smooth, sinusoidal curve. This conversion requires both precise and simultaneous motions in the knee, ankle, and foot.

The center of gravity of the body reaches its maximum elevation immediately after passage over the weight-bearing leg, then begins to fall. This fall must be stopped at the termination of the swing phase of the other leg as the heel strikes the ground. Actually the falling center of gravity of the body is smoothly decelerated, because relative shortening of the leg occurs at the time of impact against a gradually increasing resistance. The knee flexes against a gradual contraction of the quadriceps muscle and the ankle plantar flexes against the resisting anterior crural muscles. After the foot-flat position is reached, further shortening is achieved by pronation of the foot.

After decelerating to zero, the center of gravity must now evenly accelerate upward to advance over the opposite leg. The kinetics (the study of motion, acceleration, or rate of change) is complex, but the kinematics is simple. The leg is relatively elongated as a result of extension of the knee, plantar flexion of the ankle, and supination of the foot. Heel lift is the major component contributing to upward acceleration of the center of gravity at this time.

**Horizontal Body Displacements**

In addition to vertical displacements of the body, a series of axial rotational movements occur that can be observed within the horizontal plane. These horizontal rotations of the pelvis and the shoulder girdle are familiar to all clinicians who observe gait. Similar horizontal rotations occur in the femoral and tibial segments of the extremities.

The tibias rotate about their long axes, internally during swing phase and into the first part of stance phase and externally during the latter part of stance. This motion continues until the toes leave the ground; the degree of these rotations is subject to marked individual variations. The largest amount of this rotation occurs when the foot is firmly placed on the floor. For these movements to occur, a mechanism must exist in the foot that permits the rotations but offers resistance to them of such magnitude that they are transmitted through the foot to the floor and are recorded on a force plate as torques.

**Lateral Body Displacements**

When a person is walking, the body does not remain precisely in the plane of progression but oscillates slightly from side to side to keep the center of gravity approximately over the weight-bearing foot. Everyone has experienced this lateral shift of the body walking in tandem with a companion. If one gets out of step with the other, their bodies are likely to bump. The body is shifted slightly over the weight-bearing leg with each step; therefore a total lateral displacement of the body of approximately 4 to 5 cm occurs from
side to side with each complete stride. This lateral displacement can be increased by walking with the feet more widely separated, and decreased by keeping the feet close to the line of progression. Normally the presence of the adult tibiofemoral angle (carrying angle) of 6-12 degrees (slight genu valgum) permits the tibia to remain essentially vertical and the feet close together while the femurs diverge to articulate with the pelvis. Again the lateral displacement of the body is through a smooth sinusoidal pathway.

The slower an individual walks, the less movement of the center of gravity and the less the recorded force. Conversely, the faster the gait, the greater the movement of the center of gravity and the larger the force.

**BIOMECHANICS OF WEIGHT BEARING**

The vertical force curve demonstrates an initial spike against the ground, after which the force declines. This initial spike is the reaction of the heel against the ground. The shoe material can alter the magnitude of the spike: a softer heel will result in a smaller initial spike, and a harder heel in a larger spike. When the first peak occurs, which is 10 percent to 15 percent greater than body weight it is caused by the upward acceleration of the body's center of gravity. This is followed by a dip in which the weight against the ground is approximately 20 percent less than body weight. This dip occurs because after the initial force has been exerted to raise the center of gravity the stance foot is unloaded as the center of gravity reaches the top of its trajectory before starting to fall. A second peak, again 10 percent to 15 percent greater than body weight, is caused by the falling of the center of gravity, after which the force rapidly declines to zero at toe-off and subsequent weight transfer to the opposite limb.

**Shear Forces**

Fore shear represents the initial braking of the body at the time of heel strike, and occurs because the center of gravity is behind the foot at the time of heel strike. After the center of gravity has passed in front of the weight bearing foot an aft shear is noted. The aft shear reaches a maximum as the opposite limb strikes the ground at 50 percent of the walking cycle, at which time a fore shear is noted. The magnitude of the fore-aft shear, however, is only about 10 percent to 15 percent of body weight.

Medial shear forces are exerted toward the midline at the time of heel strike, after which there is a persistent lateral shear until opposite heel strike at 50 percent of the cycle, when the medial shear occurs again. Following heel strike there is an internal torque that reaches a maximum at the time of foot flat, after which there is a progressive external torque that reaches a maximum just prior to toe-off. This torque corresponds to the inward and outward rotation of the lower extremity.

Another way of visualizing the force against the ground is to observe the movement of the center of pressure. The movement of the center of pressure along the bottom of the foot follows a consistent pattern in a normal person.
The center of pressure moves rapidly along the bottom of the foot following heel strike until it reaches the metatarsal area, where it dwells about half of the stance phase, then passes distally to the great toe. A greater appreciation of the movement of the center of pressure is observed in a patient with rheumatoid arthritis who has a hallux valgus deformity with painful metatarsalgia. In this circumstance the center of pressure remains in the posterior aspect of the foot, avoiding the painful metatarsal area, then rapidly passes over the metatarsal heads along the middle of the foot, compared with weight bearing under the great toe in the normal foot. In a study carried out in patients with amputation of the great toe, the center of pressure passed in a more lateral direction.

Although the movement of the center of pressure presents a visualization of the movement of the center of gravity, it represents an average of pressure against the ground. New techniques and computerization, have demonstrated graphically the distribution of forces on the plantar aspect of the foot in such a way that a more quantitative visual concept of the weight-bearing pattern on the plantar aspect of the foot is obtained. This new type of representation again demonstrates how rapidly the pressure leaves the heel and dwells in the metatarsal region. It further demonstrates the importance of the toes in weight bearing in the last 30 percent of the stance phase of walking.

Further quantification and localization of plantar forces utilizing various types of pressure platforms and in-shoe transducers allow further insight into the pressure distribution on the plantar aspect of the foot in gait. During the propulsive phase of gait, approximately 80 percent of the population demonstrate a peak plantar pressure either under the hallux, first metatarsal or 2nd metatarsal. Clinical correlations using these pressure measurements have been established with respect to various clinical problems. In the diabetic neuropathic foot, areas of ulceration correlate well with the areas demonstrating maximum vertical and shear forces. The weight-bearing pattern in these patients tends to shift from the medial to the lateral border of the forefoot, and the load taken by the toes is reduced.

The rheumatoid foot demonstrates findings similar to those of the neuropathic foot. After a hindfoot fusion, greater contact force at heel strike has been observed. This could be due to the inability of the calcaneus to move into a valgus position after heel strike. The alterations in weight bearing about the hallux have demonstrated that in hallux valgus there is decreased weight bearing of the first and second toes associated with an increased transfer of weight to the lateral metatarsals. Similar findings have been demonstrated after a Keller resection-type arthroplasty.

Although floor reactions are important in demonstrating the totality of the forces transmitted through the foot, they give little information concerning the movements of the various articulations of the foot and ankle or about the activity of the muscles controlling these movements. Continuous geometric recordings and electromyographic studies are required to indicate joint motion and phasic activity of the intrinsic and extrinsic muscles. From the moment of heel strike to the instant of toe-off, floor reactions, joint motions, and muscular actions change constantly. The walking cycle will be reviewed to reinforce your understanding.
WALKING CYCLE

The walking cycle consists of the stance phase and the swing phase of the same leg. The mean walking or gait cycle is based upon a mean time of 1 second. This is the mean time that it takes to travel forward from one heel strike to the same heel strike again. This walking or gait cycle begins at 0 percent and ends at 100 percent. The stance phase usually consumes about 62 percent of the cycle or 0.62 seconds, and the swing phase 38 percent of the cycle or 0.38 seconds. The stance phase is further divided into a period of initial double limb support (heel contact with toe off) from (0 percent to 12 percent) in which both feet are on the ground, followed by a period of single limb support from (12 percent to 50 percent) and a terminal or second period of double limb support (toe off with heel contact) from (50 percent to 62 percent), after which the swing phase begins.

The initiation of the walking cycle is heel strike which is 0 percent, being followed by foot flat which is observed by 7 percent of the cycle, opposite toe-off at 12 percent, heel rise beginning at 34 percent as the swing leg passes the stance foot, and opposite heel strike at 50 percent of the cycle.

In a patient with spasticity, the initial heel strike may be toe contact, and foot flat may not occur by 7 percent of the cycle. Heel rise may be premature if spasticity or a contracture is present, or delayed in the case of weakness of the gastrocnemius-soleus muscle group.

The walking cycle being one of continuous motion is difficult to describe in its entirety because so many events occur simultaneously. However, a reasonably accurate summary of the events can be presented if the stance phase is divided into three stages.

Stage One: Heel Strike to Flat Foot

Stage one occurs during approximately the first 15 percent of the walking cycle. The center of gravity of the body is decelerated by ground contact, then immediately accelerated upward to carry it over the extending lower extremity. The body's impact and shift of the center of gravity account for a vertical floor reaction that exceeds body weight by 15 percent to 25 percent. The ankle joint undergoes rapid plantar flexion until foot flat, at 7 percent of the cycle, after which dorsiflexion begins. The plantar flexion is under the control of the anterior compartment muscles, which undergo an eccentric contraction to prevent foot slap. The posterior calf muscles all are electrically silent, as are the intrinsic muscles in the sole of the foot. There is no muscular response in those muscles usually considered important in supporting the longitudinal arch of the foot.

At this time the foot is being loaded with the weight of the body, and flattening of the longitudinal arch occurs. Gait analysis during walking reveals rapid eversion of the calcaneus and flattening of the longitudinal arch as a result of the impact of the body weight. This flattening of the arch originates in the subtalar joint and reaches a maximum during this interval. The pronation that occurs at initial ground contact is a passive mechanism, and the amount of motion appears to depend entirely on the configuration of the articulating surfaces, their capsular attachments, and ligamentous support. No
significant muscle function appears to play a role in restricting this motion at initial ground contact.

Because of the relationship of the leg to the foot, which occurs through the subtalar joint, the eversion of the calcaneus is translated proximally into inward rotation that is transmitted across the ankle joint into the lower extremity. Distally this eversion theoretically unlocks the transverse tarsal joint. The main thrust of what occurs during the first interval is that of absorption and dissipation of the forces generated by the foot striking the ground.

**Stage Two: Flat Foot Just Prior to Heel Off**

Stage two, or the single leg support phase extends from 15 percent to 50 percent of the walking cycle. During this interval the center of gravity of the body passes over the weight-bearing leg at about 35 percent of the cycle, after which it commences to fall. Force plate recordings show that the foot is supporting less than actual body weight. The load on the foot may be as low as 70 percent to 80 percent of actual body weight.

The ankle joint is undergoing progressive dorsiflexion, reaching its peak at 40 percent of the walking cycle. This is when the force across the ankle joint has reached a maximum 4.5 times body weight. Heel rise begins at 34 percent of the gait cycle and precedes the onset of plantar flexion, which begins at 40 percent.

During stage two, important functional changes occur in both foot and leg, which are the results of muscular action. The triceps surae, peroneals, tibialis posterior, long toe flexors, and intrinsic muscles in the sole of the foot demonstrate electrical activity. The activity in the intrinsic muscles of the normal foot begin at 30 percent of the cycle, whereas in flatfoot activity they begin earlier at 15 percent of the cycle. The posterior calf musculature is functioning to control the forward movement of the tibia over the fixed foot, which permits the contralateral limb to increase its step length.

The mean linear distance from heel strike of one foot to heel strike of the same foot is approximately 39 inches; this is called the stride length. The linear distance from heel contact of one foot to heel contact of the opposite (contra lateral) foot is called the step length. Step lengths are not symmetrical and vary from side to side depending on structural and functional limb length differences.

Subtalar joint motion demonstrates progressive inversion in flatfoot at the beginning of this period, and in a normal foot at about 30 percent of the cycle. The inversion is brought about by multiple factors, and precisely which plays the greatest role is unclear. The factors occurring above the subtalar joint consist of the external rotation of the lower extremity brought about by the swinging contralateral limb, its transmittal to the stance limb as an external rotation torque, its transmittal across the ankle joint, and its translation by the subtalar joint into inversion. Inversion of the subtalar joint is passed distally into the foot, realigning the transverse tarsal articulation. The progressive inversion rearranges the skeletal components of the foot, which theoretically transforms
the flexible midfoot into a rigid structure. During this interval full body weight is not borne on the foot.

**Stage Three: Heel Off to Toe Off**

Heel off to toe off constitutes the last of the stance phase and extends from 40 percent to 62 percent of the walking cycle. Force plate recordings demonstrate an increase in the percentage of body weight as a result of the falling of the center of gravity at the beginning of this interval; the load on the foot again exceeds body weight by approximately 20 percent. The vertical floor reaction promptly falls to zero during this period as the body weight is being transferred to the opposite foot.

The ankle joint demonstrates rapid plantar flexion during this interval. The flexion is caused primarily by the concentric contraction of the posterior calf musculature, in particular the triceps surae. The plantar flexion leads to relative elongation of the extremity. Although full plantar flexion at the ankle joint occurs during this interval, electrical activity is observed only until 50 percent of the cycle, after which there is no longer electrical activity in the extrinsic muscles. The remainder of ankle joint plantar flexion occurs because of the transfer of weight from the stance leg to the contralateral limb.

The intrinsic muscles of the foot are active until toe-off. Although the intrinsic muscles help to stabilize the longitudinal arch, the main stabilizer is the plantar aponeurosis, which is said to function maximally during this period as the toes are brought into dorsiflexion and the plantar aponeurosis is wrapped around the metatarsal heads, forcing them into plantar flexion and; theoretically elevating the longitudinal arch. One would question at this point the long-term results of plantar fasciectomy if the theoretical function of the plantar fascia was as functionally important as proposed by many clinicians and anatomists.

The anterior crurals fire at the last 5 percent of the stance phase, probably to initiate dorsiflexion of the ankle joint immediately after toe-off. The subtalar joint continues to invert during this interval, reaching its maximum supinated position at toe-off; probably as the result of the limb above the foot externally rotating and the passage of this movement across the ankle and subtalar joints to help bring about supination. The supination, however, is enhanced by the obliquity of the ankle joint axis in accordance with the plantar aponeurosis, and oblique metatarsal break. The talonavicular joint also is stabilized during this period by the pressure brought to bear across this joint, by both body weight and the intrinsic force created by the plantar aponeurosis.

**MEASUREMENT OF FORCES ON THE PLANTAR FOOT SURFACES**

We clinically must be able to quantitate the pressures on the plantar surface of the foot and their relative locations. This is the main importance of such in-shoe transducers, which can aid us to evaluate patients with peripheral neuropathy in the hope that we can reduce peak plantar pressures while still keeping these individuals ambulatory.
All of the manufacturers of in-shoe transducers have varying designs that function on different principles. The emphasis in this article is not to explain the physics of each in-shoe system but to enable the clinician to evaluate the results of such examinations and their relevance to the neuropathic foot.

The System International (SI) unit of FORCE is the Newton (1 N is the force required to give a mass of 1 kg an acceleration of 1 m/s.) and the unit of pressure is the Pascal (1 Pa results from a force of 1N distributed over an area of 1 m². In many research articles values underneath the foot are measured in kilopascal (kPa) or megapascal (Mpa) ranges. While other studies utilize other units of pressure measurements like kg.cm², N.cm², or pounds per square inch. When comparing peak plantar measurements from one program to the next be aware of the variances in measurement units. The documentation of peak plantar pressures in the diabetic neuropathic patient could be performed routinely with in-shoe transducer systems in order to enhance the effectiveness of shoe and orthotic pressure reduction.

Materials used for pressure reduction and or redistribution that have proven to be effective are Plastazote™, Spenco™, PPT™ and Poron™. These materials can be used in combination or laminations, and in various thicknesses to redistribute peak pressures. The clinical importance of an in-shoe transducer system is the relative ease in which the documentation of pressure reduction can be performed pre and post shoe/orthotic intervention. This procedure could be performed with each shoe/orthotic modifications/fitting in order to see if your mechanical therapy is reducing the peaks as expected. When this protocol is instituted, individual variances can be adjusted for via the information from the in-shoe sensor

CONCLUSION

Human gait can be best analyzed visually, when the observer is clinically experienced. He or she cannot document peak plantar pressures unless there is some type of pressure analysis system, which is reliable and reproducible.

Force plates are the gold standard for force analysis and can document the pressure either bare foot or from the sole of the shoe. In-shoe systems are clinically superior for the documentation of mechanical shoe/orthotic therapy because multiple steps can be averaged to identify the location and quantity of the peak pressure with and without shoes and orthoses. Therapy can be individually fine-tuned to maximize the reduction of peak plantar pressures.

We must continue to tactfully reinforce the fact to the diabetic neuropathic patient that his or her condition will not go away. Diabetic patients must help us care for their feet by daily inspection and routine office checkups.

*Plastazote(R) is a registered trademark of Zoteforms, Inc.*
Questions

1. The theory in which the unremitting tension of static stance results in deformity is most commonly associated with symptoms in which structures?
   A. plantar fascia and spring ligament
   B. sinus tarsi and cervical ligament
   C. tibialis anterior and posterior
   D. peroneus longus and brevis

2. Which anatomical structure participates as the adaptor, compensator and regulator of gait in relation to the ground?
   A. the spine
   B. the quadriceps muscles
   C. the triceps surae
   D. the foot

3. Which one of the following is NOT a cause of individual locomotion characteristics?
   A. length and mass of body segments
   B. position of joint axes'
   C. minor variations in lever arms
   D. evolutionary atavistic traits

4. An efficient locomotor system results from?
   A. the morphology of the foot
   B. average morphology of the foot
   C. functional interrelationships
   D. descriptive anatomy

5. Vertical body displacement is lowest during which phase of the gait cycle?
   A. swing
   B. double support
   C. single support
   D. heel off
6. All of the following contribute to the smoothing out of the deceleration of center of gravity during gait except for?

A. knee flexion  
B. knee extension  
C. ankle plantarflexion  
D. foot pronation

7. In gait the tibias rotate internally about their long axes during?

A. heel off  
B. propulsion  
C. toe off  
D. swing

8. With each complete stride, a total lateral displacement of the body occurs which is approximately?

A. 4 to 5 cm  
B. 4 to 5 inches  
C. 4 to 5 mm  
D. 4 to 5 m

9. The mean adult tibiofemoral angle is?

A. 2-70 varus  
B. 6-100 varus  
C. 6-120 valgus  
D. 12-150 valgus

10. The initial spike in the vertical force curve of the gait cycle is?

A. 20% to 30% greater than body weight  
B. the reaction of the heel against the ground  
C. is followed by an increase in which the weight against the ground is 20% more than body weight  
D. is caused by the downward acceleration of the body's center of gravity

11. Fore shear occurs during which phase of the gait cycle?

A. mid stance  
B. toe off
C. heel contact  
D. heel off  

12. The center of pressure dwells about half of the stance phase with in what part of the foot?.

A. the heel area  
B. the hallux area  
C. the mid foot area  
D. the metatarsal area  

13. During the propulsive phase of gait the mean location of peak plantar pressure is?

A. beneath the hallux  
B. beneath the 2nd metatarsal  
C. beneath the 1st metatarsal  
D. all of the above  

14. An individual with hallux valgus will most probably demonstrate what type of weight bearing alteration during gait?

A. increased weight under the 1st and 2nd toes  
B. decreased weight under the 1st and 2nd toes  
C. increased weight on heel contact  
D. decreased weight on heel contact  

15. The most important reason to use in-shoe sensors as a screening tool for the diabetic neuropathic patient is?

A. to help cure the neuropathy  
B. to make foot orthoses without plaster castings  
C. to regulate the blood glucose level  
D. to quantitate the peak plantar pressures  

16. The plantar fascia is wrapped around which structures?

A. The cuboid  
B. The navicular  
C. The calcaneus  
D. The metatarsals  

17. The System International (SI) unit of Force is?
A. The Pascal  
B. The Newton  
C. The Kilogram  
D. The Pound

18. Which one of the following materials would not be a good choice for pressure reduction in the neuropathic diabetic foot?

A. Stainless steel  
B. Plastazote  
C. Poron  
D. PPT

19. The goal in shoe/orthotic therapy and modification for the neuropathic diabetic patient is?

A. To increase peak plantar pressures on the forefoot  
B. To increase peak plantar pressures under the hallux  
C. To decrease peak plantar pressures under at risk locations  
D. To decrease peak plantar on the heel

20. The most important aspect of neuropathic diabetic care would be?

A. By pass surgery  
B. Daily inspection of feet and routine foot check ups  
C. Elective foot surgery  
D. Deep muscle massage

References


