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Plantar Fasciitis and the Windlass Mechanism: A Biomechanical Link to Clinical Practice

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Objective: Plantar fasciitis is a prevalent problem, with limited consensus among clinicians regarding the most effective treatment. The purpose of this literature review is to provide a systematic approach to the treatment of plantar fasciitis based on the windlass mechanism model.

Data Sources: We searched MEDLINE, SPORT Discus, and CINAHL from 1966 to 2003 using the key words *plantar fasciitis, windlass mechanism, pronation, heel pain,* and *heel spur.*

Data Synthesis: We offer a biomechanical application for the evaluation and treatment of plantar fasciitis based on a review of the literature for the windlass mechanism model. This model provides a means for describing plantar fasciitis conditions such that clinicians can formulate a potential causal relationship between the conditions and their treatments.

Conclusions/Recommendations: Clinicians' understanding of the biomechanical causes of plantar fasciitis should guide the decision-making process concerning the evaluation and treatment of heel pain. Use of this approach may improve clinical outcomes because intervention does not merely treat physical symptoms but actively addresses the influences that resulted in the condition. Principles from this approach might also provide a basis for future research investigating the efficacy of plantar fascia treatment.

Key Words: heel pain, pronation, rehabilitation

Plantar fasciitis is a commonly encountered orthopaedic problem[1,2] affecting a wide range of athletic adults. Chandler and Kibler[3] reported a 10% occurrence rate in runners. Plantar fasciitis is an inflammation of the plantar fascia and the perifascial structures.[4,5] Kwong et al[4] classified it as a syndrome resulting from repeated trauma to the plantar fascia at its origin on the medial tubercle of the calcaneus.

Historically, the literature attributes plantar fasciitis to faulty biomechanics such as excessive pronation.[3,4,6,7] Structural deformities such as forefoot varus may result in excessive pronation during gait. Overpronation contributes to excessive foot mobility, which can increase the level of stresses applied to the musculofascial and soft tissue structures through plantar fascial elongation and increased tissue stress.[5,8,9]

Pronation does not necessarily lead to lower extremity problems. Donatelli et al[10] analyzed the static and dynamic foot postures of 74 professional baseball players. Although 43% of subjects demonstrating excessive pronation reported previous lower extremity injuries, the remaining 57% with similar pronatory patterns experienced no difficulties. These researchers concluded that excessive pronators were no more likely to be injured than those without excessive pronation. Other researchers similarly reported that excessive pronation, in and of itself, did not result in lower extremity abnormalities.[11,12]

Many studies have demonstrated that excessive foot motion is not deterministic of lower extremity problems.[13–15] Cornwall[16] stated that difficulties result when the joints of the foot are continually functioning beyond a normal end range. This can lead to greater stress along the medial joint capsules and ligamentous structures. Additionally, muscles such as the posterior tibialis can be in a lengthened position and are easily fatigued in an attempt to control excess motion. These stresses lead to pain, discomfort, and further lengthening.[3,4] These authors concluded that plantar fasciitis results from the duration of motion and not merely from the motion itself.

Researchers have also reported faulty biomechanics and plantar fasciitis in subjects with a higher-arched foot.[16–18] A higher-arched foot lacks the mobility needed to assist in absorbing ground reaction forces. Consequently, its inability to dissipate the forces from heel strike to midstance increases the load applied to the plantar fascia, much like a stretch on a bowstring.[4]

A review of the literature reveals that a person displaying either a lower- or higher-arched foot can experience plantar fasciitis. Patients with lower arches have conditions resulting from too much motion, whereas patients with higher arches have conditions resulting from too little motion.[4,16,19] Therefore, people with different foot types experience plantar fascia pain resulting from different biomechanical stresses.

The ''windlass mechanism'' is a mechanical model that provides a thorough explanation of these biomechanical factors and stresses. The windlass mechanism describes the manner by which the plantar fascia supports the foot during weight-bearing activities and provides information regarding the bio-

Figure 1. The triangle shows the truss formed by the calcaneus, midtarsal joint, and metatarsals. The hypotenuse (horizontal line) represents the plantar fascia. The upward arrows depict ground reaction forces. The downward arrow depicts the body's vertical force. The orientation of the vertical and ground reaction forces would cause a collapse of the truss; however, increased plantar-fascia tension in response to these forces maintains the truss's integrity.

mechanical stresses placed on the plantar fascia. Such information is important clinically because it may provide health care professionals with a clear understanding about the relationship between abnormalities and biomechanical influences.[14–16] A clear understanding of these principles will enhance the decision-making process involved in the evaluation and treatment of patients with plantar fasciitis.[20]

Our purpose is to describe and explain the causes and appropriate treatment of plantar fasciitis from a biomechanical perspective. This article will (1) define the windlass mechanism, (2) relate normal foot biomechanics to the gait cycle, (3) explain changes in arch height during gait, and (4) relate biomechanical dysfunction to plantar fascia abnormalities. We will conclude by applying biomechanical principles to clinical practice. This application will provide the clinician with an evidence-based approach toward the evaluation and treatment of plantar fasciitis.

The Windlass Mechanism

Hicks[21] originally described the foot and its ligaments as an arch-like triangular structure or truss. The calcaneus, midtarsal joint, and metatarsals (the medial longitudinal arch) formed the truss's arch. The plantar fascia formed the tie-rod that ran from the calcaneus to the phalanges. Vertical forces from body weight travel downward via the tibia and tend to flatten the medial longitudinal arch. Furthermore, ground reaction forces travel upward on the calcaneus and the metatarsal heads, which can further attenuate the flattening effect because these forces fall both posterior and anterior to the tibia (Figure 1).[22]

The plantar fascia prevents foot collapse by virtue of its anatomical orientation and tensile strength. The plantar aponeurosis originates from the base of the calcaneus and extends distally to the phalanges (Figure 2). Stretch tension from the plantar fascia prevents the spreading of the calcaneus and the metatarsals and maintains the medial longitudinal arch.[14,20,23]

A ‘‘windlass’’ is the tightening of a rope or cable.[14] The plantar fascia simulates a cable attached to the calcaneus and the metatarsophalangeal joints. Dorsiflexion during the propulsive phase of gait winds the plantar fascia around the head of the metatarsal. This winding of the plantar fascia shortens the distance between the calcaneus and metatarsals to elevate the medial longitudinal arch. The plantar fascia shortening that results from hallux dorsiflexion is the essence of the windlass mechanism principle.[4,5,20,22–25]

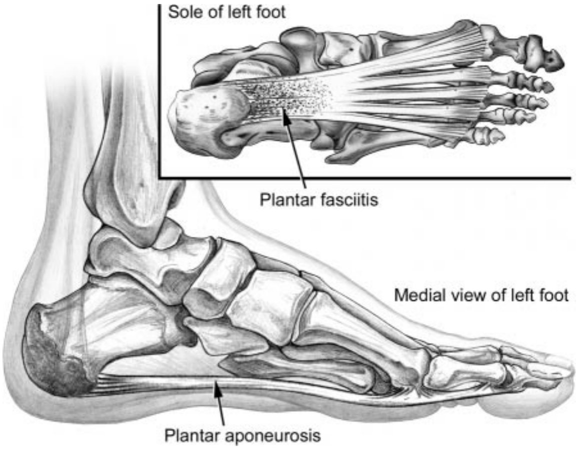

Figure 2. The plantar aponeurosis originates from the base of the calcaneus and extends distally to the phalanges.

Biomechanical Considerations of the Foot During Gait

The foot serves several important functions.[26] It enables propulsion through space, adaptation to uneven terrain, absorption of shock, and support of body weight. The foot forms a rigid lever arm that gives us the ability to push off, primarily from the hallux, during the terminal-stance phase of gait. Terrain adaptability is necessary to walk or run on uneven surfaces.[19] Shock absorption refers to dissipation of ground reaction forces. Ground reaction force represents the force generated when the foot contacts the ground; this force is equal but opposite to the force the foot applies to the ground.[27] Finally, the foot supports the body's weight in both static and dynamic weight-bearing positions.[19]

Donatelli[6] described the following phases of gait during stance: heel contact, weight acceptance, midstance, push-off and propulsion, and toe-off. The gait cycle begins with the foot in a supinated position at heel strike. The subtalar joint then immediately pronates when going from heel strike to weight acceptance. This period of pronation results in the increased foot mobility needed to absorb ground reaction forces and adapt to uneven terrain.[18] The foot reaches maximum pronation at the end of the weight-acceptance phase, and the subtalar joint supinates the foot from midstance through toe-off.[26] This supination movement transforms the foot into the rigid lever arm needed for propulsion.

During gait, many forces stress the foot and could disrupt the medial longitudinal arch. Without a mechanism to maintain this arch, we could not walk in a systematic and efficient manner. The orientation of the plantar fascia helps maintain the arch throughout gait and contributes significantly to the appropriate amount and timing of pronation and supination during the gait cycle.

Variations During Gait

Radiographic examination of the foot can describe the changes in the medial longitudinal arch height. The articular facets of the talonavicular and calcaneocuboid joints form a continuous S-shaped curve on lateral radiograph named the Cyma line.[28] During pronation, the talus slides anteriorly, forms an anterior break in the Cyma line, and places the talonavicular joint distal to the calcaneocuboid joint. During supination, the talus moves posteriorly into the ankle mortise. This translation forms a posterior break in the Cyma line because the talonavicular joint is now proximal to the calcaneocuboid joint. These radiographic data depict the normal stresses placed on the plantar fascia in the pronated and supinated positions.

These radiographic data also depict the stresses placed on the plantar fascia during gait. From heel strike to weight acceptance, pronation increases the relative distance between the calcaneus and metatarsals and applies a tension stress to the plantar fascia (Figure 3). From midstance through the propulsive phase, supination occurs so that the foot can become a rigid lever arm, using the windlass mechanism, to propel the body forward. Forces generated during supination also apply tension to the plantar fascia, just as in pronation.[14,20]

Forces generated during pronation and supination increase plantar fascia tension. Inefficient foot function can lead to increased tissue stress.[4,16] The foot must have a balance between pronation and supination. Too much or too little of either motion at the wrong time of the gait cycle leads to inefficient foot function and potential dysfunction.

Biomechanical Influences on Plantar Fascia Abnormalities

The previous discussion illustrates how the vertical and ground reaction forces stress the plantar fascia tissues. Integral to this discussion is the fact that plantar fascia pain results from excessive traction forces (increased tension) applied to the calcaneus. Fuller[20] stated that fascial stretching caused pain either to the plantar fascia itself or at the attachment to the bone. High tension in the fascia could also cause a periosteal lifting at its insertion on the calcaneus, and bone healing could cause growth of a spur that might be seen at the calcaneus. An understanding of this traction stress explains why the bone spur grows in a direction horizontal to the ground. The Wolff law states that mechanical stresses influence and modulate bone growth.[29,30] The direction and amount of pull from the fascia on the calcaneus form the bone spur.

Onwuanyi[31] noted that plantar heel pain in combination with heel-spur formation occurs in about 50% of patients; however, other researchers doubt the contribution of the heel spur to the condition.[13,18] Tountas and Fornasier[13] retrospectively reviewed the charts of 20 patients who had undergone resection of the proximal plantar fascia and heel spur. They took radiographic images an average of 40 months after surgery and found that subjects with a re-emergence of the bone spur still reported high functional outcomes. The authors concluded that the intrinsic changes within the plantar fascia rather than the heel spur itself resulted in the condition.

These results support the belief that pain occurs not from the bone spur but from the excessive tension applied to the plantar fascia.[4,8] Excessive tension causes tissue irritation to the plantar fascia as well as to its origin at the medial calcaneal tubercle. Clinicians can reproduce this symptom using the windlass test, as described by Brown[32] in a weight-bearing position. This test employs forceful great-toe extension with the person standing; a positive test reproduces pain at the medial calcaneal tubercle. Even though researchers[33] have reported 100% specificity but only 31.8% sensitivity with this test, clinicians may find it useful in determining plantar-fascial tissue irritation. In summary, the review of the literature provides evidence that plantar fasciitis results from increased plantar fascia tension; therefore, successful management depends on reversing the factors leading to excessive strain.

Bridging Science to Clinical Practice

Abnormalities Resulting From Overpronation. One cause of plantar fasciitis is prolonged foot pronation.[3,8,16,17] Patients with pronation problems have a more flexible, lower-arched foot; thus, effective treatment depends on controlling pronation. Factors that contribute to excessive pronation include muscle weakness, heel-cord tightness, and structural foot deformities.[4,16]

Thordarson et al[34] found that the posterior tibialis muscle provided the most significant dynamic arch support during the stance phase of gait. The posterior tibialis eccentrically lengthens to control pronation and reduce the tension applied to the plantar fascia during weight acceptance. Excessive pronation can cause posterior tibialis weakness and plantar fascia elongation. The elongation minimizes efficient use of the foot's windlass mechanism because of instability during the propulsive phase of gait.[17,18,35] Alternately, controlled pronation provides for the appropriate timing of supination during gait.

The combined effects of the flexor digitorum longus, flexor hallucis longus, peroneus longus, and Achilles tendons permit the supination needed to enhance the windlass mechanism.[34] The peroneus longus courses under the cuboid and attaches to the base of the first ray. Supination from midstance to the propulsive phase transforms the cuboid into a rigid structure that enhances the peroneus longus pulley system.[6] This pulley system assists the peroneus longus with first metatarsal plantar flexion.[6] Therefore, the plantar flexors enhance supination so that the cuboid pulley system can plantar flex the first ray and promote efficient use of the windlass mechanism.

Proximal muscle weakness from the gluteus medius, gluteus minimus, tensor fascia latae, or quadriceps muscles can contribute to plantar fascia abnormalities. Weakness in these muscles inhibits their ability to assist with the lower extremity load response, which results in greater transmission of shock to the supporting foot structures.[3] Furthermore, gluteus medius, gluteus minimus, and tensor fascia latae weakness can accelerate lower extremity pronation.[36] In summary, proximal muscle weaknesses can lead to poor shock absorption and decreased pronation control.

The literature reports heel-cord tightness in patients with plantar fasciitis.[15] Ankle dorsiflexion is necessary during the gait cycle to allow the body to pass over the foot[26]; a tight Achilles tendon limits the amount of dorsiflexion available during gait. A person with a flexible foot type can compensate for this lack of ankle dorsiflexion by unlocking the midtarsal joint because dorsiflexion and abduction are movements allowed at the midtarsal joint's oblique axis. This increased motion results in excessive pronation that can stress the plantar fascia.[6,8,15]

Structural deformities such as an excessive subtalar or forefoot varus can contribute to plantar fascia problems. An ex-

Exercises to Control Excessive Pronation*

Impairment	Goal	Intervention
Decreased intrinsic ankle pronation control	■ Improved posterior tibialis strength	■ Ankle inversion using elastic band, emphasizing eccentric control ■ Side-lying ankle inversion using ankle weight, emphasizing eccentric-phase control ■ Single-leg–stance balance activities with a neutral foot position (progress by incorporating uneven surfaces and eliminating visual cues)
Decreased intrinsic ankle supination control	■ Improved ankle plantar-flexor strength ■ Improved intrinsic foot musculature strength	■ Heel raises with the foot in a toed-in position ■ Arch raises with the foot in a weight-bearing position ■ Stand and bring the foot into and out of weight-bearing pronation-supination
Decreased extrinsic ankle pronation control	■ Improved proximal hip-musculature strength	■ Wall slides with a neutral foot position ■ Lateral step-downs on 4-in (10.16-cm) step with a neutral foot position ■ Single-leg stance with neutral foot position while performing proprioceptive neuromuscular facilitation patterns using elastic band with contralateral leg

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cessive forefoot varus is a frontal-plane deformity in which the forefoot is in an inverted position of more than 8° relative to the rearfoot.[6,8,37] Johanson et al[37] defined a compensated forefoot varus as compensatory subtalar pronation that allows the medial metatarsal heads to contact the weight-bearing surface. In other words, when the heel initially hits the ground, the foot must pronate excessively to allow the forefoot to contact the ground. This excessive pronation stresses the plantar fascia and inhibits efficient use of the windlass mechanism. A subtalar varus deformity of more than 10° can similarly contribute to excessive pronation.[38]

Treatment Principles Related to Abnormalities Resulting From Overpronation. When the cause is mechanical, the rehabilitation plan should use interventions designed to relieve plantar fascia inflammation while correcting mechanical factors.[4,9,19] Rehabilitation interventions should focus on restoring normal muscle strength, improving muscle flexibility, and normalizing biomechanical influences. First, strengthening should incorporate all muscles involved with controlling pronation and facilitating the windlass mechanism. The program should strengthen the posterior tibialis, ankle plantar flexors, and peroneus longus muscles as well as the proximal hip and knee musculature. The Table summarizes exercises that effectively strengthen these muscle groups.

The rehabilitation program should also include pain-free calf stretching. Worrell et al[39] reported increased ankle dorsiflexion after calf stretching regardless of foot position. Patients may perform stretches in a non–weight-bearing position and progress to a more aggressive weight-bearing position. Backstrom and Moore[8] also suggested stretching using a contract-relax-contract proprioceptive neuromuscular facilitation method.

Finally, the clinician should consider biomechanical control if the patient has a foot deformity that contributes to excessive pronation. Orthoses are commonly prescribed, and the literature supports the use of medial wedging in controlling pronation.[4,37,40] Alternatively, Kogler et al[41] measured plantar aponeurosis strain in cadaveric lower limbs using different wedging combinations under the forefoot and hindfoot. They reported that a 6° wedge placed under the lateral aspect of the forefoot demonstrated the greatest reduction in plantar aponeurosis strain. Although these researchers suggested a lateral wedging approach, we believe that further studies should be conducted to determine the effectiveness of lateral wedging in people with plantar fasciitis.

Proper shoe wear is another very important component because a shoe's design can enhance stability.[42] Today's market offers motion-control and stability shoes. Features of these shoes include a semicurved outer sole shape with either a slip or combination last (construction of the insole). The shoes should have sufficient toe-box width and forefoot flexibility to enable the midfoot and rearfoot to easily roll over the forefoot.

Motion-control and stability shoes also have a firm heel counter and a firm midsole to control the amount of pronation.[4] Polyurethane or a combination of polyurethane and ethylene vinyl acetate is commonly used in midsole construction. Polyurethane is a synthetic rubber material that can enhance shoe support and durability. Ethylene vinyl acetate is a lightweight material that provides cushioning and resiliency against compressive forces. The clinician's choice between either a motion-control or stability shoe generally depends on the degree of pronation control required in relation to the person's size.

Abnormalities Resulting From Underpronation. Plantar fasciitis in the rigid, higher-arched foot (pes cavus) results from the foot's inability to dissipate force.[16,19] Effective treatment depends on improving flexibility. Factors that contribute to underpronation include limited joint mobility, decreased plantar fascia extensibility, and increased muscle tightness.

A cavus foot lacks normal joint mobility; it also has limited pronation to dissipate forces.[43] Decreased shock absorption results in increased tension forces being applied to the insertion of the plantar fascia at the medial calcaneal tubercle. Kwong et al[4] described this increased load to the plantar fascia as a stretch on a bowstring.

Patients with a cavus foot have a decreased distance between the calcaneus and metatarsal heads (Figure 3). People with a cavus foot also have a rigid, plantar-flexed first ray that

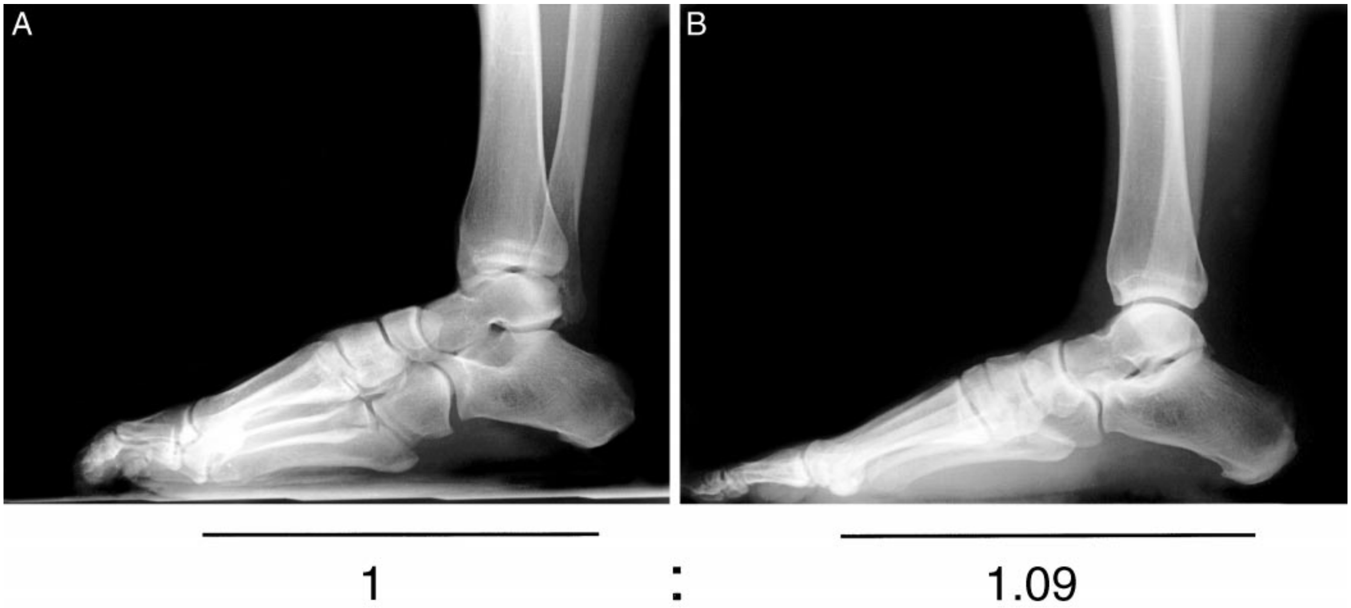

Figure 3. The figure compares the length of the plantar fascia in different foot positions. A, The foot in a supinated (higher-arch) position. B, The foot is in a pronated (lower-arch) position. The ratio of the supination length to the pronation length is 1:1.09.

can further shorten this distance. A plantar-flexed first ray occurs when the first ray has dropped to a relatively plantar-flexed position in comparison with the other rays.[8] This position effectively increases the ''winding'' under the first metatarsal head as described by the windlass model. Therefore, the combination of a high arch and plantar-flexed first ray places a continuous tension on the plantar fascia that can lead to adaptive tissue shortening.

People with a cavus foot also have decreased gastrocnemius, soleus, and Achilles tendon flexibility. Collagen fibers from the Achilles tendon surround the posterior aspect of the calcaneus to blend into the superficial layers of the plantar fascia.[14] By virtue of this orientation, ankle dorsiflexion during the gait cycle applies more tension to the plantar fascia. This increased tension leads to inflammation either at the medial calcaneal tubercle or within the plantar fascia itself.

Treatment Principles Related to Abnormalities Resulting From Underpronation. Rehabilitation interventions should focus on improving plantar fascia extensibility, normalizing joint mobility, improving muscle flexibility, and supporting the longitudinal arch. Ultrasound and soft tissue techniques can improve plantar fascia extensibility; joint mobilization techniques can improve first ray and subtalar joint mobility. Together, soft tissue extensibility and improved joint mobility will enhance normal pronation to assist with shock absorption.

Gastrocnemius and soleus muscle stretching is most frequently recommended in the literature.[3] Pfeffer et al[44] reported a 72% improvement in subjects participating in an 8-week stretching program. This study demonstrates the efficacy of stretching because improved Achilles tendon flexibility decreases the tension applied directly to the plantar fascia.[14] Clinicians can also use proprioceptive neuromuscular facilitation techniques to improve flexibility.[8]

The literature also supports using a night splint to improve flexibility.[1,45] Plantar fascia pain is the most severe in the morning.[3,9,45] Overnight, the foot is in a prolonged plantar-flexed position. Consequently, the first steps taken in the morning result in pain because of the stretch to the inflamed tissues. The premise of night splints is to keep the foot in a slightly dorsiflexed position to minimize plantar-fascial shortening during sleeping hours.

During waking hours, arch taping is a viable treatment choice. Low-dye taping helps support the foot to optimize ligament and muscle function that can help decrease the tensile forces placed on the plantar fascia.[46] Taping is a cost-efficient treatment choice, especially for people having acute symptoms of plantar fascia problems.[46,47]

Shoe wear is an important treatment consideration. A cushion-type running shoe can provide shock absorption. Features of a cushion shoe include a curved outer sole shape with a slip last. This shoe should allow for mobility in both the rearfoot and forefoot and should not contain features such as a heel counter. Unlike the motion-control or stability shoe, the cushion shoe midsole is commonly made with ethylene vinyl acetate. As mentioned previously, ethylene vinyl acetate is a lightweight material that is resilient against compressive forces and offers much shock absorption. Finally, an accommodative orthosis or silicone heel pad can further enhance shock absorption.[8,44]

CONCLUSIONS

Plantar fasciitis is a commonly treated foot problem and affects a variety of people with different foot types. Although plantar fasciitis is a prevalent problem, little scientific evidence exists concerning the most appropriate intervention.[1] We provide a biomechanical application for the evaluation and treatment of plantar fasciitis based on the windlass mechanism model. This model can describe plantar fascia abnormalities in terms of overpronation and underpronation to help formulate possible relationships between conditions and treatments. Such relationships should guide the decision-making process concerning the evaluation and treatment of heel pain. Use of this approach may improve clinical outcomes because rehabilitation intervention does not merely treat physical symptoms but actively addresses the influences that resulted in the condition. Finally, principles from this approach might provide a basis for future research investigating the efficacy of plantar fascia interventions.

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