Sagittal Plane Biomechanics

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During walking, the center of body mass must pass from behind the weightbearing foot to in front of it. For this to take place, the foot must function as a sagittal plane pivot. Because the range required for this motion is approximately five times as great as both frontal and transverse plane motion, its evaluation should become an essential part of a podiatric biomechanical assessment. Lack of proper sagittal plane motion and its sequelae are described. (J Am Podiatr Med Assoc 90(1): 47-50, 2000)

Traditionally, the biomechanical treatment of podiatric problems has depended on the attenuation of impact loading and the control of contact pronation. Pressure analysis during walking, however, has shown unmistakably that the loads on the forefoot are significantly higher than those on the heel during the normal gait cycle. Rearfoot posting has also been shown to alter the rate of pronation, but it does not consistently alter the amount of pronation. Clearly, a different type of model is needed, one that will explain both the successes and failures of treatment and that, at the same time, will be consistent with the physical forces that are present during the gait cycle. Sagittal plane biomechanics—specifically, the temporary, functional loss of available sagittal plane motion at the time it is most required during the single-support phase of the step—provides the basis for this different model.

Required Sagittal Motions

During the course of any step, the center of body mass must pass from behind the weightbearing foot to in front of it (Fig. 1). Approximately 75° of the step motion is required to complete this task during the single-support phase of the step. There is a simultaneous need for both internal and external rotation of the weightbearing side, with approximately 15° of motion necessary. Therefore, the amount of sagittal plane motion required with every step is 500% that of transverse or frontal plane motion. The significance of this sagittal plane motion should not be minimized.

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The design of the typical podiatric physician's office has generally caused gait analysis to consist of the clinician watching patients walk in the hallway. The clinician stands or squats at one end of the hallway and observes the patient walking from the front and rear only. A side view is simply not available in such circumstances. If the maxim "seeing is believing" is true, then the inability to view sagittal plane motion during gait analysis has prevented it from becoming more ingrained in podiatric doctrine.

McGeer,[1] a renowned mathematician, showed that a bipedal "walking machine" could be constructed that required no muscular interaction. Essentially, there exists an interrelationship during walking between the stance and swing limbs such that the movement of the swinging side provides sufficient energy to pull the body over the standing side. This theory has been carefully studied by researchers at the Cornell University Department of Applied Mathematics.[2] Working models of a "muscle-less" walking figure have been constructed, tested, and proven accurate. This is not to say that muscles are unnecessary, but rather that bipedal gait is based inherently on the integration of the functional anatomical components, gravity, and momentum, and not exclusively on direct muscle power.

The significance of McGeer's principles involves the interrelationship between stance and swing during walking. Other researchers have also shown that the power for walking is generated predominantly by the swinging limb pulling the body over the standing limb.[3, 4] The force created against the ground by the stance side acts as a lever, and depends on the center of mass movement over it. In other words, the stance limb is passive, and permits and amplifies rather than

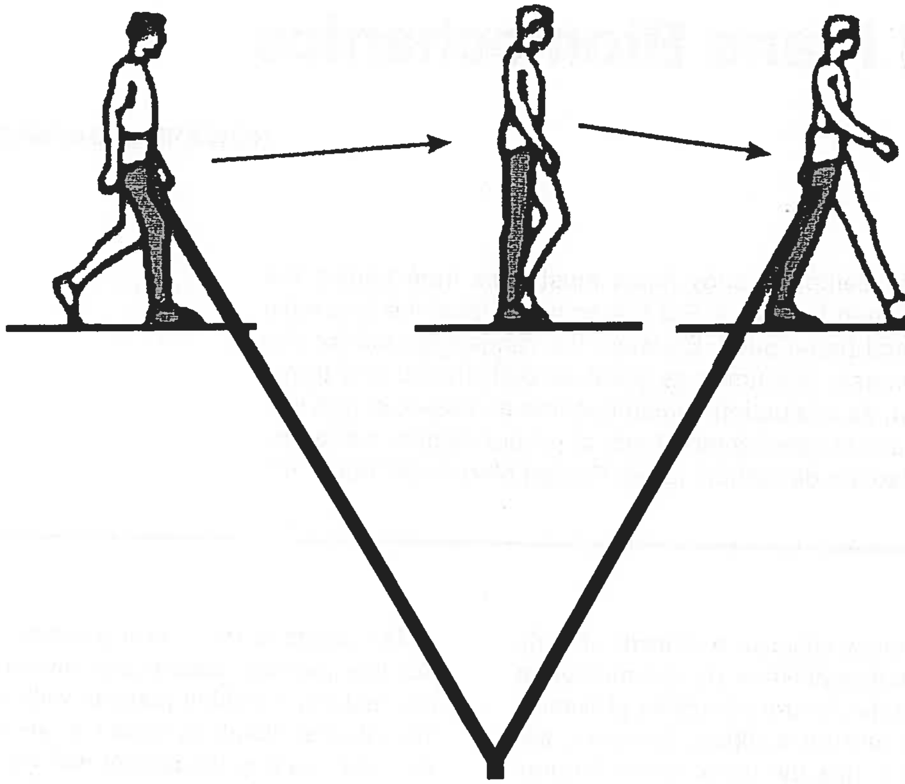

Figure 1. The center of body mass must pass from behind to in front of the weightbearing limb. The arc of motion is permitted by the pivotal ability of the sagittal plane of the weightbearing foot.

creates motion.[5] Because the weightbearing foot represents the point of contact with the ground, it becomes a primary pivotal site for efficient and timely sagittal plane motion during the single-support phase of the gait cycle.

Perry[6] has shown that the ability of the foot to provide sagittal plane efficiency depends on a series of three "rockers" that transmit motion successively and rapidly from heel to forefoot during the single-support phase. The initial rocker site is the round underside of the calcaneus, which permits motion from heel strike to forefoot contact. As forefoot contact occurs, motion is transferred to the ankle joint, where the tibia dorsiflexes 10° on the talus prior to heel-off. With heel-off, the rocker at the metatarsophalangeal joint provides the final pivotal site. The heel is therefore permitted to move through the sagittal plane, rising up and over the metatarsals as the bases rotate about the heads through the completion of the single-support phase. With this final motion, foot stability develops by means of the windlass mechanism, as described by Hicks.[7] The average single-support phase lasts less than 0.5 sec, so any delay in motion transfer represents an irrecoverable loss of the integrated support-movement process.

Sagittal Plane Restrictions

There are essentially three types of sagittal plane blockages within the foot during walking. The initial blockage is a limitation of forward ankle motion, or ankle equinus, in which less than 10° of dorsiflexion is available. Forefoot equinus, typical of a cavus type of foot, is the second type of sagittal plane blockage. In this case, the forefoot is lower on the ground plane relative to the heel, creating an uphill position that can impede forward advancement. The final blockage is a loss of motion at the metatarsophalangeal joints. This loss of motion can be either structural, as in hallux limitus or hallux rigidus, or performance-related, as in functional hallux limitus. In functional hallux limitus, there is full nonweightbearing motion, but when the foot is loaded, its ability to dorsiflex is momentarily and completely restricted. In either the structural or functional type of hallux limitus, the ability of the heel to be efficiently lifted up and over the forefoot is impeded by loss of metatarsophalangeal joint range of motion.

Perhaps the most difficult blockage to envision is functional hallux limitus blockage. Because there is a fluid range of motion during the nonweightbearing examination, the hallux limitus blockage, with its impedance of motion during walking, requires a specific sagittal viewpoint to be detected. The hallway view during gait analysis, mentioned earlier, would prevent observation of this blockage. In fact, once the hallux touches the ground, it does not move again until toe-off. Therefore, it is the relative motion of the foot or its compensations for loss of metatarsophalangeal joint dorsiflexion that become the visible events during gait analysis. The ability to determine the cause from the effect is therefore paramount in understanding the influence of functional hallux limitus on late-midstance excessive foot pronation, the timing and direction of knee and hip motion, and improper flexion motions of the torso.

The Effect of Loss of Sagittal Range of Motion

To better understand the remote effects on the joints that are distal and proximal to the actual sites of sagittal plane motion restriction, the action of the common scissor-jack serves as a useful analogy. As this mechanical structure is raised and lowered, each of its joints must provide the necessary range of motion (Fig. 2). A fixation at any joint axis will alter the motion of the entire structure. The scissor-jack will either stop moving or tip laterally, depending on the amount of force supplied to it. When one looks at the joints on either the right or left side of the jack, the reverse motion of each adjacent joint axis becomes readily apparent. One joint may extend with the open side to the left, while the joint axis proximal and distal to it extends with the opening to the right. This interrelationship is the precise arrangement of the joints of the lower extremity. The hip, knee, ankle, and metatarsophalangeal joints all extend and flex in an opposite direction from their adjacent joints (Fig. 3). Just as with the scissor-jack, failure of any joint to move will therefore affect the others. If there is a restriction of sagittal plane motion at one location, then accommodation can occur at either the other foot, more proximal joint sites, or both.

Because the amount of sagittal plane motion being discussed is so high relative to the available frontal or transverse ranges, the magnitude of the effect of sagittal plane blockage is consistent with the changes seen in analysis of abnormal gait. For instance, limitations in hip joint extension have been shown to equate with the motion restrictions associated with functional hallux limitus.[8] This blockage has also been shown to be a causative factor in chronic low-back pain.[9] In fact, treatment of the foot with an orthotic intervention has been shown to be an effective method of care for patients with chronic low-back pain.[10]

The motions within the foot itself are also subject to similar compensation requirements when dorsiflexion of the ankle and metatarsophalangeal joints is restricted. The rocker-bottom type of foot represents a classic form of sagittal accommodation. Should ankle equinus and functional hallux limitus exist simultaneously, the only available site in the

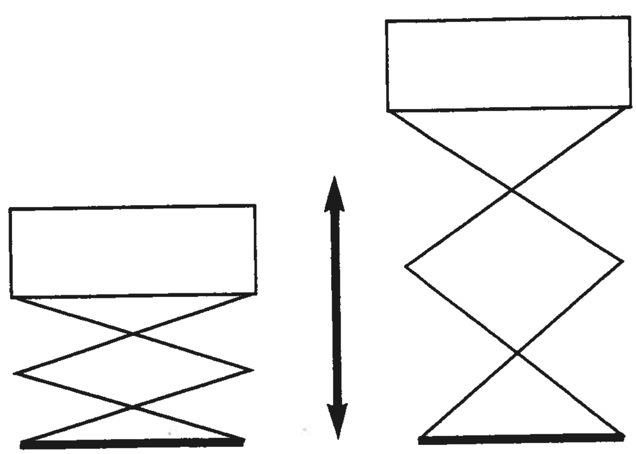

Figure 2. As the scissor-jack is raised, all of the joints extend. The motion of each joint is part of and contributes to the motion of the whole. Failure of one joint to move properly alters the motion of the entire structure.

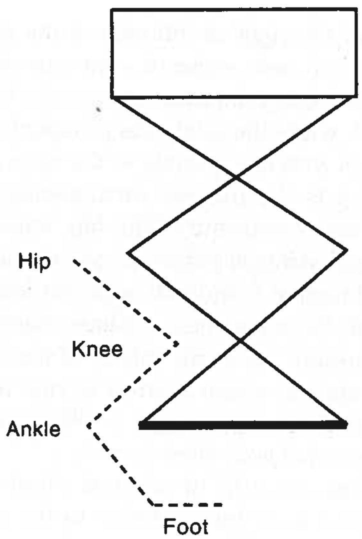

Figure 3. The motion of the scissor-jack is similar to the arrangement of the hip, knee, and ankle. Each joint extends and flexes in the opposite direction, permitting the limb to completely straighten as it extends and contract when it flexes. Failure of the ground pivot to develop creates a need for adjustment in the segments more proximal to the foot.

foot for sagittal plane accommodation is the midtarsal joint oblique axis. In normal biomechanics, the distal and proximal aspects of the plantar side of the midtarsal joint oblique axis move closer to each other during the second half of the single-support phase. If sagittal plane accommodation is required, then these same aspects will instead separate inferiorly and compress superiorly as the midtarsal joint oblique axis is forced to provide sagittal plane motion under the influence of the power being transmitted from above. This causes the medial longitudinal arch to collapse. When one considers that the power to propel the body forward is extrinsic to the foot and must be at least equivalent to body weight if the speed of gait is to be maintained, the magnitude multiplied by the number of steps per day is sufficient to create a continual force capable of creating deformity. There is no mechanical restriction if there is a sufficient amount of ligamentous laxity. In the case of the diabetic patient with insensate feet, there is no neurologic muscular guarding response. In both situations, the rocker-shape deformity results in large part from the pivotal accommodation in accordance with Wolfe's law, "form follows function."

Summary

The intent of this article is to demonstrate the effect of the restriction of sagittal plane motion on both pedal and postural function. The typical methods of gait analysis that are currently employed by podiatric physicians offer only frontal and transverse views and therefore prevent sagittal observation. Because sagittal plane motion is approximately five times the motion of the frontal and transverse components of movement, eliminating the sagittal view represents a compromise in diagnostic ability in the treatment of foot and gait abnormalities.

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