

Dynamic Biomechanics of the Normal Foot and Ankle During Walking and Running

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This article presents an overview of dynamic biomechanics of the asymptomatic foot and ankle that occur during walking and running. Functional descriptions for walking are provided along with a review of quantitative findings from biomechanical analyses. Foot and ankle kinematics and kinetics during running are then presented, starting with a general description that is followed by more specific current research information. An understanding of the dynamic characteristics of the symptom-free foot and ankle during the most common forms of upright locomotion provides the necessary basis for objective evaluation of movement dysfunction.

Key Words: *Ankle; Foot; Kinesiology/biomechanics, gait analysis; Kinetics; Lower extremity, ankle and foot.*

The foot and ankle, by virtue of their location, form a dynamic link between the body and the ground. The foot and ankle are basic to all upright locomotion performed by the human, constantly adjusting to enable a harmonious coupling between the body and the environment for successful movement. The dynamic characteristics of the foot and ankle have been inferred traditionally from cadaveric examination and qualitative clinical assessment. Advancements in biomechanical techniques for dynamic analysis have enabled more quantitative and accurate documentation of foot and ankle function during movement, especially during the process of walking.

The objective of this article is to provide a selected review of quantitative information relevant to the dynamic function of the foot and ankle complex. Although results have often confirmed traditional anatomical assumptions regarding foot and ankle function, they have also contradicted long-accepted theories in certain cases.

The most frequently performed movements of the foot and ankle for healthy people occur during walking. Much research has been conducted in the analysis of walking, and the majority of this article will concentrate on the dynamic biomechanics of the foot and ankle during this activity. A classical description of the biomechanics of gait

as found in clinical literature is followed by an overview of quantitative findings that document kinematic and kinetic characteristics during walking. As interest in physical fitness continues to grow, therapists are treating an increasing number of runners, both recreational and competitive. The foot and ankle kinematics and kinetics that occur during running will be presented briefly in the final section. This review includes information relevant to symptom-free individuals.

FOOT AND ANKLE KINEMATICS DURING WALKING

Although the foot has been viewed traditionally as a static tripod or a semirigid support for body weight (BW), it has evolved primarily for walking and is therefore a dynamic mechanism. The body requires a flexible foot to accommodate the variations in the external environment, a semirigid foot that can act as a spring and lever arm for the push off during gait, and a rigid foot to enable BW to be carried with adequate stability. The dynamic biomechanics of the foot and ankle complex that allow successful performance of all these requirements can only be understood when studied in relation to the biomechanics of the lower limb during walking.

The gait cycle (or stride period) provides a standardized frame of reference for the various events that occur during walking (Fig. 1). The *gait cycle* is the period of time for two steps and is measured from initial contact of one foot to

the next initial contact of the same foot. The gait cycle consists of two phases: 1) stance (when the foot is in contact with the supporting surface) and 2) swing (when the limb is swinging forward, out of contact with the supporting surface). Along with providing forward momentum of the leg, the swing phase also prepares and aligns the foot for heel-strike and ensures that the swinging foot clears the floor. Stance comprises about 60% of the total gait cycle at freely chosen speeds and functions to allow weight-bearing and provide body stability. Five distinct events occur during the stance phase: heel-strike (HS), foot flat (FF), mid-stance (MS), heel rise (HR), and toe-off (TO).

General Description

An understanding of the various joint axes of the foot and ankle (see articles by Riegger and Oatis in this issue) is essential to the discussion that follows. Figure 1 summarizes these joint motions as they relate to different phases of gait. Numerous authors have contributed to a clinical description of walking kinematics based primarily on observation.¹⁻⁷ To understand the movements of the foot and ankle during walking, other portions of the lower extremity must be included.¹ During walking, rotation of the pelvis causes the femur, fibula, and tibia to rotate about the long axis of the limb.² The magnitude of this rotational motion increases progressively from pelvis to tibia. For example, during normal walking on level ground, the pelvis undergoes a maximum rota-

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One Gait Cycle

Limb Component

	%	Events	Lower Limb	Ankle Joint	Subtalar Joint	Transverse Tarsal Joint
Stance Phase	0	heel-strike	medial rotation	plantar flexion	pronation	free motion
	20	foot flat	lateral rotation	dorsiflexion	supination	increasingly restricted
	40	mid-stance				
	60	heel rise	plantar flexion			
Swing Phase	80	toe-off	medial rotation	dorsiflexion	pronation	free motion
	100	heel-strike				

Fig. 1. Summary of phases of gait cycle and accompanying motions of lower limb joints. (Adapted from Mann.⁶)

tion in each gait cycle of about 6 degrees, and the tibia undergoes a rotation of about 18 degrees in the same period. Generally, the limb rotates medially (internally) during the swing phase and early stance phase and then laterally (externally) until the stance phase is complete and TO has occurred.³

At HS, the tibia is rotated medially about 5 degrees from its neutral position, and the ankle joint is either in its neutral position or in slight plantar flexion.⁴ According to Perry, compression of the heel pad occurs at HS and is followed by traction on both anterior and posterior calcaneal attachments during terminal stance.⁵ Immediately following HS, the foot flexes toward the floor, with the dorsiflexors controlling this plantar motion to prevent the foot from slapping down to the FF position. From HS to just before FF, the increasing medial rotation of the tibia and fibula is transmitted through the ankle mortise to the talus.⁶ The medial rotation of the mortise, combined with the plantar-flexed position of the ankle, tends to shift the forefoot medially from its neutral, toe-out position. The heel contact with the ground is lateral to the center of the ankle joint where BW is transmitted to the talus, creating a pronatory moment at the subtalar joint that, in turn, stresses the structures of the medial arch. The talus rotates me-

dially on the calcaneus about the subtalar axis forcing the calcaneus into pronation. According to Wright and associates, the foot quickly pronates, about 10 degrees within the first 8% of stance at an average walking speed.⁷ In this pronated position, free motion is available at the transverse tarsal joint so that the foot remains flexible, distal to the navicular and cuboid, and can bend into close contact with the supporting surface.

At the FF position, the lower limb begins to rotate laterally. Because the forefoot is now fixed on the ground, the entire lateral rotation of the ankle mortise is transmitted to the talus. As lateral rotation continues, the foot supinates, increasing stability at the transverse tarsal joint and along the longitudinal arch of the foot. The stability of the transverse tarsal joint is further improved by the increasing body load being carried and by the firm fit of the convex head of the talus into the concave face of the navicular bone.^{1,3,6}

When the leg has passed over the foot, the ankle begins dorsiflexion. After HR, the ankle joint moves back into plantar flexion forcing the metatarsophalangeal joints to dorsiflex. Because the plantar aponeurosis wraps around the metatarsal heads, a "windlass" effect takes place that increases tension across the longitudinal arch, further elevating the arch

and increasing foot stability. Just before TO, the combination of weight-bearing, windlass effect, and supination ensures that the foot is in a maximally stable position for lift-off. After TO, some authors report that the leg rotates medially, again pronating the foot and unlocking the transverse tarsal joint so that the foot returns to its flexible state for the swing phase of gait.^{1,3,6} It should be noted that other authors report that the leg continues to be in lateral rotation throughout mid-swing and that the foot remains supinated throughout swing.²

Kinematic Studies

Kinematics refers to the description of motion, independent of the forces that cause the movement to take place. Linear and angular displacements, velocities, accelerations, center of rotation for joints, and joint angles are all examples of kinematics.⁸ Kinematic information can be collected using direct measurement techniques (ie, goniometers, accelerometers) and with indirect measurement using imaging techniques (ie, cinematography, high-speed video, stroboscopy). Each technique has advantages and disadvantages that have been described by several authors and will not be detailed in this discussion.^{9,10} Instead, the results of selected studies relevant to dynamic biomechanics of the foot and ankle during walking and running will be presented.

Walking cadence and velocity. Many factors affect foot and ankle biomechanics during walking, including the velocity of gait and anthropometric characteristics (ie, limb length). Winter defines *natural cadence*, or *free cadence*, as the number of steps per minute when a subject walks as naturally as possible and reports an average natural cadence range of 101 to 122 steps/min.¹¹ In general, the natural cadence for women is 6 to 9 steps/min higher than that of men. Foot and ankle kinematic measurements also are directly related to the walking velocity. Studies have documented the changes that occur with increasing speed.^{12,13} For this reason, walking velocity must be considered when comparing biomechanical findings.

Displacements—paths of movement. Motion of the heel in walking has been reported by Winter in a study with 14 subjects walking at their natural cadences.¹¹ Vertical displacement of the heel begins well before TO and reaches maximum upward velocity just before

TO. The heel reaches its highest displacement shortly after TO. Horizontal velocity increases gradually after HR, reaching its maximum late in the swing phase, and then rapidly decreases just before HS. Vertical velocity of the heel slows abruptly at about 1 cm above ground level, after which the heel is lowered very gently to the ground.

The path of the forefoot differs from that of the heel. For the same sample of 14 subjects, Winter reports an initial rise in the forefoot during late push-off and early swing.¹¹ As the leg and foot are swung forward, the forefoot just clears the ground and then rises to a second peak just before HS. Because the toe is the last part of the foot to leave the ground, and because of the accompanying leg and foot angles, the toe rises to no more than 2.5 cm above the ground and then drops to only 0.87 cm of clearance at mid-swing. As the knee extends and foot dorsiflexes, the toe rises to a maximum of 13 cm just before HS.

Ankle range of motion, foot placement, and arch movement. Ankle-joint angles, foot-placement angles, and arch movement are other kinematic characteristics that have been investigated. Winter reported mean ankle-joint ranges of motion during walking for 19 subjects as a maximum of 9.6 degrees of dorsiflexion and 19.8 degrees of plantar flexion.¹¹ Murray and associates found that foot-placement angle showed high variability on successive steps of the same foot.¹⁴ A mean value of 6.8 degrees of foot abduction (out-toing) was reported, with the average difference between successive foot angles being 2.4 degrees.

Dynamic arch movement was studied by Kayano using an "electro arch gauge."¹⁵ He found that the medial longitudinal arch lengthens from the vertical force of BW from early stance to FF. It then shortens with the decrease in BW and activation of the arch supporting muscles. As the calf muscles activate for push-off, the arch lengthens again. It finally shortens rapidly because of the windlass action of the plantar aponeurosis as the toes dorsiflex for TO.

FOOT AND ANKLE KINETICS DURING WALKING

General Description

Kinetics is the study of the forces that cause movement, both medially (muscle activity, ligaments, friction in muscles and joints) and laterally (from the ground, active bodies, passive bodies).⁸

A large number of researchers have analyzed muscular activity and ground reaction forces (GRFs) during gait. Joint moments, segmental energy, joint reaction, and pressure distribution beneath the foot during walking have received less attention. The findings from electromyographic studies of the foot and ankle muscles during walking will be presented in the first subsection, followed by findings from force-plate and pressure-distribution studies. Calculated kinetic variables, such as ankle-joint moments and joint reaction forces, will be included in the final subsection.

Electromyographic studies of foot and ankle muscles during walking. Many researchers have investigated the electrical activity of muscles during walking, and Basmajian and Deluca have presented a

review of their findings.¹⁶ In general, studies have shown that many of the changes in levels of muscular activity occur at 15% to 20% of the gait cycle (FF), when the foot adapts to the supporting surface.

Winter and Yack have contributed extensively to the literature on EMG during walking.¹⁷ Specific EMG patterns for several of the foot and ankle muscle groups that are active during walking are shown in Figure 2. The tibialis anterior muscle (TA) has its major activity at the end of swing to keep the foot in a dorsiflexed position. Immediately after HS, the TA peaks and generates forces to lower the foot to the ground in opposition to the plantar-flexing GRFs. The TA is the only inverting muscle active during the period

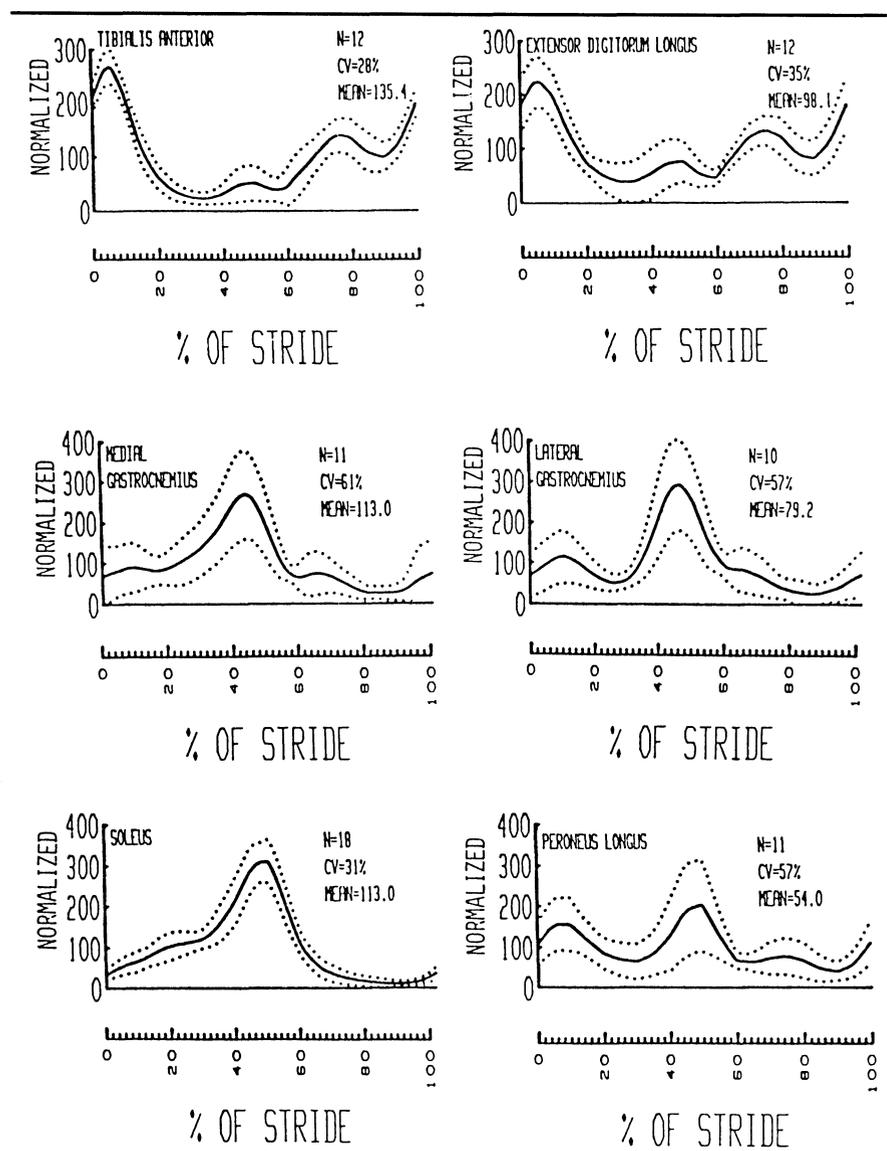


Fig. 2. Electromyographic activity (normalized to each subject's mean EMG) for six muscles during walking. Plots show mean EMG (solid line) and one standard deviation (dotted lines) for samples of varying size. Activity of medial and lateral gastrocnemius muscles is very similar and is combined for discussion in text. (Reprinted with permission.¹⁷)

of maximum eversion stress, when BW is completely on the heel. In some individuals, the TA plays a minor role in pulling the leg forward over the foot shortly after FF. A second burst of activity commences at TO and results in dorsiflexion for foot clearance during mid-swing.

The extensor digitorum longus muscle (EDL) has almost identical activity to the TA. It functions to lower the foot after HS and to dorsiflex the foot and toes for clearance during swing. A minor third phase occurs during push-off and appears to be a co-contraction to stabilize the ankle joint.¹⁷

The gastrocnemius muscle (GA) and soleus muscle (SO) exhibit one major long-duration phase of activity throughout the single-limb support period. It begins just before HS and rises during stance, reaching peak just before mid-push-off (50% of stride). From FF to 40% of stride, the muscles lengthen as the leg rotates forward about the ankle under its control. During push-off, the calf muscles shorten to actively plantar flex the foot and to generate an explosive push-off (estimated at 250% of BW in tension). Activity rapidly drops until TO where low-level GA activity continues

into swing, probably showing the GA acting as a knee flexor to cause adequate knee flexion before swing-through.¹⁷

The peroneus longus muscle (PL) has a small burst of activity during weight acceptance (10% of stride), which appears to stabilize the ankle (possibly as a co-contraction to the TA). A larger burst during push-off (50% of stride) shows the PL acting as a plantar flexor. Low-level PL activity during early swing is likely a co-contraction to the TA to control the amount of foot dorsiflexion and supination.¹⁷

Other investigators have reported their findings of intrinsic muscle activity in the foot during walking.^{18,19} The group of intrinsic muscles covered by the plantar fascia (flexor digitorum brevis, abductor hallucis, and abductor digiti minimi muscles) were shown to be active at 35% of the gait cycle. This part of the gait cycle includes the onset of HR, the concentration of BW on the forefoot, and the beginning of foot re-supination.

Force-plate studies. Force platforms are commonly found in gait laboratories, and GRFs are one of the most commonly measured biomechanical variables. The GRFs show the magni-

tude and direction of loading directly applied to the foot and ankle structures during locomotion. Because the foot and ankle are the first parts of the body involved in contact with the ground during walking, they must be able to withstand and transmit these GRFs. The GRF data also provide information necessary for the calculation of ankle-joint reaction forces, which will be discussed later.

Figure 3 shows a graph of typical vertical GRFs during walking. The magnitude of vertical GRFs has been reported to range from 1.1 to 1.3 times BW, depending on walking speed.²⁰ Footwear has been shown to attenuate the peak vertical GRF values.²⁰ A rapid loading rate, often seen in vertical GRFs during the first 25 msec after contact, has been described as a possible contributing factor in joint degeneration.²¹

The force plate provides only one instantaneous measure of force distribution. This measure is called the center of pressure (COP), and it identifies the geometric centroid of the applied force distribution.⁸ The path of the COP is created by plotting the instantaneous COP at regular time intervals during the entire stance phase of gait (Fig. 3). Studies of the COP show a normal progression of the path from just slightly lateral to the midline of the heel, along the midline of the foot, up to the metatarsal heads.^{20,22} At this point, medial migration occurs so that by TO the COP lies under the first or second toe. This medial migration aspect of the COP path has been described as the most variable among subjects. The COP path is altered by different footwear, as illustrated by the findings of Katoh and associates (Fig. 4).²²

Pressure-distribution studies. Force-plate systems are limited in the analysis of foot movement because the force information is not specific to foot anatomical locations. For example, the forces recorded may occur underneath both the fore and rear parts of the foot simultaneously so that the COP may fall at some intermediate point, which may not actually be loaded. Pressure-distribution devices provide the specific location of pressures as they occur beneath the moving foot. Recent studies in pressure distribution have revealed new information regarding dynamic foot function during walking.²³⁻²⁷

Although a great deal of individual variability exists in foot pressures during walking, the usual location of peak pressure is beneath the heel. A comparison of mean regional peak pressures found

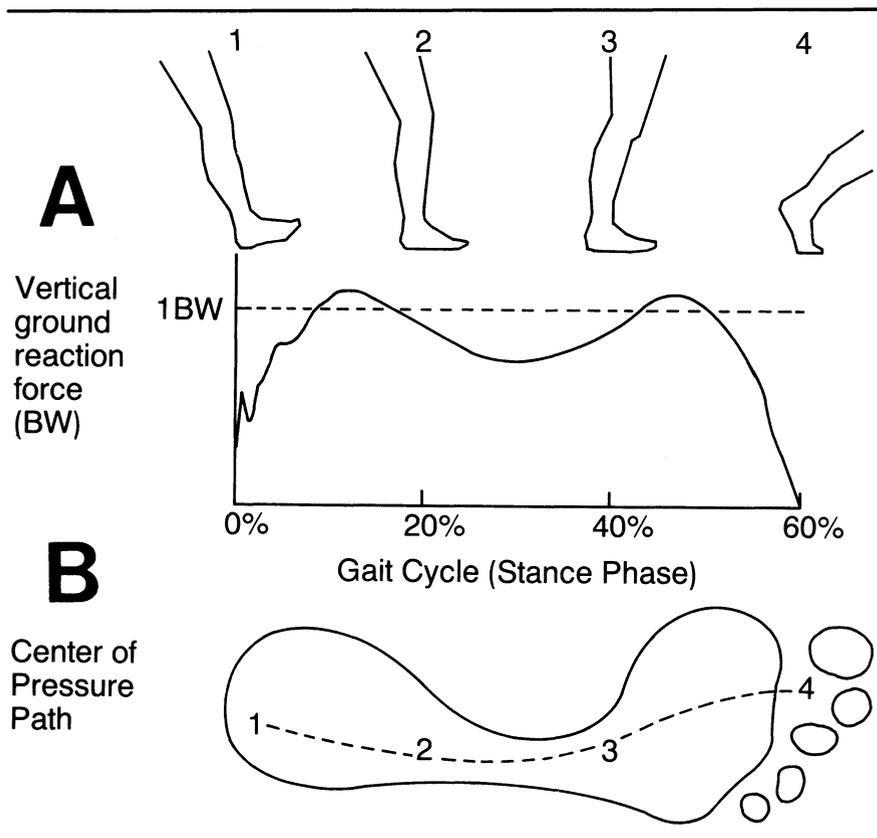


Fig. 3. Ground reaction forces (GRFs) beneath foot during walking: (A) Graph of classic vertical GRF during stance phase of gait cycle (BW = body weight; 1 = heel-strike; 2 = foot flat; 3 = midstance; 4 = toe-off); (B) path of the center of pressure, which represents series of instantaneous centroids of GRF during walking.

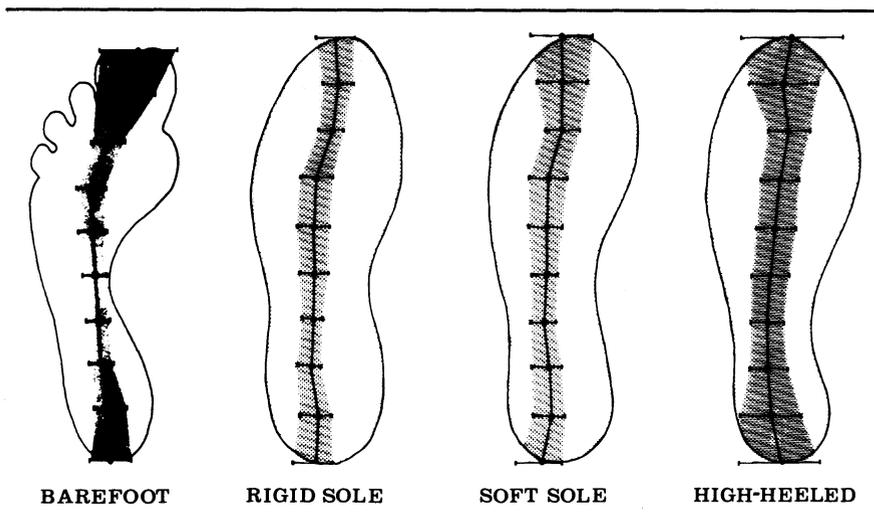


Fig. 4. Mean and one standard deviation for center-of-pressure paths during normal walking in different foot conditions: barefoot and wearing rigid-soled, soft-soled, and high-heeled shoes. (Reprinted with permission.²²)

TABLE
Comparison of Mean Regional Peak Pressures (in Kilopascals) from Pressure-Distribution Studies

Region	Rodgers ²³	Soames ^a	Grieve and Rashdi ^b	Betts et al ^c	Clarke ²⁴
Hallux	219	400	178	432	...
Medial toes	180	300	378
Lateral toes	163	200	160
First metatarsal	245	520	163	353	319
Second metatarsal	336	510	212	392	319
Lateral metatarsals	312	550	151	281	324
Medial midfoot	60	...	68	...	43
Lateral midfoot	103	150	6	...	95
Medial heel	337	780	208	363	443
Lateral heel	333	450	208	363	391

^a Soames RW: Foot pressure patterns during gait. *J Biomed Eng* 7:120-126, 1985.

^b Grieve DW, Rashdi T: Pressures under normal feet in standing and walking as measured by foil pedobarography. *Ann Rheum Dis* 43:816-818, 1984.

^c Betts RP, Franks CI, Duckworth T: Analysis of loads under the foot: Part 2. Quantification of the dynamic distribution. *Clinical Physics and Physiological Measurement* 1(2):113-124, 1980.

by several different investigators is shown in the Table. Differences in values reported result from the variety of techniques and subject samples used by investigators.²³ These pressure-distribution studies have shown that all metatarsal heads are loaded during the stance phase of gait. This finding negates the concept of tripod stance, which would not allow pressure beneath the middle metatarsal heads.

Many variables have been identified that directly influence pressure distribution beneath the foot. Clarke found that with increasing speed, pressures increase and shift medially.²⁴ The toes contribute more as the walking speed increases. Walking barefoot alters both kinetic and kinematic variables when

compared with walking in shoes.²⁰ Structural characteristics of the foot, such as arch type, also affect pressure distribution.²⁵ As shown in Figure 5, the more rigid high-arched foot tends to concentrate pressure beneath the heel and forefoot, with minimal pressure beneath the midfoot. This absence of midfoot pressure is present even in the higher loading conditions that occur with increasing speed of locomotion. The flexible flat-arched foot shows more spreading of pressure, including the area beneath the midfoot.

The classic Morton's foot structure, characterized by a second metatarsal head that is placed more distally than the first, has also been shown to influence pressure distribution. Rodgers and

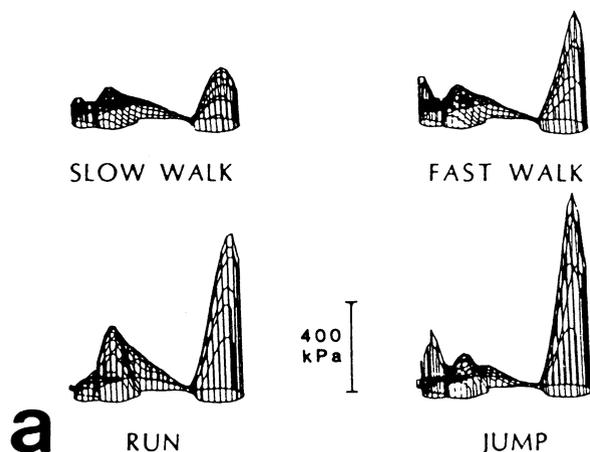
Cavanagh reported that second metatarsal head pressures were significantly higher in subjects with Morton's foot when compared with control subjects without Morton's foot.²⁶ This finding suggests that individuals with a Morton's foot structure may be more prone to second metatarsal pressure problems than individuals with other foot structures. Pressure-distribution studies have also been useful in identifying areas of concentrated pressure that may lead to pressure ulcers for individuals with insensitive feet.²⁷

Joint moments and joint reaction forces. Indirect methods have been used to calculate gait kinetics when direct methods are not feasible. These methods are necessary to calculate forces within the joint because force transducers currently cannot be used safely in subjects. Winter^{9,11} and Winter and Robertson²⁸ have made significant contributions in the calculation of joint moments of force and energy patterns during walking. The mean maximum ankle-joint moment (normalized to body mass) generated during walking was found to be a plantar moment of 1.6 N·m/kg, occurring between 40% and 60% of the gait cycle. Plantar flexors were found to absorb energy during the early stance and MS phases of the gait cycle as the leg rotates over the foot. Late in stance, these same muscles plantar flex rapidly (producing the plantar moment) and generate an explosive burst of energy (push-off).

As mentioned in the section on force-plate studies, the GRFs during gait are transmitted proximally to the rest of the body through the foot and ankle, compressing each joint along the way. These compressive forces have been shown to contribute to the formation of osteoarthritis.^{21,29} Joint reaction studies of the ankle have been few, probably because this joint demonstrates osteoarthritic changes less often than the hip and knee joints. Stauffer and co-workers have shown ankle-joint compressive forces of about 3 times BW from HS to FF.³⁰ A further rise to a peak value of 4.5 to 5.5 times BW occurs during heel-off when the plantar flexors are undergoing strong contraction. Seireg and Arvikar have derived maximal ankle-joint reaction forces of 5.2 times BW from mathematical models.³¹ Procter and Paul found a peak of 3.9 times BW for ankle-joint reaction force during walking.³²

Stauffer and associates also reported ankle shear forces of 0.6 times BW in a posterior direction.³⁰ After HR, talo-

PEAK PRESSURE - HIGH ARCH DURING 4 ACTIVITIES



PEAK PRESSURE - FLAT ARCH DURING 4 ACTIVITIES

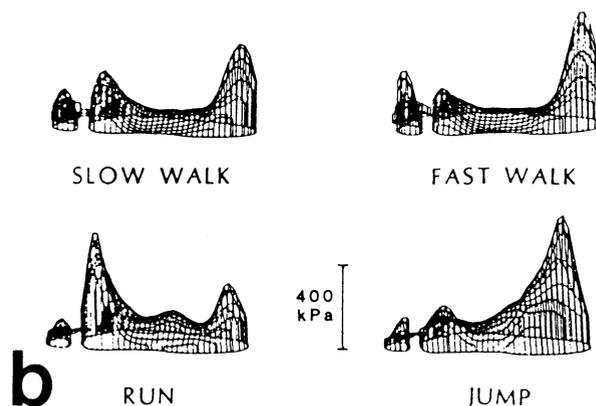


Fig. 5. Pressure-distribution patterns during slow and fast walking, running, and landing from a jump beneath a high-arched (a) and a flat-arched (b) foot. The flat-arched foot shows more spreading of pressure beneath the midfoot region. (Reprinted with permission of Martinus Nijhoff/Dr W Junk Publishers.²⁵)

crural shear was anterior and reduced to less than half of the previous posterior forces. Subtalar-joint reaction forces have been calculated by Seireg and Arvikar.³¹ The peak resultant force in the anterior facet of the talocalcaneonavicular joint was 2.4 times BW and for the posterior facet, 2.8 times BW. Peaks for both locations occurred in the late stance phase of the gait cycle.

FOOT AND ANKLE KINEMATICS DURING RUNNING

A considerable amount of research has been conducted in the area of running biomechanics and is presented in a detailed review by Williams.³³ The position of other body parts and the timing of their movements are basic to an understanding of the motion of the foot and ankle. Although other body parts (primarily the hip and knee) have received most of the attention, several investigators have contributed to a functional description specific to foot and ankle motions during running at moderate speeds.^{34,35}

General Description

For the running gait in which HS occurs, initial contact is at the lateral heel with the foot slightly supinated.^{34,35} This position results from swinging of the leg toward the line of progression.

Slight plantar flexion of the subtalar joint occurs along with supination of the forefoot and calcaneus. The subtalar joint passes from a supinated to a pronated position between HS and 20% into the support phase. The foot remains pronated between 55% and 85% of the support phase. Maximum pronation occurs between 35% and 40% of support phase, approximately the time when total-body center of gravity passes over the base of support. Full pronation marks the end of the absorbing and braking period of support as the foot begins its propulsive period. Maximum ankle dorsiflexion occurs 50% to 55% into the support phase when the center of gravity is forward of the support leg. The foot begins to supinate and returns to the neutral position at 70% to 90% of the support phase. The foot then assumes a supinated position for push-off.^{34,35}

Kinematic Studies

Several stride variables that directly affect running kinematics and kinetics have been described by Cavanagh.³⁶ These variables include stride length at different speeds, optimal stride length, timing of the phases of running gait, and foot placement. Timing of the biomechanical events in running is variable because it depends on running speed, type of shoe, and individual anatomic variations. For example, Kaelin et al reported the interindividual (N = 70)

and intraindividual variabilities (20 repetitions each for 6 of the subjects) for several variables during running.³⁷ The maximum pronation angle during foot-ground contact showed a range of 20 degrees among the subjects, but only 7 to 12 degrees within the same individual. Vertical touchdown velocity of the foot during running varied between 0.64 and 2.3 m/sec among the subjects. Scranton and associates reported an average duration of the support phase for jogging of 0.2 sec and for sprinting of 0.1 sec.³⁸

Clinical evaluations have suggested a relationship between pronation of the foot during running and a variety of lower extremity problems such as shin splints and knee pain. Currently, quantitative data do not support the relationship, although this finding may result from inadequate analytical techniques. For example, studies of rear-foot motion have been conducted in two dimensions, although pronation occurs in more than one plane. Clarke and associates have reviewed several different studies of rear-foot movement in running (Fig. 6).³⁹ They reported an average maximum pronation angle of 9.4 degrees over all studies. The authors suggest that a maximum pronation angle of 13 degrees and total rear-foot motion greater than 19 degrees during running would be considered excessive. Currently, however, no single variable reliably predicts safe rear-foot movement during running.

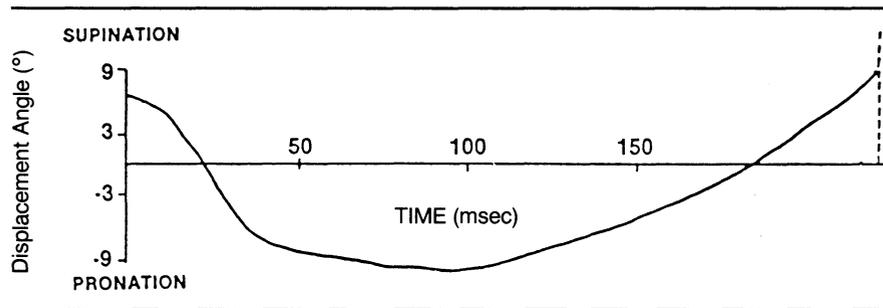


Fig. 6. Curve showing average rear-foot angular displacement during support phase of running based on rear-foot motion studies conducted by various researchers. The foot remains pronated for the majority of the support phase. (Adapted from Clarke TE, Frederick EC, Hamill CL: The study of rearfoot movement in running. In Frederick EC (ed): *Sport Shoes and Playing Surfaces: Biomechanical Properties*. Champaign, IL, Human Kinetics Publishers Inc, 1984, p 180.)

FOOT AND ANKLE KINETICS DURING RUNNING

General Description

Direct measurement of running kinetics poses more difficult technical problems than during the slower speeds of walking gait. Targeting a force plate is more difficult at higher speeds without altering the normal running gait patterns. The faster motion requires more distance for running, and longer cables or telemetry systems therefore must be used for EMG data collection. Treadmill running has been used for EMG data collection, although the pattern of running is different from that seen over natural terrain or on a track. Because of these problems, few researchers have directly measured foot and ankle muscle activity.³³ More research has been conducted in GRFs and pressure distribution during running. Indirect calculations of foot and ankle muscle forces, segmental moments, and joint reaction forces during running have been performed by a few researchers.

Electromyographic studies of foot and ankle muscles during running. Studies have shown that EMG activity increases with running as compared with walking. Miyashita and associates have reported that integrated EMG (IEMG) activity of the TA and GA increases exponentially with increasing speed.⁴⁰ Ito et al report that with increasing running speed, the IEMG increased during swing but remained the same during the support phase.⁴¹

Force-plate studies. Several authors have suggested a link between common running injuries and the impact forces at foot-strike that can occur thousands of times during running.^{34,42} Force-plate analysis has shown that peak loading force during running is more than twice that of walking and occurs at least twice

as fast. Perry extrapolates that the forces imposed on the supporting tissues would reflect a fourfold increase in strain.⁵ Because microtrauma is cumulative, running creates symptoms that do not arise with ordinary walking.

Force-plate data for jogging and running are much more variable from step to step when compared with walking. The pattern and magnitude of the vertical GRFs during running also differ significantly from those that occur during walking. Variables that affect vertical GRF data include touchdown velocity of the heel, position of the foot and lower leg before contact, and movement of these structures during impact.⁴³ The vertical GRF curve for heel-toe running ("heel strikers") usually shows two distinct peaks: 1) the impact force peak and 2) the active force peak.^{44,45} Typical peak vertical GRF values for distance running speeds are 2.5 to 3.0 times BW.

The pattern of force is dependent on the orientation of the foot at initial contact, which is determined by whether the runner is a "forefoot striker," a "midfoot striker," or a "rear-foot striker."⁴⁴ Most runners initially contact the ground with the outside border of the shoe, some with the rear lateral border (rear-foot strikers), and some with the middle lateral border (midfoot strikers). Harrison and associates report that mean foot contact time is reduced in forefoot strikers as compared with rear-foot strikers (0.20 vs 0.19 seconds, respectively).⁴⁶ Cavanagh and LaFortune also found slightly shorter contact times for the midfoot strikers compared with the rear-foot strikers.⁴⁴

Additional differences in GRF patterns have been described.⁴⁴ Rear-foot strikers demonstrate a sharp initial spike in vertical GRF that is generally absent from the midfoot-striker patterns. Midfoot strikers produced two positive

peaks in the anteroposterior force during the braking phase. The mean peak-to-peak amplitude for mediolateral (ML) GRF was three times greater in the midfoot strikers than that for the rear-foot strikers (0.35 and 0.12 BW, respectively). These findings indicate that the loading rates within the muscle and joints are affected by the type of initial foot contact during running.

The path of the COP also depends on the type of initial foot contact during running (Fig. 7). Cavanagh and LaFortune found that the COP path for rear-foot strikers followed from the rear lateral border to the midline within 15 msec of contact.⁴⁴ The COP path then continued along the midline to the center of the forefoot where it remained for almost two thirds of the entire 200-msec support phase. Midfoot strikers running at the same running speed made initial contact at 50% of shoe length. The COP path then migrated posteriorly as the rear part of the shoe made contact with the ground. This posterior movement coincided with a drop in the AP GRF. When the end of posterior migration was reached, the COP rapidly moved to the forefoot where it remained for most of the support phase.

Pressure-distribution studies. Very little information is available regarding pressure distribution under the foot during running. Pressure patterns during running vary with foot type (Fig. 5). The increased loading that occurs with running remains concentrated under the heel and forefoot in the more rigid high-arched foot. In the more flexible flat-arched foot, the increased load is spread beneath the entire foot, including the midfoot region.²⁵ Cavanagh and Hennig found that the average peak pressure during the contact phase of running (868.0 kPa) occurred under the heel for a sample of 10 rear-foot strikers.⁴⁷ Although pressures were much higher beneath the heel of these rear-foot strikers, more of the contact time was spent on the forefoot.

Muscle forces, segmental impulse, and joint reaction forces. Several investigators have developed mathematical models to predict muscle forces during running. Forces generated by the dorsiflexors and the GA have been calculated by Harrison and associates.⁴⁶ They report peak forces in the dorsiflexors of 0.5 times BW, which are active only during the first 10% of the stance phase. The GA generated a substantially greater peak force of 7.5 times BW. Calculations by Burdett revealed that the

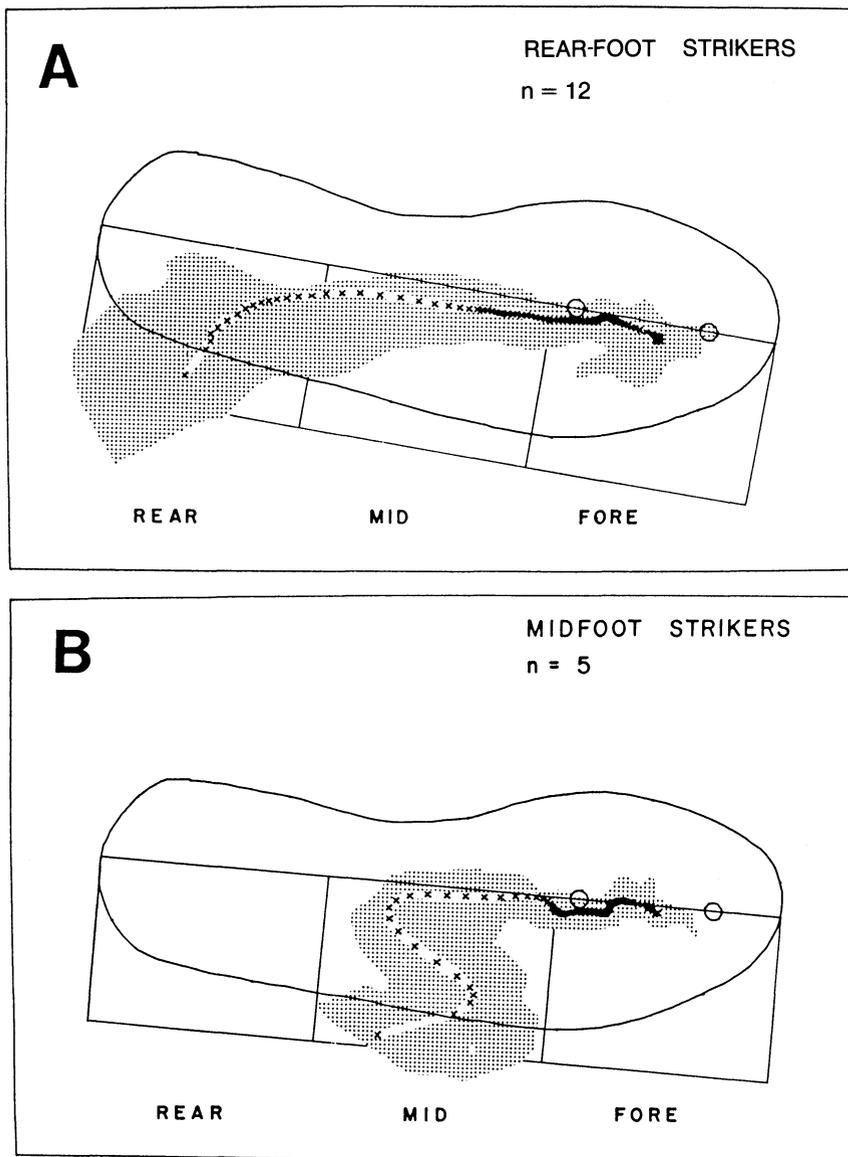


Fig. 7. Comparison of center-of-pressure paths during running for rear-foot (A) and midfoot (B) strikers. (Reprinted with permission.⁴⁴)

GA-SO group had the highest predicted force (5.3-10.0 times BW) of the ankle muscle groups.⁴⁸ Predicted forces in the tibialis posterior, flexor digitorum longus, and flexor hallucis longus musculature ranged from 4.0 to 5.3 times BW. The peroneus tertius muscle and EDL did not show any predicted force during the stance phase of running.

Impulse is the effect of a force acting over a period of time and is determined mathematically as the integral of the force-time curve.⁸ Ae and associates calculated the impulse generated by different body segments during running.⁴⁹ The researchers found that the foot generated the largest mean impulse compared with other body segments. This impulse increased with faster running, suggesting that the foot plays an impor-

tant role in projecting the body and increasing running velocity.

Ankle-joint reaction forces during running have also been calculated by several investigators. Harrison and associates reported maximum ankle-joint reactions of 8.97 and 4.15 times BW for the compressive and shear components, respectively.⁴⁶ Burdett predicted that compressive forces on the foot along the longitudinal axis of the leg reached peak values of 3.3 to 5.5 times BW during running.⁴⁸ In addition, he reported ML shear forces that ranged from a medial force of 0.8 times BW to a lateral force of 0.5 times BW. Furthermore, the vertical reaction forces and other calculated forces were determined to be about 2.5 times larger in running (at a 4.47-m/sec pace) when compared with walking.

SUMMARY

Physical therapists can provide more effective programs for prevention and rehabilitation of foot and ankle injuries if dynamic characteristics are taken into consideration. This article has described current findings related to the dynamic biomechanics of the asymptomatic foot and ankle during walking and running. Functional descriptions of walking and running biomechanics have been provided along with quantitative findings from current biomechanical studies. Extensive databases are still unavailable for many of the biomechanical variables that affect dynamic foot and ankle motion. As advances in biomechanical methods continue and more clinicians include quantitative techniques in their routine evaluations, however, more insight into dynamic foot and ankle function will be provided.

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