Rethinking the Role of the Plantar Fascia's Windlass Mechanism

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Ever since *Sahelanthropus tchadensis* stood upright 7 million years ago, the feet of our common ancestors have undergone a series of important structural changes necessary to accommodate the functional requirements of bipedal locomotion. While the feet of arboreal primates were well-adapted for grasping branches during movement through tree canopies, their hypermobile midfoot and adducted great toe led to instability and buckling during the pushoff phase of gait, limiting their effectiveness for upright walking and running.

Over millions of years, evolutionary adaptations resulted in modern humans developing an arched foot that is two to three times stiffer than that of current flat-footed primates (1). This increased rigidity facilitates efficient force transfer through the Achilles tendon, midfoot, forefoot, and ultimately into the ground. Although various anatomical factors have contributed to the increased rigidity of the arched foot, such as the development of a stable first ray and the establishment of the transverse tarsal arch (2), the windlass mechanism remains the predominant theory accounting for the human foot's capacity to effectively stiffen its arch during propulsion.

Originally described by Hicks in 1954 (3), the underlying premise of the windlass mechanism is that because the plantar fascia is inherently stiff and unyielding, passive dorsiflexion of the toes during pushoff tractions the plantar fascia around the metatarsal heads, which in turn creates a compressive force that locks the midfoot by tractioning the forefoot and rearfoot together (Fig. 1). Because the first metatarsal head has a larger diameter, the medial band of the plantar fascia is especially effective at increasing arch height. According to Hicks (3), the windlass mechanism is passive in that no muscle activity is necessary to raise the arch. The beauty of this theory is that because the plantar fascia does not consume calories as the windlass mechanism stabilizes the arch, the metabolic cost of locomotion is greatly reduced.

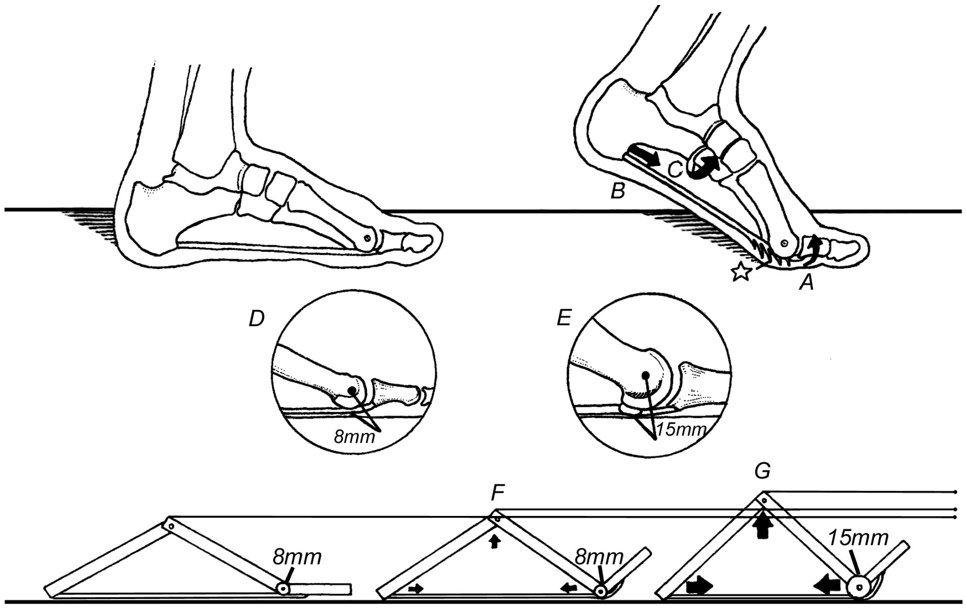


Fig. 1. The Windlass Mechanism. During the propulsive period, ground-reactive forces dorsiflex the toes, which pulls the plantar fascia around the metatarsal heads (**A**). This action results in the approximation of the rearfoot and forefoot (**B**) and allows for the increased arch height necessary for stability (**C**). The amount of pull generated by the plantar fascia is directly related to the distance between the transverse axis of the metatarsophalangeal joint and the passage of the plantar fascia: the greater the distance, the greater the pull placed upon the plantar fascia while the digit dorsiflexes. For example, the average lesser metatarsal has an average of 8 mm between its transverse axis and the passage of the plantar fascia (**D**) while the first metatarsal, with its larger head and the presence of sesamoid bones (which the plantar fascia invest) has a distance of nearly 15 mm between the transverse axis and the plantar fascia (**E**).

Although Hicks' model is widely accepted, some researchers challenge the passive role of the windlass mechanism, as cadaver studies show it produces only a third of the force needed for foot rigidity (4, 5). While some studies show that dorsiflexion of the toes during propulsion does stiffen the plantar fascia (6,7), other studies prove that the plantar fascia actually undergoes appreciable elongation as the toes reach their peak range of dorsiflexion, which goes counter to the entire concept of the windlass mechanism (8,9). Even more significant, some research shows that as the windlass mechanism elevates the arch, the arch actually becomes more compliant or flexible, rather than rigid and stiff. This was conclusively proven by Welte et al. (10). These researchers used linear actuators to compress the longitudinal arch as the toes were placed in a neutral, plantarflexed, or extended position. To their surprise, the authors found that the medial longitudinal arch was more flexible when the windlass mechanism was engaged. The authors theorized that engaging the windlass mechanism places the long and short plantar ligaments in a more midline position, allowing them to store and return energy as the arch compressed. Welte et al. (10) also observed that as the windlass mechanism reached peak tension, the axis of the midfoot shifted vertically, causing the forefoot to abduct. This sudden abduction allowed the abductor hallucis muscle to help stabilize the arch by decelerating forefoot abduction.

The ability of the intrinsic arch muscles to support the plantar fascia and improve stiffness of the midfoot was demonstrated in a particularly well-done study by Farris et al. (11). These researchers used nerve blocks to temporarily paralyze the plantar intrinsic arch muscles before having the subjects walk and run on a treadmill. The authors noted that when the intrinsic arch muscles were paralyzed, the participants were unable to effectively generate power during propulsion, and they were forced to avoid the propulsive period by increasing their step frequency and prematurely lifting their feet off the ground via excessive hip flexion. Farris et al. (11) clearly demonstrate that active muscle contraction, not passive windlass action, creates midfoot rigidity during propulsion. Note that it is not just the intrinsic muscles that play a role in stiffening the arch. A previous cadaveric study demonstrated that when the long digital flexors contract, they create a compressive force in the metatarsal shafts, which helps stabilize the forefoot during propulsion and prevents the metatarsal shafts from bending (12) (Fig. 2).

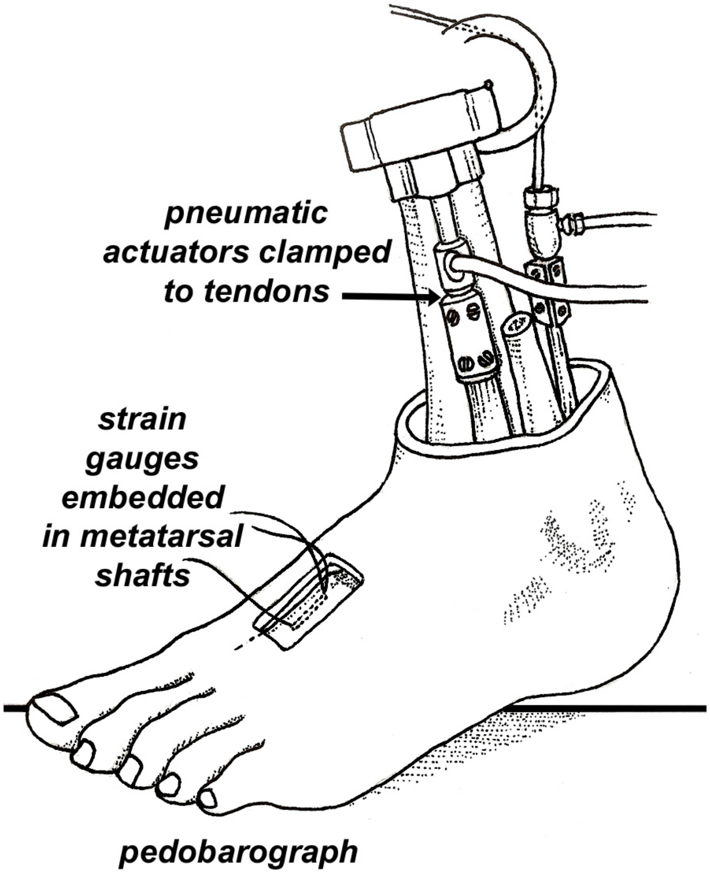
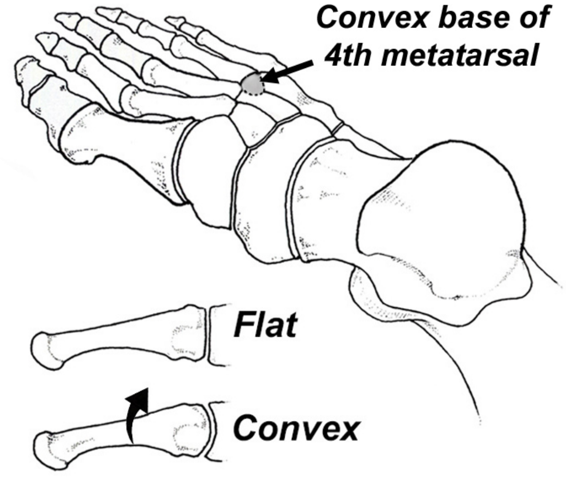


Fig. 2. Ferris et al. (12) mounted cadaveric feet in a heel rise position and measured pressure beneath the forefoot and bending strains in the metatarsal shafts before and after sequentially applying tension to a series of tendons clamped to pneumatic actuators. The authors also embedded strain gauges into the second metatarsal shafts in order to measure bending forces present in the bone with and without simulated muscle contraction. Using this elaborate technique, the authors determined that the primary role of the long digital flexors is to create a compressive force in the metatarsal shafts that protects them from buckling during propulsion. The authors emphasize that weakness of the long digital flexors can have a profound effect on forefoot stability and plantar pressures. Adapted from a photograph by Ferris et al. (12).

According to Kevin Kirby (13), the intrinsic and extrinsic muscles are under direct control of the central nervous system and have the capacity to reinforce the passive ligamentous mechanisms necessary for arch stability as needed. Kirby (13) refers to the interaction between the muscular and ligamentous restraining mechanisms as the Longitudinal Arch Load-Sharing System (LALSS), which he claims allows the body to increase or decrease the stiffness of the medial arch depending upon the stresses the foot is being exposed to. Interestingly, recent research shows that when muscles are engaged to provide stability, the first fibers to be recruited are those with the longest lever arms responsible for limiting excessive articular motion (14). Referred to as the principle of Neural Mechanical Matching, the central nervous system's ability to precisely recruit just the right muscle fibers at the right time would be invaluable for stabilizing the arch against the rapid, and often unpredictable motions associated with walking and running over uneven terrain.

Note the previously described mechanisms in which the plantar fascia and the supporting musculature work to stiffen the midfoot occurs primarily in people with well-formed medial longitudinal arches. As noted by DeSilva et al. (15), a small subset of the population presents with what is known as a "midtarsal break," in which the lateral midfoot maintains ground contact during propulsion as the lateral tarsometatarsal articulations buckle under the stresses of propulsion. The authors note that a midtarsal break is more likely to occur in someone with a convex-shaped base of the proximal fourth metatarsal, which allows the lateral forefoot to dorsiflex during propulsion (Fig. 3). DeSilva et al. (15) state that excessive pronation associated with the midtarsal break prevents the plantar fascia from engaging the windlass mechanism, which undermines the mechanical stability of the foot during propulsion. The authors also note that the excessive pronation associated with the midtarsal break can be countered by a strong abductor digiti minimi muscle and a stiff long plantar ligament. The authors claim the development of a midtarsal break may be "a function of increased foot mobility in western, shod

Fig. 3. As demonstrated by DeSilva (15), while the base of the fourth metatarsal in most individuals is flat, some people have a convex fourth metatarsal base, which allows the entire lateral forefoot to dorsiflex (arrow) under the stresses of propulsion. This sudden dorsiflexion causes the midfoot to buckle as vertical forces peak during pushoff.



humans who do not always develop the musculature necessary to maintain a stiff midfoot." This is consistent with research by Rao and Josephs (16) showing that individuals who are barefoot during childhood are significantly more likely to develop well-formed arches than individuals who wear shoes. Along this same line of reasoning, Miller et al. (17) show that wearing minimalist shoes for 12 weeks produces significant hypertrophy of the abductor digiti minimi muscle, which DeSilva et al. (15) claims may play an important role in stabilizing the lateral midfoot in people presenting with a midtarsal break.

According to Aquino and Payne (18), people with excessive pronation presenting with a hypermobile flatfoot may receive some support for the medial longitudinal arch via what is known as the reverse windlass mechanism. According to these authors, excessive pronation increases strain in the plantar fascia, which in turn allows the plantar fascia to create a compressive force through the midfoot by approximating the rearfoot and forefoot. The increased tension in the plantar fascia is maintained as the proximal phalanx collides into the dorsal aspect of the first metatarsal head (Fig. 4). In this situation, the midfoot is made more stable as the plantar fascia becomes taut. Although potentially destructive to the first metatarsophalangeal joint, tensioning the plantar fascia via the reverse windlass mechanism can reduce tension in some of the supporting musculature, explaining why the cross-sectional area of the abductor hallucis and flexor hallucis brevis muscle are frequently reduced in people with flat feet (19). In contrast, people with low arches often have hypertrophy of other arch-supporting muscles, especially the flexor hallucis longus and flexor digitorum longus (20). This latter finding explains recent findings by Haelewijn et al. (21), who note that it is possible to distinguish between symptomatic and asymptomatic flat-footed individuals by the volume of their flexor digitorum longus and quadratus plantae muscles.

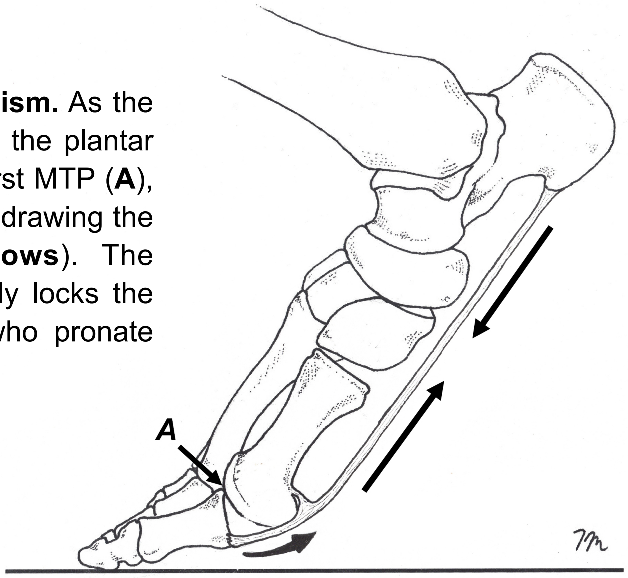


Fig. 4. The reverse windlass mechanism. As the midfoot collapses, increased tension in the plantar fascia prevents upward motion of the first MTP (**A**), but it also creates a stabilizing force by drawing the rearfoot and forefoot together (**arrows**). The reverse windlass mechanism essentially locks the midfoot during propulsion in people who pronate excessively.

Given the key roles the foot and ankle muscles play in stabilizing the foot during propulsion, we suggest practitioners move away from Hicks' passive stability model to a functional approach that prioritizes foot strengthening exercises as a way to stiffen the arch during propulsion. Strength of flexor digitorum longus, flexor hallucis longus, and peroneus longus can easily be evaluated with a toe strength dynamometer (Fig. 5). Because this device has an interrater reliability of 0.95 (22), it allows the practitioner to accurately monitor progress when performing foot strengthening protocols. Keep in mind that while many foot strengthening programs are commonly recommended, not all are equally effective. Osborne et al. (23) recently assessed EMG activity and torque generated at the metatarsophalangeal joints with 16 commonly prescribed foot and ankle exercises and discovered an intriguing paradox: certain exercises elicited substantial muscle activation, yet these EMG increases did not correspond to greater force output beneath the forefoot. Specifically, the short foot, squat, and toe spread exercises, which are frequently prescribed in foot strengthening programs, were relatively ineffective at increasing metatarsophalangeal joint torque. The authors state the mismatch between muscle activation and force output occurs because the muscles are exercised in their shortened positions, which greatly impairs force production.

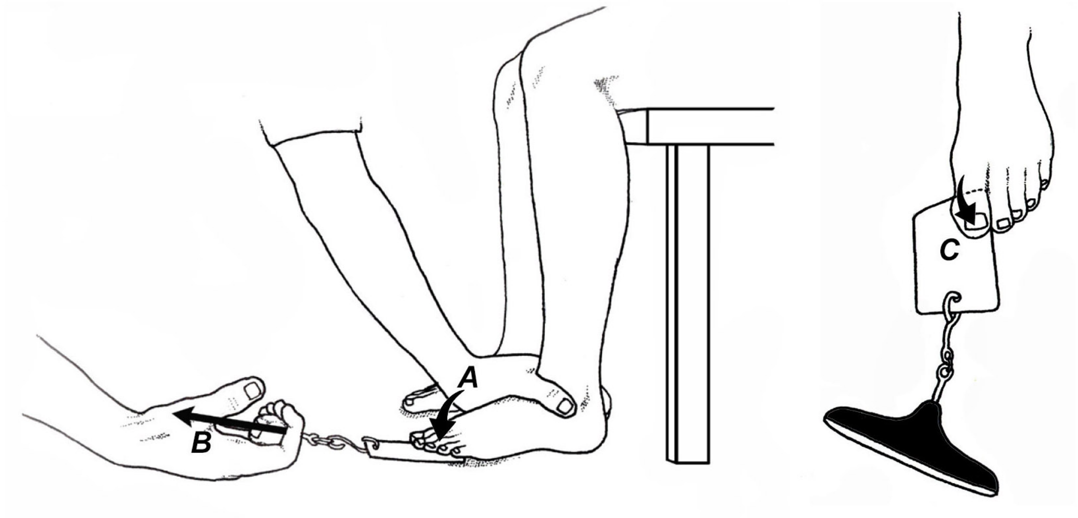
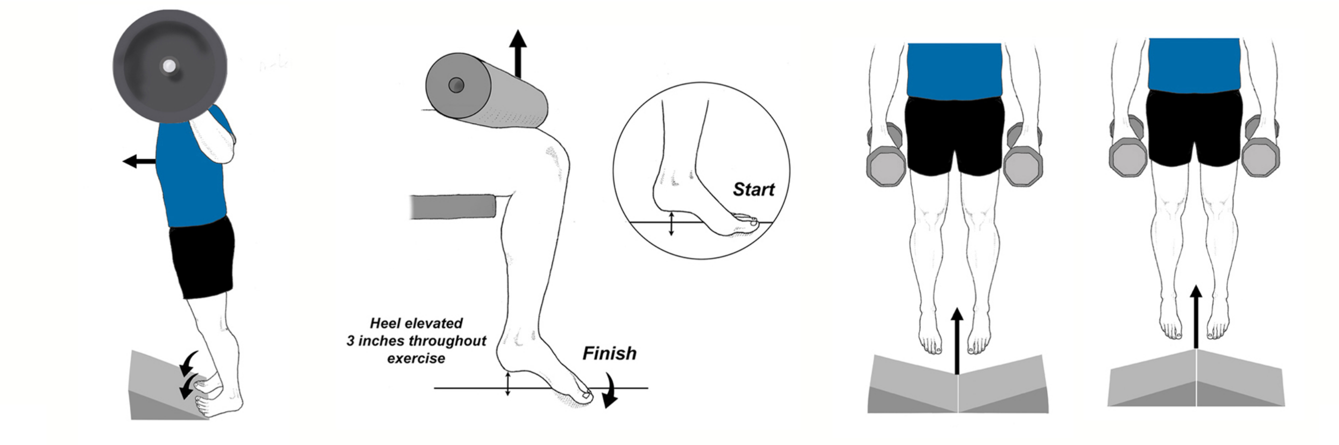


Fig. 5. The toe strength dynamometer makes it possible to easily measure and record toe strength. With the device placed beneath the second through fifth toes, the patient pushes down (**A**) as the examiner tries to pull the card out from beneath the toes (**B**). A digital score is recorded, and the test is repeated beneath the hallux (**C**). Ideally, the patient should generate 10% body weight beneath the hallux and 7% body weight beneath the lesser toes. Peroneus longus can be tested by placing the tip of the card beneath the first metatarsal head, and people should generate approximately 10% body weight with this test.

Following this logic, other commonly prescribed foot strengthening exercises, such as towel curl and marble pickup exercises, would also produce negligible changes in force output beneath the toes and should therefore be avoided. As demonstrated by Goldman et al. (24), optimal effectiveness in strengthening the toe muscles is achieved when exercises are performed with toe muscles in their lengthened positions, resulting in strength gains that are four times greater than those observed with conventional exercise methods.

One of the most effective foot strengthening routines is the ToePro exercise platform. A pilot study from Temple University (25) demonstrated that performing ToePro exercises three times a week for six weeks led to a 35% increase in force generated beneath the hallux and lesser toes. As strength improves, more challenging exercises can be introduced. Tourillon et al. (26) recently conducted an eight-week strength program with 28 highly trained athletes. The authors discovered that these exercises, many of which are illustrated in figure 6, not only strengthen the intrinsic and extrinsic muscles of the arch but they also improve athletic performance. Specifically, the prescribed foot strengthening exercises enhanced cutting ability, improved side-to-side force transfer, and resulted in greater vertical propulsion at top running speeds. The improved athletic performance was probably due to both the intrinsic and extrinsic muscles' effectiveness in stabilizing the arch, which allowed accelerational forces created in the foot and leg to be transferred efficiently into the ground.



Weighted forward lean with toes on slant board

Full effort first MTP plantarflexion

Forefoot rebound jumps on slant boards

Fig. 6. The foot strengthening routine recommended by Tourillon et al. (26). Note that this is an open access journal and the entire training routine is available at the following website: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0313979

While historically healthcare professionals have attempted to reinforce the windlass mechanism by prescribing orthotics with varus posts that lock the midfoot, this treatment approach comes at a price. Several studies have shown that prolonged use of arch supports can cause atrophy of the intrinsic muscles of the foot (27,28). Another important consideration is that arch supports have been proven to limit the storage and return of energy while running (29). While orthotics have a long-term record of effectively reducing symptoms in people with hypermobile flat feet, they should always be prescribed with specific foot strengthening exercises to prevent atrophy and maintain a strong arch. The upside of strengthening interventions is that they are easy to perform, inexpensive, and have been repeatedly proven to improve athletic performance, particularly horizontal jump distances, and medio/lateral cutting. By prescribing orthotics with foot strengthening exercises, you get the best of both worlds as the orthotics can enhance proprioception and decelerate the velocity of pronation; while strengthening exercises can reinforce the windlass mechanism, making the foot a more effective lever while walking and running.

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