Functional Hallux Limitus and Its Relationship To Gait Efficiency*

HOWARD J. DANANBERG, DPM†

The author describes a new method of viewing gait efficiency, and presents a new entity not visible to even the most trained observer of gait. New theories regarding methods of understanding propulsive efficiency and the symptomatic conditions which result are discussed.

The technological advance of the Electrodynogram®1 system readily reveals the presence of functional hallux limitus. In an abstract way, functional hallux limitus was described over 30 years ago, but because of its inadequate range of motion off weightbearing, it has been overlooked.

In 1953, Hicks[1] described the windlass effect, an automatic, completely mechanical method of raising the arch with every step. It simply involves the extension of the great toe on the first metatarsal, which functionally shortens the plantar aponeurosis. This creates a decrease in the distance between the plantar aspect of the calcaneus and the first metatarsophalangeal joint. A mechanical arch raising and external rotation of the lower leg result.[2] The windlass, however, was thought of as an ineffective mechanism that would stretch out in flat feet.[2]

Data from the Electrodynogram system seem to indicate that it is the functional inability of the great toe to extend, ie, functional hallux limitus, rather than the ineffectiveness of the windlass, that is responsible for the failure of the arch to be raised. It is the belief of the author that it is the functional inability of hallux extension that accounts for much mechanical pathology.

Electrodynogram System

The Electrodynogram system is a highly sensitive, segmental vertical force detector.[3] It consists of a desk top computer console, printer, and unique components capable of sensing, collecting, and storing force data from the plantar surface of the foot. The information is then transferred for further analysis. There are seven separate sensors for each foot. Six are located on the plantar surface as follows: medial heel; lateral heel; first, second, and fifth metatarsal heads; and the interphalangeal joint of the hallux. The seventh sensor is a variable or "X" sensor and can be placed on any site. The data collected are then displayed on a graph as a series of force/time wave forms.

The Electrodynogram system is a major technological advance for studying gait efficiency, providing a new method for examining weight transfer through the foot.

Mechanics of Gait

There are some similarities in locomotion by four-legged creatures and humans.[4] One is the method of generating the power segment of the step. The power, or kinetic energy, is developed by the non-weightbearing limb or limbs. In four-legged propulsion, it can be the forelegs kicking forward and pulling the animal while the hind legs are in ground contact and creating a relative push. In humans, it is the leg engaged in swing phase activity that performs this task.[5] Since the power stroke occurs on the non-weightbearing limb, no friction besides air resistance is present to impede its progress.[4] It is the freedom of movement of this swinging limb that is so important in efficient motion.

The weightbearing limb is responsible for supporting the body. In order to accomplish this, it

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† *Mailing address*: 700 Maple St, Manchester, NH 03194.

®1 The Langer Biomechanics Group, Deer Park, NY.

must function in a fashion so as not to collapse under the stress of body weight. The major osseous components, the femur and tibia, are sturdy and capable of withstanding high levels of vertical force. The knee can be stabilized by the muscle activity of the hamstrings, quadriceps, and gastrocnemius. The trunk is stabilized on the thigh by the hip extensors, gluteus maximus and adductor magnus.[5] The ability to stabilize these joints at the correct time leads to the temporary rigidity necessary for body support. With these joints stable, the stance side can additionally function as a lever arm with respect to the swing limb.

Since a lever is a simple machine, it has a mechanical advantage and efficient work can be performed. This work, which occurs at the contact surface with the ground, can efficiently use the power created by the non-weightbearing, free swinging limb at the opposite end. It can, in effect, use this power to force the ground backwards. If the ground is immobile, then the body can advance. It is this lever effect of the body against the ground that forms the basis for efficient forward propulsion.

Gait is initiated by the swing limb. The body begins in double support phase or, simply, with two feet on the support surface. A slight backward, then forward rocking is created, with the swing limb then lifting off the support surface.[7] As the hip joint flexes, the knee joint extends and simultaneously creates anterior motion to both the knee and foot. This anterior driving motion creates sufficient inertia to advance the body's center of gravity. When the mass center has moved sufficiently forward, its own weight creates a pull on the stance limb.[5] This pulling force causes the stance side foot to begin to unweight from the ground, first from the heel and later from the forefoot. It is this progressive process of unweighting from the heel to the metatarsal heads that creates the driving force against the ground necessary for efficient forward ambulation.[5]

This driving force is known as reactive longitudinal ground shear[8] and can be thought of as a rearward thrust. The body through its path of least resistance, the swing limb, initiates a pull on the center of gravity. The advancing center then acts on the weightbearing limb and uses its length as a lever arm against the ground to create the necessary rearward thrust to push the body ahead. This process is repeated over and over and walking ensues. Conservation of momentum allows for the continued forward progress of the body while the system recycles for the next power phase.[8]

Swing limb activity appears to be the same when compared in subjects examined at equal walking speeds, regardless of body morphology, age, or style of gait.[8] The angular displacement of the hip to the knee to the ankle present in the swing limb appears without significant variation among neurologically normal subjects.[8] The differences in any individual's swing limb activity varies so little that it is statistically insignificant and can be considered a constant when gait is evaluated. It is believed that neural control mechanics govern swing phase motion and that it is a born instinct, rather than a learned response.[8] Infants, prior to learning to walk or crawl, when held erect can create the motion consistent with a normal swing phase. Variations in walking appear to be associated with the stance limb. The ability to use the stance limb appears to be the learned part of walking.[8]

Reactive longitudinal ground shear appears to maximize from a point just after forefoot contact to a point slightly after heel-off (Fig. 1).[8] This peak in rearward thrust, therefore, occurs in the middle of peak activity of the swing limb and corresponds to the midpoint of the single support phase of the stance limb. In other words, the peak propulsive portion of the step occurs in the middle of the stance phase. It is the foot's unique ability to transfer weight and act as a fulcrum that allows the process to occur.[8] Weight transfer occurs as forefoot weightbearing increases. "Weight, however, does not flow through the foot like water through a hose."[9] The forefoot's ability to transfer this increasing weight while acting as an efficient fulcrum is directly related to its angulation to the support surface. Simply stated, the more parallel the longitudinal axis of the metatarsals are to the ground, the less able they are to transfer weight. The more perpendicular the longitudinal axis is to the support surface, the more effectively it can transfer this weight.[9] In order for these weightbearing metatarsals to achieve the efficient vertical position, the foot is provided with a hinge mechanism at the metatarsophalangeal joints. These joints permit sagittal plane motion to occur while the forefoot remains in contact with the ground. It is this motion which must take place so the metatarsals can move toward the vertical position to transfer the weight of the forward moving upper body. It is the ability to efficiently transfer this weight that allows for the proper use of the kinetic energy created by swing limb activity.

Gait Efficiency as Related to Energy Utilization

Since it is during the midportion of the single support phase that the peak force described above

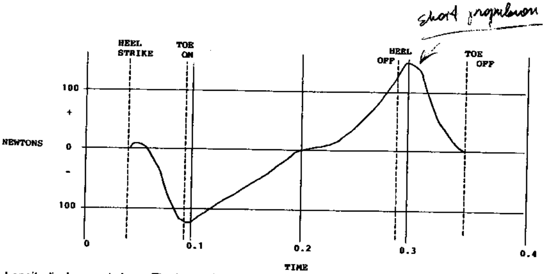

Figure 1. Longitudinal ground shear. The increasing slope of the curve indicates an increase in the reverse thrust. Note the increase between the toe-on and just after the heel-off, indicating peak thrust. Heel-off to toe-off is actually decreasing by comparison to peak thrust.

is generated, it is advantageous to be able to examine the foot during this time in terms of its ability to transfer weight. Since this transfer of weight can be thought of as the foot's level of efficiency in handling these extrinsic forces, then, conversely, lack of this weight transfer can be viewed as inefficiency. It is important to recall the constant nature of swing limb activity. Its ability to generate the power necessary for efficient ambulation is present regardless of the ability of the remainder of the body to use it effectively.

If the foot fails to transfer the weight necessary for the creation of longitudinal ground shear, the kinetic energy developed for that purpose by the swing limb must, therefore, be stored as potential energy. Once potential energy builds, the need to expend it also builds. The visualization of this lack of energy transfer, although present in the electrodynographic analysis of the foot, does not indicate that only pedal symptoms are present. In fact, structural complaints related to improper foot mechanics, ie, low back, knee, or hip pain, may be present when the foot is totally asymptomatic. The level of compensation for the build-up of this potential energy can vary considerably. The author believes that it is this process that may lead to various musculoskeletal pathologies so common in our society.

Functional Hallux Limitus

Functional hallux limitus can be defined as the functional inability of the proximal phalanx of the hallux to extend on the first metatarsal head. During non-weightbearing examination full range of motion can be present in the first metatarsophalangeal joint. The inability of the hallux to extend on the first metatarsal is present only during the stance phase of gait. This restriction of first metatarsophalangeal joint motion may vary in length and be less than 100 msec in duration and invisible to the naked eye. Pain may or may not be present in the joint and the first metatarsophalangeal joint may or may not be associated with the patient's chief complaint.

Functional hallux limitus can occur at almost any point after forefoot contact in the stance phase of the gait cycle. If this blockade coincided with the power segment of the swing phase, the kinetic energy created must be stored as potential energy until such time as release of this energy is possible. Heel lift, created by the pull of the advancing upper body, occurs through sagittal plane motion as well. Since it is sagittal plane motion that is blocked by the inability of the hallux to extend, heel lift must, therefore, be either blocked or delayed.

The two other pedal joints capable of sagittal plane motion are the midtarsal and ankle joints. If functional toe lock occurs, then some compensation may take place in either or both of these joints. These motions, along with forced stretching of the soft tissues inferior to the midtarsal joint, result from the power generated to raise the heel.

To the naked eye, hallux extension can only be seen in relation to heel lift. Metatarsophalangeal joint extension, however, begins to occur before the heel can be seen leaving the support surface. This occurs after the initial shock of impact is reduced. The calcaneus reaches its peak of weightbearing and then gradually unweights until it is no longer in contact with the ground. It is during this period of calcaneal unweighting that extension of the first metatarsophalangeal joint must begin. It allows for the forward transference of weight from the calcaneus to the metatarsal heads.

Prior to the occurrence of visual heel lift, the ability of the metatarsophalangeal joints to extend is not visible to the unaided eye. It is only detectable by analysis of the vertical forces occurring at the forefoot to ground contact. Lowering of medial longitudinal arch is related to the inability of the hallux to extend. Electronic analysis indicates the secondary nature of this midtarsal joint compensation. Failure of this weight transfer to occur is readily visible through computerized vertical force analysis and suggests a pathologic build-up of potential energy as described earlier.

Progressive Variations of Gait

Since it is the stance phase of gait that is the learned, variable portion of the gait cycle, then any changes that may occur can be expected to be seen in this phase. The need for variation in gait patterns seems to be related to the efficiency of the foot to allow for normal sagittal plane motion. Progressive changes related to the necessity of expending stored energy can be expected to occur. As age increases, the ability to create the power necessary to compensate for failure of sagittal plane motion decreases. The decrease in this muscle power associated with the aging process seems to be the underlying factor in the methods utilized in avoiding a locked hallux.

Normal Function. Normal hallux extension at the first metatarsophalangeal joint is accomplished as follows. Heel lift begins as does subtalar supination. The peroneus longus continues to fire and the first metatarsal plantarflexes, using the sesamoids as a fulcrum. Weight transfers from the first to the longer second metatarsal head. This allows for the movement of the proximal phalanx in a dorsal fashion over the head of the first metatarsal in the sagittal plane. This also allows for efficient forward weight transfer through the bones of the foot.[9] The hallux, once making contact with the ground, does not move, but rather the entire foot passes over it.

Forefoot Inversion. The simple process of forefoot inversion is generally sufficient to allow continued sagittal plane motion to occur. This inversion allows two possible compensations. First, the shift of weightbearing to the lateral column of the foot, allows for an unweighting of the first metatarsal head. When sufficient unweighting occurs to allow the peroneus longus relative functional superiority, then appropriate first metatarsal plantarflexion can occur over the sesamoids and allow the hallux to extend. This appears as normal function. When viewed with the Electrodynogram, it is obvious that delayed hallux extension has, in fact, occurred. The second method of compensation is to complete the toe-off phase from the lateral column of the foot. The lateral metatarsals are then used for weight transfer and the associated fulcrum action. Generally, little or no great toe extension occurs in this variation. It may only happen when shoe gear is in place, and, therefore, not be noticed visually.

Premature Liftoff. The midstance to toe-off part of the stance phase of gait needs to follow through smoothly. The normal sequence is the fifth metatarsal, followed by the second then first, or first then second, and the hallux last. This indicates proximal to distal weight flow in an efficient manner. When the toe joints are fully extended, the firing of the extensor tendons allows for ground clearance of the digits and dorsiflexion of the foot as toe-off takes place. When the hallux begins to unweight from the ground before the metatarsals, it is being pulled off prematurely. The heel-off to metatarsal head-off to toe-off sequence is no longer present. The toes are lifted off the ground before the metatarsal heads. Contracted interphalangeal joints can result. The flow of weight then travels in a direction opposite to the reactive longitudinal ground shear. The efficient nature of the follow-through of the step is lost, as is a portion of the conservation of momentum.

Vertical Toe-off with Secondary Bipedal Stance. The final step in the chain of progressive events is vertical toe-off. If hallux lockup is present, then the easiest method of compensation is lifting the foot vertically. This, however, completely removes the ability to create ground shear necessary for efficient propulsion. It also involves a stopping and starting that fails to make use of momentum. The less momentum is utilized, the greater the energy expenditure necessary to accomplish the same task.

Vertical toe-off seems to occur most often in the geriatric population. The loss of the effectiveness in the creation of ground shear is replaced with increased muscular output. Fatigue develops as the speed of gait slows. It has been shown that subjects systematically increased their ratio of double to single support to maintain stability as the pace reduces.[8] It is important to recall the constant nature of the swing phase limb. Since no fulcrum action or ground shear is developed, the energy created must be stored, then released. Locomotion occurs through apropulsive mechanics. Forward bending takes place at the neck and waist. This advances the center of gravity to a point ahead of the foot. Swing activity is used to catch up to the already advanced upper body.

Conclusion

The body's ability to create kinetic energy and subsequent failure to use it effectively seems directly related to the degenerative process that occurs with age. It is the belief of the author that joint stiffness present in these conditions seems to be related to the chronic nature of this process. Reversals in the process have been noted by the author and appear to be related to the effectiveness of the treatments performed. Electrodynographic analysis appears to be a method that is capable of actually viewing and recording these inefficiencies and detecting successes and failures of their treatment.

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