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Biomechanics and Analysis of Running Gait

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The increased awareness of aerobic exercise to maintain a healthy lifestyle has made jogging and running more popular than ever. As the number of people that is engaged in these activities grows, increased incidences of acute and chronic running injuries naturally occur. To prevent and properly treat these injuries, a thorough understanding of normal walking and running gait is critical.

Proper running biomechanics involves synchronous movements of all of the components of the kinetic chain. The foot serves as the link between the ambulatory surface and the remainder of this chain. The foot's many functions include adaptation to uneven terrain, proprioception for proper position and balance, and leverage for propulsion. During the gait cycle, foot motion facilitates, and can be affected by, compensatory movement of the other bones and joints in the lower extremity. Improper alignment from the lumbar spine and lower limb below can alter mechanics and lead to injury. Therefore, it is essential to understand the biomechanics of running gait along the entire kinetic chain.

This article describes the anatomy of the foot and its relation to the gait cycle, discusses similarities and differences between walking and running gait, explains the contributions of the muscles and joints intrinsic and extrinsic to the foot, and demonstrates the effect of velocity on the economy of gait. The concepts of pronation and supination are discussed in detail. Running biomechanics of lower limb joints and muscles are described in all three cardinal planes (sagittal, frontal, and transverse). Also, the use of various methods of gait analysis are described along with their relevance to particular constituents of the running gait cycle. A thorough understanding of running gait allows a treating physician to recognize different

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mechanisms of injury and allows proper treatment and prevention of running injuries.

Anatomy and biomechanics

Running biomechanics are dictated by lower limb anatomy, particularly the joints of the foot and ankle. The axis of rotation with each joint allows for joints to have a predominant plane of motion, perpendicular to that axis. For example, the talocrural joint's anatomy allows for an axis of rotation that mostly is in the frontal plane (Fig. 1). Consequently, the talocrural joint has its predominant range of motion in the sagittal plane. Each joint moves in all planes with a predominant plane of motion. So-called "pronation" and "supination" are triplanar movements that involve multiple joints of the foot and ankle (Box 1). Pronation and supination of the foot and ankle causes obligate motion in the entire lower limb kinetic chain (Table 1).

The true ankle joint, also termed the talocrural joint, incorporates the articulation between the surface of the tibia and fibula with the superior surface of the talus. This joint primarily moves in the sagittal plane and allows dorsiflexion and plantarflexion. Because the lateral malleolus is located posterior relative to the medial malleolus, the talocrural joint axis travels primarily in the frontal plane with some posterior orientation from

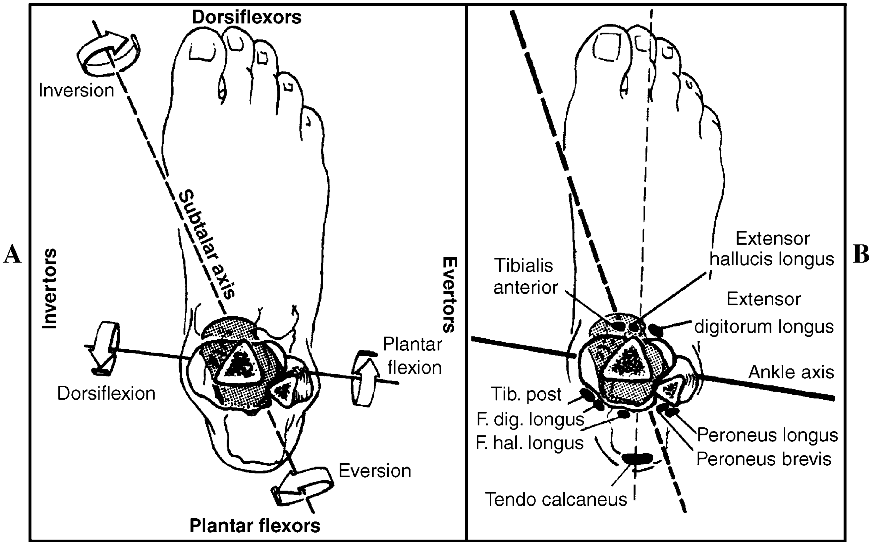


Fig. 1. (*A*) Rotation about the ankle and subtalar joint axes. (*B*) Musculotendinous unit position in relation to the ankle and subtalar joint axes. Tib post, tibialis posterior; F. dig, flexor digitorum; F. hal, flexor hallucis. (*From* Mann RA, Mann JA. Biomechanics of the foot. In: Goldberg B, Hsu JD, editors. Atlas of orthoses and assistive devices. 3rd edition. St. Louis (MO): Mosby; 1997. p. 145; with permission.)

Box 1. Multiplanar motions of pronation and supination in the foot and ankle in weight bearing

Pronation
Ankle dorsiflexion
Subtalar eversion
Forefoot abduction

Supination
Ankle plantarflexion
Subtalar inversion
Forefoot adduction

(Nonweight-bearing pronation = ankle plantarflexion, talus internal rotation, and talus adduction)

the medial to lateral side. Functionally, this results in talocrural joint movement in the transverse plane and little movement in the frontal plane. In the open kinetic chain, as dorsiflexion occurs, there is accompanying external rotation of the tibia. In the closed kinetic chain, as with the stance phase of ambulation, dorsiflexion causes pronation of the foot with internal rotation of the tibia [1]. The average range of motion in the ankle joint is approximately 45°, with up to 20° of dorsiflexion and 25° to 35° of plantarflexion [2].

Table 1
Effects of pronation and supination up the kinetic chain

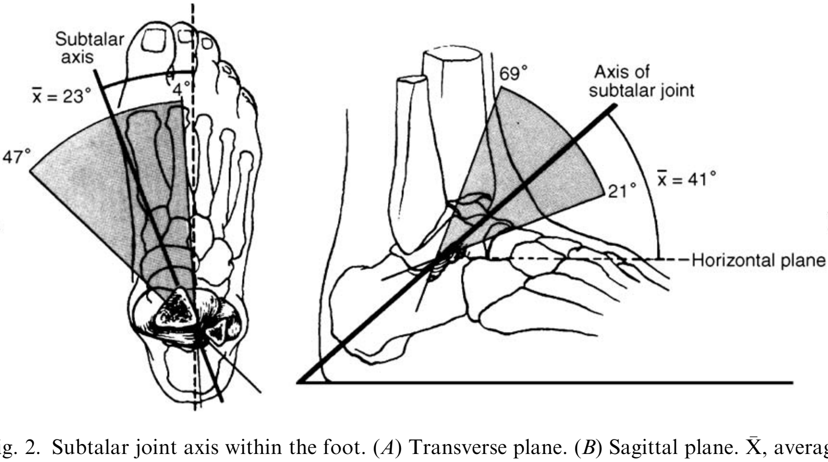
	Pronation			Supination		
	Sagittal	Frontal	Transverse	Sagittal	Frontal	Transverse
Lumbosacral	Extension	Lat flexion same side	Protraction	Extension	Lat flexion opp side	Retraction
Pelvis	Anterior rotation	Translation and elevation, same side	Forward rot same side	Anterior rotation	Translation opp side; depression same side	Rear rot same side
Hip	Flexion	Adduction	Internal rotation	Extension	Abduction	External rotation
Knee	Flexion	Abduction	Internal rotation	Extension	Adduction	External rotation
Ankle	PF-DF		Internal rotation	DF-PF		External rotation
STJ	PF	Eversion	Adduction	DF	Inversion	Abduction
MTJ	DF	Inversion	Abduction	PF	Eversion	Adduction

Abbreviations: DF, dorsiflexion; Lat, lateral; MTJ, midtalar joint; Opp, opposite; PF, plantarflexion; rot, rotation; STJ, subtalar joint.

The subtalar joint (STJ), between the talus and calcaneus, consists of three articular facets—anterior, middle, and posterior. These separate articulations function as a single joint and allow the complex triplanar motions of pronation and supination. The axis of this joint runs downward, posteriorly in the sagittal plane and laterally in the transverse plane (see Fig. 1; Fig. 2). In the transverse plane, the joint axis is oriented approximately 23° medial to the long axis of the foot [3]. Interindividual variation in orientation does occur, with a range of 4° to 47° (see Fig. 2A). In the sagittal plane, the joint axis is oriented, on average, 41° relative to the sole of the foot and runs posteriorly and distally from the dorsal aspect of the neck of the talus to the posterolateral corner of the calcaneus [3]. Interindividual variation ranges from 21° to 69° (see Fig. 2B). As the joint axis becomes more horizontal, such as with a flat foot, eversion and inversion occur to a greater extent than abduction and adduction. Also, as the axis gets closer to the sagittal plane, less dorsiflexion and plantarflexion is allowed [4]. The STJ is analogous to an oblique hinge because of its configuration in relation to the remainder of the foot [5]. This allows the foot to move in a complex, but predictable, manner.

Pronation is defined classically as abduction and eversion of the foot along with hindfoot eversion. Supination is described classically as adduction and inversion of the foot along with hindfoot inversion; however, pronation and supination will cause multiple, multiplanar proximal joint movement. The orientation of the STJ relative to the tibia also results in a mitered hinge effect. Torque that is developed by movement of the foot is transmitted proximally and results in internal or external rotation of the tibia [1]. In weight bearing,

A



B

Fig. 2. Subtalar joint axis within the foot. (*A*) Transverse plane. (*B*) Sagittal plane. $\bar{X}$, average angle of joint axis. (*From* Mann RA, Mann JA. Biomechanics of the foot. In: Goldberg B, Hsu JD, editors. Atlas of orthoses and assistive devices. 3rd edition. St. Louis (MO): Mosby; 1997. p. 139; with permission.)

there is a 1:1 relationship between the degree of supination relative to tibial external rotation and pronation relative to tibial internal rotation [6].

The STJ has several functions during normal ambulation. Control of plantar surface pressure and contact with the ground is dictated by motion at the STJ. Stress dampening on the heel occurs during gait as forces are transmitted through the STJ to the midfoot and forefoot. Also, triplanar motion about this joint axis results in either a flexible or rigid foot during progression of gait (see later discussion).

STJ or calcaneal eversion, caused by ground reaction forces after foot strike, precipitates a cascade of events in the rest of the foot. The midfoot joints, namely the calcaneocuboid and talonavicular joints, allow eversion/abduction and inversion/adduction of the forefoot. The midfoot joints, also collectively termed the transverse tarsal joint, have longitudinal axes that are similar to the STJ. Thus, these pair of joints also have been dubbed as the secondary STJ. Their oblique axes are close to that of the talocrural joint and provide mainly plantarflexion and dorsiflexion. When the hindfoot everts, the axes of these two separate joint components become parallel, and allow for pronation and increased motion within this two-joint complex. With hindfoot inversion, supination occurs and the joint axes converge, which causes this joint complex to ‘‘lock’’ into a rigid configuration [7]. This concept is important to consider as the foot progresses through the stance phase from initial contact to terminal stance. In essence, pronation necessitates a flexible foot for shock absorption, whereas supination necessitates a rigid foot for propulsion.

The tarsometatarsal (TMT) joints can be divided into five rays. The first ray is composed of the medial cuneiform and the first metatarsal. Motion allowed at this joint is primarily a combination of dorsiflexion/inversion/adduction and plantarflexion/eversion/abduction [5]. The second ray contains the intermediate cuneiform and second metatarsal. The second metatarsal is recessed and firmly mortised into the base of the first and third metatarsal–cuneiform joints. This bone is subjected to high stress as a result of the inherent stability as the foot progresses through the stance phase in preparation for propulsion [5]. The lateral cuneiform and third metatarsal along with the fourth metatarsal make up the third and fourth rays. Motion at these rays is limited primarily to plantarflexion and dorsiflexion. The fifth ray (fifth metatarsal) allows some pronation and supination in relation to the cuboid.

The metatarsal break is an important phenomenon that is created by the metatarsophalangeal joints. These joints extend about an oblique joint axis that extends from the head of the second metatarsal to the head of the fifth metatarsal [5]. Motion at this joint predominantly is flexion and extension. As the foot progresses through the stance phase just before toe-off, this axis allows the foot to become rigid as this joint is extending [8]. This supination results in an ideal rigid platform for efficient propulsion as the leg prepares to advance through the swing phase.

The anatomic uniqueness of the plantar fascia also helps to create the solid structural platform that is needed for propulsion. It originates from the medial tubercle of the calcaneus and inserts around the metatarsal heads to the base of the proximal phalanges. It crosses the transverse tarsal and metatarsophalangeal joints and serves as a passive restraint. At the metatarsophalangeal attachment, the Spanish windlass mechanism is formed (Fig. 3). As extension occurs at the metatarsophalangeal joint just before toe-off, the plantar fascia tightens and pulls the calcaneus and metatarsal heads together [9]. This heightens the longitudinal arch of the foot and forces the transverse tarsal joint into a forced flexion position, and thereby, creates a solid structural support. In addition, the intrinsic foot muscles actively contract to provide further stability of the foot.

The ligaments within the foot also provide passive stability. Ligaments, along with muscular support and the unique bone architecture of the foot, form two longitudinal arches (medial and lateral) and a transverse arch. The medial foot ligaments are thicker than the lateral ligaments. This design prevents hyperpronation during ambulation. The arches of the foot create weight-bearing points, primarily on the calcaneus and the metatarsal heads. The sesamoid bones decrease force on the plantar surface of the first metatarsal head just before toe-off. The unique configuration of these arches allows the foot to be mobile to adjust to the ground surface and rigid in preparation to push off the ground for the sake of propulsion.

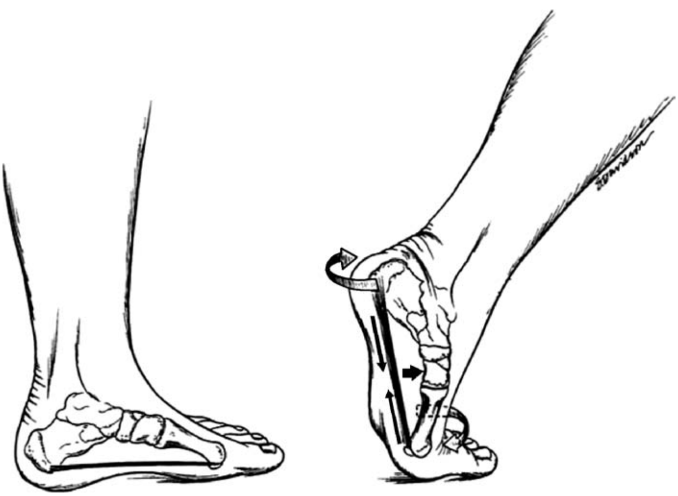


Fig. 3. The windlass mechanism. After heel-off, metatarsophalangeal extension increases tension on the plantar fascia (*converging arrows*). The transverse tarsal joint is forced into flexion (*arrowhead*), which increases stability as the foot prepares to push off. (*From* Geiringer SR. Biomechanics of the running foot and related injuries. Phys Med Rehabil State Art Rev 1997;11(3):569–82; with permission.)

The muscles of the lower leg and foot work in an eccentric and concentric fashion. Eccentric work is muscle contraction while fibers are lengthening; concentric work is muscle contraction while fibers are shortening. With running, the greatest amount of muscle work is done in an eccentric fashion. The pronation phase of gait involves mostly eccentric contraction to provide for joint control and shock absorption. The supination phase of gait involves mostly concentric contraction of various muscles, particularly the gluteals, to provide for acceleration and propulsion.

Although muscles can work in all three planes, muscle fiber orientation often dictates a preferred plane. For instance, the gluteus maximus has muscle fibers that are oriented in an oblique (transverse) fashion; therefore, this powerful muscle becomes an ideal leg external rotator (by way of concentric contraction) and controls leg internal rotation (by way of eccentric contraction). Another key muscle in running is the gastrosoleus complex, commonly considered to be a pure plantarflexor. Yet, this complex also contributes to the transverse plane motion of hindfoot inversion because of its location in relation to the STJ axis [8]. This allows the gastrocnemius-soleus to contribute to supination as the foot progresses through the gait cycle.

Walking versus running

Running, like walking, is a series of pronations and supinations. Running is distinguished from walking by increased velocity, or distance traveled per unit time, and the presence of an airborne or float phase (Box 2). Judges in race walking determine that participants are running illegally if they observe a period of time when both feet are off the ground. During a running gait cycle, there are two periods of float when neither foot is in contact with the ground (Fig. 4). This results in decreased time in stance phase and increased

Box 2. Differences between running and walking

Increased velocity
Increased ground reaction forces
Float phase
No double stance phase
Decreased stance phase and increased swing phase
Overlap of swing phase rather than stance phase
Requires more range of motion of all lower limb joints
Requires greater eccentric muscle contraction
Initial contact varies, depending on speed
Decreased center of gravity with increased speed
Decreased base of support

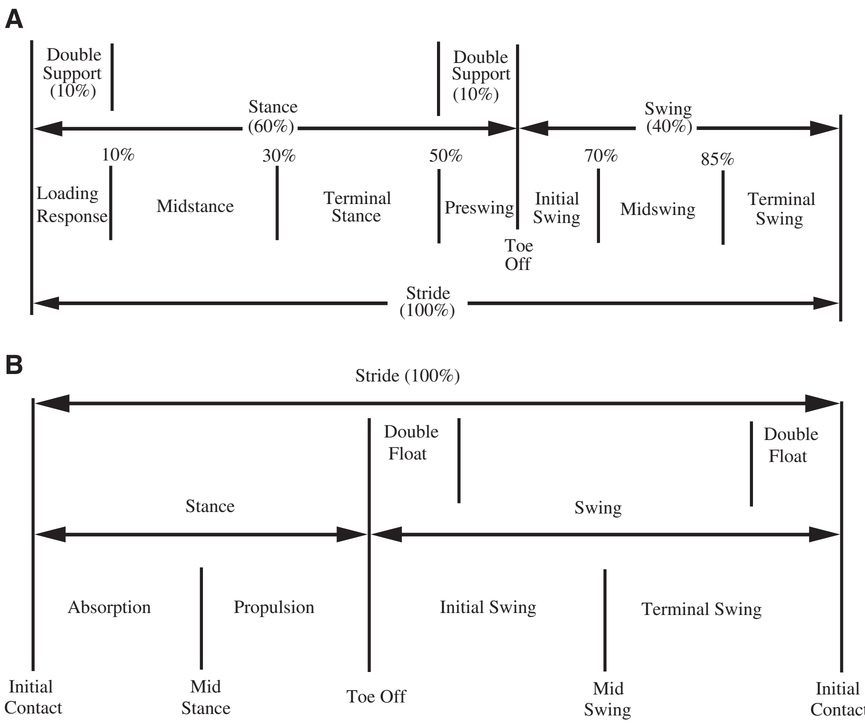


Fig. 4. Gait cycle with phases and individual components. (*A*) Walking. (*B*) Running. (*From* Ounpuu S. The biomechanics of walking and running. Clin Sport Med 1994;13(4):843–63; with permission.)

time in swing phase. As velocity continues to increase, further reduction in stance phase occurs, whereas swing phase duration increases. Unlike walking, the forward momentum that is needed for running is produced by the swinging leg and arms, rather than the stance leg [10].

Runners also require more from their joints and muscles than walkers. A greater joint excursion has been noted with hip flexion, knee flexion, and ankle dorsiflexion with running [11]. Other joints also likely go through a greater range of motion with running, such as the joints of the lumbar spine and pelvis. Increasing speed of running increases the amount of joint excursion, particularly in the sagittal plane [11]. Some investigators empirically noted a greater degree of transverse plane motion with sprinting. To control this motion, greater eccentric work is required from the muscles of the lower leg.

Changes in running gait with increased velocity

Running can be classified by speed. Jogging, or submaximal running, can be defined as velocity from 5 mph to 10 mph, whereas sprinting occurs at speeds of greater than 10 mph [6]. Characteristic changes in gait occur as velocity increases. As with walking, the center of gravity of the body shifts during running in a sinusoidal curve in space; however, during running, the body maintains a forward lean throughout the gait cycle. The line of progression from step to step is at or near the midline to minimize lateral shift in center of gravity. As speed is increased, the lower extremity joints increase their range of motion to decrease the vertical shift in center of gravity [3,12]. Thus, faster runners require more flexibility and eccentric muscle strength than slower runners.

Speed and length of gait can be described using the terms: cadence, stride length, and step length. Cadence is equal to the number of steps per unit time (usually steps/min). Stride length is the distance between successive initial contacts of the same foot. Step length is the distance from initial contact of one foot to initial contact of the opposite foot. Temporal and spatial variables during running generally are interrelated. Velocity increase is achieved by increasing step lengths followed by increasing cadence [11]. With elevation in velocity, there is more time spent in float phase. Stride and step lengths are a function of leg length and total height and coincide with the ability to increase these lengths while velocity increases [11].

As running velocity increases, the point of initial contact can change. During submaximal running, the lateral heel typically contacts the ground first, whereas in sprinting, the midfoot makes initial contact [3]. This places the foot in slight plantarflexion at impact [13]. Dorsiflexion still occurs directly after initial contact as during submaximal running, but the heel does not touch the ground during sprinting [3]. The remainder of stance phase mimics submaximal running, except for increased joint range of motion. During the terminal portion of swing phase, the foot begins to plantarflex during sprinting so that the midfoot can contact the ground [5].

Total gait cycle duration, as well as stance phase duration in relation to swing phase, diminishes as velocity of running increases. This results in increased velocity of lower extremity range of motion as events of the gait cycle need to occur within a shorter period of time [6]. The higher eccentric contractions that occur to control joint motion will result in higher energy expenditure. The increased range of motion in the lower extremity also serves to minimize vertical displacement of the body center of gravity [12]. The end result is increased energy cost as velocity increases to a sprint, which therefore limits the absolute running distance.

As velocity increases, running efficiency or economy changes. Running economy was traditionally measured by assessing oxygen use at a given velocity [14]. The energy cost of running is not only determined by speed but also by running biomechanics. An ideal model for economic running has yet to be found. Numerous factors, which are beyond the scope of this chapter, may affect running efficiency. For a particular individual, training allows the body to biomechanically adapt over time to achieve the least energy-expending pattern of running gait.

Gait cycle

The gait cycle is the period from initial contact of one foot to the next initial contact of the same foot. In normal walking, there are two phases of gait – stance and swing. During one gait cycle in walking, stance phase represents 60% of the cycle while swing phase represents the remaining 40% (Fig. 4). Double support, when two limbs are in contact with ground, occurs during the first and last 10% of a particular stance phase. Single limb support is equal to the swing time of the opposite limb.

The running gait cycle can be divided into stance phase, swing phase, and float phase. The first half of the stance phase is concerned with force absorption (pronation), whereas the second half is responsible for propulsion (supination). In Fig. 4B, stance phase is divided into subphases of initial contact to midstance, and midstance to toe-off. To understand the biomechanical events during running, stance phase can be divided into three major components: (1) initial contact to foot flat, (2) foot flat to heel-off, and (3) heel-off to toe-off [1]. Swing phase during running can be divided into initial swing and terminal swing; float phase occurs at the beginning of initial swing and the end of terminal swing.

Initial contact to foot flat

At initial contact during running, the lateral heel contacts the ground with the foot in a slightly supinated position [3,15]. This occurs as the leg swings toward the line of progression in midline, with the leg in a functional varus of 8° to 14° at this point. The calcaneus is inverted approximately 4° at initial contact in an average runner [12,16]. During walking, the ankle is plantarflexed, on average, 8° at heel strike and continues to 14° as the remainder of the foot contacts the ground [17]. In running, there is no plantarflexion after heel strike as the foot actually progresses into dorsiflexion [18]. This lack of plantarflexion in running causes increased pronation, but less supination. The tibialis anterior acts eccentrically during walking to cause a smooth plantarflexion, and contracts concentrically during running to stabilize the ankle and possibly to accelerate the tibia over the fixed foot as a mechanism to maintain and increase velocity [3,19]. At the same time, the gastrocnemius-soleus contracts eccentrically to control forward tibial progression and provide stability to the ankle [3].

Energy absorption or weight acceptance is a key function of the lower extremity during this phase of running gait. Vertical ground reaction force may reach a magnitude of 2.2 times body weight after heel contact in running compared with 1.1 times body weight during walking [10,20,21]. Factors that allow proper impact absorption are joint motion, eccentric muscle contraction, and articular cartilage compression [22]. Along with dorsiflexion at the ankle joint, hip and knee flexion help to dissipate the force of impact at heel contact [3].

STJ pronation is another major mechanism of shock absorption. As forward progression occurs, the STJ pronates within the first 20% of the stance phase to allow solid contact of the foot with the ground [23]. AS a result of the mitered hinge effect, pronation is accompanied by hindfoot eversion and tibial internal rotation. Pronation allows the transverse tarsal joint axes to become parallel, and increases mobility at this joint and in the forefoot. The foot can accommodate to uneven terrain and dissipate energy as it conforms to the ground surface.

Eccentric contraction of the rectus femoris after initial contact controls the height of the body center of gravity and resists excess knee flexion as the line of ground reaction force passes posterior to the knee joint. The hamstrings, which act as hip extensors, are active throughout the stance phase as the body progresses forward on the fixed limb [11]. Stability of the lower extremity at initial contact is provided by the hip adductors [24]. The adductors remain active throughout the running cycle as opposed to walking, when they are active only from swing phase to the middle of stance phase [25].

Foot flat to heel-off

As forward progression continues through the middle of stance phase, dorsiflexion increases to a maximum of 20° in running as compared with 14° during walking [16,26,27]. During this portion of gait the foot is fixed to the ground; therefore, dorsiflexion occurs as a result of the forward progression of the tibia. Maximum dorsiflexion occurs when the body center of gravity already has passed anterior to the base of support. Just before this, maximum pronation occurs, approximately when the body center of gravity has passed anterior to the base of support [23]. At maximum pronation, the transverse tarsal joint axes are parallel, and allow increased mobility and forefoot accommodation to the underfoot surface [10,28]. The point of maximum pronation also marks the end of the absorptive component of stance phase; the subsequent propulsion component occurs through the remainder of the stance phase.

Control of pronation is provided by eccentric contraction of the tibialis posterior and gastrocnemius-soleus complex [29,30]. Forward progression of the tibia is controlled by the gastrocnemius-soleus. As ground reaction force travels anteriorly through the knee joint, cocontraction of the quadriceps and hamstring stabilizes the knee joint.

After maximum pronation, supination at the STJ begins [5]. As the opposite limb swings forward, pelvic rotation occurs and results in an external rotation torque of the stance limb. The external rotation of the tibia causes inversion at the calcaneus with subsequent supination of the foot. Initiation of supination marks the end of this phase as the heel begins to rise off the ground.

Heel-off to toe-off

Continued forward progression of the opposite limb and body prepares the stance limb to initiate propulsion. Ankle plantarflexion under concentric contraction of the gastrocnemius-soleus serves a few important functions at this point in the running gait. Acceleration of the stance limb as it prepares for propulsion is initiated by plantarflexion [24]. Also, as plantarflexion occurs while the forefoot is fixed to the ground, the stance phase limb is lengthened, and thus, minimizes the decrease in center of gravity as the opposite limb swings forward and prepares to contact the ground [28,31]. Lastly, plantarflexion contributes to increased contralateral stride length, and enhances the efficiency of running [8].

Supination of the foot starts at heel-off and continues for the remainder of the stance phase. Supination causes convergence of the transverse tarsal joint axes and results in a rigid foot configuration. Several important factors allow this to occur and provide increased stability of the foot as it prepares to push off the ground powerfully and efficiently to propel the limb forward [8]. External rotation of the stance limb causes STJ supination as a result of the mitered hinge effect. Gastrocnemius-soleus contraction causes hindfoot inversion and leads to STJ supination. The metatarsal break phenomenon contributes to supination as extension occurs at the metatarsophalangeal joint. This joint extension also leads to increased tension of the plantar fascia, which provides stability to the transverse tarsal joint through the Spanish windlass mechanism. Finally, the intrinsic foot muscles (in particular the abductor hallucis, flexor hallucis brevis, abductor digiti minimi, and flexor digiti minimi brevis), which cross the transverse tarsal joint, contract and stabilize this joint in a similar fashion to the plantar fascia [8].

During this portion of stance phase, maximum ground reaction force occurs as the foot pushes off the ground and thrusts the body forward. The magnitude of vertical ground reaction force may reach 2.8 times body weight with running compared with 1.3 times body weight in walking [20,21]. Each of the factors that contribute to the formation of a rigid foot is crucial to generate the force that is required at this instant of running gait.

At the termination of stance phase, the gastrocnemius-soleus stops functioning and contraction of the anterior tibialis begins. As the foot prepares to leave the ground, knee and hip extension is needed to add to the thrust of the body as it progresses into the initial float phase. Neither the hip nor the knee extends beyond neutral with running, even at toe-off [27]. The hamstrings convert from a stabilizing flexor of the knee to an active extensor of the hip [6]. The rectus femoris begins to contract concentrically just before toe-off to maximize knee extension.

Initial swing

After toe-off, the body is thrust into the first float phase. The line of ground reaction force at toe-off passes posterior to the knee joint, which flexes the knee as the body is propelled forward. This knee flexion is resisted by eccentric contraction of the rectus femoris, which also acts concentrically with the iliopsoas to flex the hip and advance the limb forward [11].

During initial swing, the hip abducts in relation to events that occur on the opposite side [11]. After the float phase, the opposite limb strikes the ground and the hip abductors are activated to stabilize the pelvis. As the swinging limb advances forward, pelvic rotation pushes the hip into abduction. Pelvic rotation of the swing leg also helps to place the stance leg in relative external rotation and helps initiate more supination. This motion is resisted by the hip adductors, which remain active throughout this phase.

Throughout the initial swing phase, the anterior tibialis acts concentrically to dorsiflex the ankle [11]. This action is more important in walking to clear the foot as the limb advances forward. In running, the amount of knee flexion that occurs will negate the importance of dorsiflexion to allow foot clearance.

Terminal swing

After the opposite limb has undergone toe-off, the second float phase occurs. At this point, the swinging limb is preparing to contact the ground. Hip flexion terminates and extension begins under concentric control of the hamstrings and gluteus maximus [11]. Knee extension occurs rapidly as a result of forward momentum and contraction of the rectus femoris. In preparation for initial contact, eccentric contraction of the hamstrings slows down knee extension at the end of terminal swing [11].

During terminal swing, the hip adducts as the foot prepares to contact the ground along the line of progression. The hip adductors concentrically bring the femur toward the midline during this portion of swing phase. They continue to be active throughout the stance phase to stabilize the lower extremity, and thereby, function throughout the entirety of the running gait cycle [23].

As the foot prepares to contact the ground, the gastrocnemius-soleus begins to contract. The anterior tibialis remains active throughout the swing phase and into a portion of the stance phase [3]. At initial contact, cocontraction of the anterior tibialis and gastrocnemius-soleus creates a stable foot for weight acceptance [11]. At this point, one complete gait cycle has occurred and the patterns that were described above are repeated as the next cycle begins.

Running gait analysis

As with walking gait, running gait analysis is done along a continuum from real time observational gait analysis to the use of high-resolution cameras and video recording devices; force plates; computer systems; and other laboratory measuring devices. Five gait measurement systems have been described, including motion analysis, dynamic electromyography, force plate recordings, energy cost measurements or energetics, and measurement of stride characteristics [32]. Kinetic analysis relates to force production, whereas kinematics is the measure of movement itself and reflects the effect of the kinetics [33]. Gait kinematic analysis is done best in a steady state outside of starting and stopping and requires enough space for the subject to start, walk/run, and stop [34]. Use of a treadmill allows for continuous observation and monitoring but may cause variation in movement pattern compared with nontreadmill running. Treadmill running forces runners to use a more secure gait, including spending increased time in stance phase. A recent review demonstrated that ground reaction forces, as measured by pressure-sensitive insoles in the shoes of female long-distance runners who were tested on a treadmill, were reproducible across different running velocities and stride frequencies [35]. EMG analyses across these differing running techniques varied depending on the muscle that was tested.

Observational gait analysis

Observational gait analysis is used to some extent by all health care professionals. It is the easiest and least expensive method of analysis. Several manuals have been developed to organize and guide observational gait analysis, such as Temple University's *A Guide to a Visual Examination of Pathological Gait* or Rancho Los Amigos Medical Center's *Observational Gait Analysis Handbook* [36,37]. The gait cycle is observed with gross focus sequentially on stance, swing, and float phase. The observations are separated into subphases of stance and swing, including initial contact, loading response, midstance, and terminal stance for the stance phase, and preswing, initial swing, midswing, and terminal swing for the swing phase. Observations are made and recorded from the frontal, sagittal, and transverse views. Reflective gait markers enhance the clinician's ability to detect transverse plane abnormalities, particularly at the knee and ankle.

After the gross inspection, analysis follows an anatomic sequence, from foot and ankle to trunk, in the frontal, transverse, and sagittal planes. The observer determines deviations from normal at each joint/anatomic region and each phase/subphase. Observations of spine rotation, arm swing, and head and neck positioning also are noted.

The observational findings are summated into two areas: (1) total limb function, as described by gait deviations at each joint/phase; and (2) functional deterrents of effective weight acceptance or limb advancement [32]. The ability to pronate or weight acceptance is evaluated starting at the foot and ankle and progresses more cephalad to observe obligate motions that occur proximally—the "bottom up" approach. The ability to supinate or limb advancement is observed using a "top down" approach, and looks for proximal muscle contraction during the propulsion phases.

Excessive pronation is the most common problem that is observed on empiric running analysis. Although a physiologic amount of pronation is required, hyperpronation causes increased ground reaction forces in the medial aspect of the lower limb kinetic chain, such as the medial tibia. Muscles may need to work harder to control the excessive pronation, which may lead to tendonitis. With excessive pronation also comes excessive internal rotation of the tibia and femur. This often leads to patellofemoral maltracking. Observed excessive supination is more uncommon and can lead to increased forces on the lateral aspect of the kinetic chain. Pelvic abnormalities, such as excessive anterior and lateral tilt, also are observed frequently in runners.

Motion analysis

In general, motion analysis provides for quantitative description of body segments in gait without quantification of forces. The simplest form of motion analysis is the use of camera for still photography or a video recording device for filming rapid events like running. Markers that are placed on the body segments allow for a more comprehensive analysis when they are imaged sequentially through a calibrated field of view. Initially, goniometers or electronically instrumented hinges were used to track limb motion [38]. Because of the changing center of knee joint motion, biaxial and triaxial systems were developed and are supplemented by a recorder that can provide immediate data on minimal and maximal arcs of motion and rates of change. More sophisticated systems have been developed in which three-dimensional coordinates can be computed by way of mathematical triangulation when two or more cameras/detectors detect the same marker. These systems are feasible to use clinically and are functionally accurate [39]. Infrared transmitters (active markers) and retroreflective markers (passive markers) can be used without long power cords; this makes the analysis less cumbersome to set up and use. Once the computer program has calculated the motion of the limb segment, measures, such as joint angle and velocity, are calculated. Motion analysis measures can be combined with force measures to allow for calculations of joint moments, powers, and mechanical energy. There are pitfalls in patient instrumentation, marker placement, and data processing that are beyond the scope of this text that must be considered with motion analysis systems [40].

Force plate analysis

Ground reaction forces are generated in the vertical, horizontal, and rotatory plane in conjunction with weight acceptance during stance phase. These forces—equal in intensity but opposite in direction to the forces experienced by the weight-bearing limb—can be measured with a force plate. When the measured forces are combined with information on the joint center location, ground reaction joint torques or moments can be calculated. Typically, the plate is mounted in the floor in an inconspicuous manner to avoid targeting for direct landing, which can alter desirable natural gait mechanics. Vertical loads, horizontal shear, vector patterns, joint torques, and center of pressure determinations are the most useful data from force plate analyses. Vector analysis includes sagittal plane vectors and frontal plane vectors. Gait velocity, or rate of limb loading, determines peak load [41]. Peak vertical loads of 2.5 times body weight have been measured during running [42]. Variation in running style (eg, heel-toe or foot-flat styles) impact the shape of the ground reaction force patterns [21].

Dynamic electromyography

Muscle activity timing and relative intensity are measured with surface or fine wire needle electrodes with dynamic EMG of multiple muscles during active running or walking. Thus, dynamic EMG can be used to assess neuromuscular control of a runner. Transmission of the myoelectric signal is done by way of cable or telemetry to allow for recording. Although timing of muscle activation would seem to be a straightforward calculation, a minimum significance level for signal activation must be defined so one can decide on the onset and cessation of active contraction accurately. This minimum level has been defined as 5% of the maximal effort that is registered on manual muscle test of the muscle [43]. Cross talk from other nearby muscles can limit the accuracy of single-muscle EMG quantification, especially with surface electrodes. Computer analyses quantify muscle activity [32]. Ultimately, integration, which consists of summing the digitized, rectified signals over time, is done over short periods that are consistent with the subphases of the gait cycle.

Energetic measurements of gait

Energy expenditure in gait is related to the alternating slowing and accelerating of body mass in conjunction with the raising and lowering center of gravity [10]. Global information on energy expenditure in normal and pathologic gait can be derived from measurements of metabolic energy expenditure and has been used to assess various pathologic gait patterns that are related to neuromuscular diseases and orthotic and prosthetic use [44]. Mechanical power has been used as a global descriptor of muscular effort, which is believed to be good surrogate of energy expenditure for gait [45]; however, several researchers have concluded that muscular effort showed no relationship with metabolic demand. Eccentric contraction is important to control the gravitational forces in a smooth, coordinated, and energy-efficient manner, primarily during stance phase. The swing phase energy expenditure may be higher than anticipated in runners [46]. The exact distribution of energy use among various muscles during human running is not known but may shed some light on running efficiency. There is no formula for the most economical running form; however, the literature on biomechanics of running gait suggests that biomechanical factors, including anthropometric dimensions, gait pattern, kinematics, and kinetics, may be related to running economy [30].

Stride analysis

Measures of gait characteristics like cadence, speed, step length, and stride length can be useful clinically. They can be measured simply with a stopwatch or in more complex ways with apparatus like an instrumented walkway. Portable units, including insole foot switches, allow for more convenient, less expensive measures of gait characteristics. These quantitative measures, in conjunction with observational, qualitative measures, can provide a quick and easy assessment that can be repeated while tracking recovery or rehabilitation.

Summary

Physical activity, including running, is important to general health by way of prevention of chronic illnesses and their precursors. To keep runners healthy, it is paramount that one has sound knowledge of the biomechanics of running and assessment of running gait. More so, improving performance in competitive runners is based in sound training and rehabilitation practices that are rooted firmly in biomechanical principles. This article summarized the biomechanics of running and the means with which one can evaluate running gait. The gait assessment techniques for collecting and analyzing kinetic and kinematic data can provide insights into injury prevention and treatment and performance enhancement.

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