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Friction Blisters of the Feet: A Critical Assessment of Current Prevention Strategies

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Friction blisters are a common injury of the feet sustained by individuals participating in sporting, recreational, and military activities. The high incidence of friction blisters brings into question the effectiveness of common prevention strategies. The purpose of this article was to review current evidence for established blister-prevention strategies and to explore how these interventions address the factors that cause friction blisters. Preventive strategies, focusing on previously overlooked elements of the blister-causing mechanism, are proposed. Areas of future research that are much needed to reduce this common skin injury in active individuals are outlined.

Key Words: shear, foot blister, blister prevention, skin injury, running injury

Key Points

- A friction blister is an intraepidemeral tear caused by repetitive shear deformation.
- Opportunities to prevent blisters include maximizing the intrinsic resilience of the skin to shear deformation, reducing the number of shear deformation episodes, and reducing the magnitude of shear deformation.

The continued high incidence of friction blisters of the feet brings into question the effectiveness of common prevention strategies. Effectively preventing friction blisters before participation in long-distance walking and running has been a daunting task for participants as well as treating clinicians, perhaps in part due to a long-held oversimplification or misunderstanding of the pathomechanics of blister formation.

Friction blisters are not the result of materials or objects rubbing on the skin surface. Rather, they represent an intraepidermal tear resulting from shear deformation beneath the skin surface.[1–5] Specifically, the underlying bones move back and forth during ambulation, while high friction forces acting between the skin surface and footwear interfaces provide traction that causes the skin surface to remain stationary for push-off.[6] The subsequent shear deformation, when repetitive, results in mechanical fatigue within the stratum spinosum,[1,3,5–8] which later fills with plasma-like fluid to create a blister.[9,10]

The 3 fundamental components of the mechanism causing friction blisters are the following: moving bone,[6,8] high friction force,[2,3] and repetition of the resulting shear events.[1,3–5,11] Until now, the contribution of bone movement to friction blisters has been largely ignored or unrecognized,[6] but it presents fruitful ground for new strategies in blister prevention. The second element, friction, is widely accepted, although often inappropriately assumed to be a rubbing phenomenon against the skin rather than the actual mechanism whereby the skin surface and footwear interfaces remain stationary and unable to move "in synch" with the underlying bone.[8] Finally, the third element, repetition, can be appreciated because blisters are known to occur primarily in endurance activities.[12–23] Given that all 3 elements are required for blister formation, appropriate preventive strategies can focus on each component.

Our purpose in preparing this article was to consider the evidence for established blister-prevention strategies and to examine how these measures take into account the factors that cause friction blisters. We propose preventive interventions that address elements of the blister-causing mechanism that have been ignored to date. We also suggest topics for future investigation to decrease the occurrence of friction blisters in active people.

PREVENTION OF FRICTION BLISTERS

A friction blister results from mechanical fatigue within the stratum spinosum layer of the epidermis. The pathomechanics of the blister event depend on the following 3 factors: (1) the number of shear cycles, (2) the intrinsic resilience of the skin to shear deformation, and (3) the magnitude of shear deformation. Each of these factors can be targeted as part of a friction blister prevention strategy (Figure 1).

Reduce the Number of Shear Cycles

Repetition of shear deformation within the skin is required for blister formation.[1,3–5,7,11] Comaish[4] observed that the blister injury results from epidermal fatigue to repetitive shearing forces, perhaps in association with increased tissue

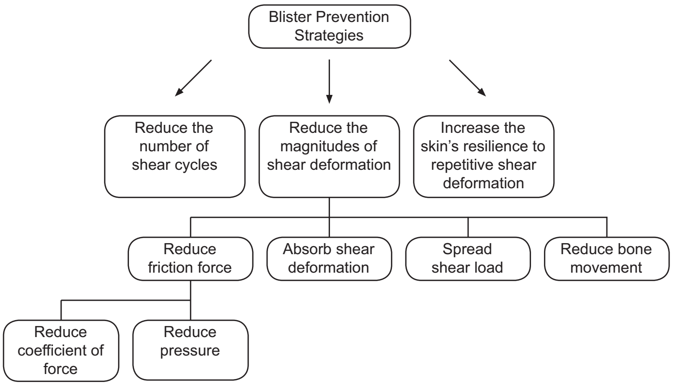

Figure 1. Blister-prevention strategies mechanisms of action.

temperature. At the same time, the author emphasized that friction injury did not depend on wear, enzymes, pressure, stretching, or ischemia and that repetition of the mechanical insult was an important cause.[4] This notion is supported by the fact that blisters are more common in activities that involve repetition of steps, such as long-distance running, hiking, endurance military training, and protracted tennis matches.[14,19–21,24–27]

In experimental blister studies, researchers[1,3,5] have used both the frequency and duration of shear cycles as data endpoints for the formation of a blister. Indeed, an inverse relationship exists between the number of shear cycles and the magnitude of shear required to produce intraepidermal mechanical fatigue.[6,11] Therefore, in spite of high shear loads, the risk of blistering can be reduced by limiting the number of shear cycles.[1,3,5] Implementing a strategy to reduce shear cycles may be feasible during training for a specific event. However, on the actual day of the event, the total number of shear cycles (foot strikes) will be determined by the requirements for exercise completion and, in most cases, cannot be modified.

Increase the Intrinsic Resilience of the Skin to Repetitive Shear Deformation

Individual variations in the time to blister are large, as shown in experimental studies, suggesting that some people are more susceptible than others.[26] Naylor[1] produced blisters on the anterior shins of 19 volunteer British medical students and physicians and found the number of shear cycles required to cause a blister ranged from 27 to 138. Sulzberger et al[3] conducted experimental blister research on the palms of 54 military personnel. A consistent frictional force was applied repetitively, and the time to blister was recorded. Some soldiers blistered in 3 minutes, and others had not blistered after 50 minutes. More recently, researchers[5] applied repetitive shear load to the soft tissues of the posterior heel of 30 volunteers and measured the time to blister. Blister onset ranged from 4 to 32 minutes.

Although large variation exists among individuals in their skin's resilience or tolerance of shear stress, scientific evidence[3,28–31] supports the concept that the skin can adapt to resist repetitive shear-deformation damage. Therefore, in anticipation of participation in activities that impose many shear cycles, individuals can embark on training programs that gradually increase the shear loads on their feet.

Adaptation occurs when the skin is subjected to the very force that threatens to damage it—repetitive shear deformation. Mackenzie[28,29] examined changes to the skin of mouse ears that were rubbed every day for 1, 7, 14, 28, or 35 days. The frictional stimulus applied each day was 10 revolutions of a rotating brush at a force of 8 to 9*g*. He found that in the ears that were rubbed, cells in the epidermis were larger and more resistant to mechanical damage than ears that were not rubbed. Importantly, the changes seen at 7 days were identical to those at 14, 28, and 35 days, indicating that adaptations maximized by 7 days.

Researchers have looked at the skin's response to shear and friction on the palms[32]; thigh[33]; anterior tibial surface[1,2]; back, buttocks, shins, forearms, upper arms, thighs, palms, and soles[3]; palms and soles of monkeys[34]; mouse ears[28,29]; and rat gums.[35] Adaptive changes that lead to an increased resistance to epidermal fatigue include an increased size and density of cells at the basement membrane and a thicker stratum corneum. More recently, investigators[30] have demonstrated that skin adaption occurs by forming new collagen fibrils with larger diameters, as opposed to increasing diameters of existing fibrils. At the same time, a breakdown of existing small-diameter fibrils occurs.[31]

Authors of several studies of endurance activities lasting days to weeks, such as marching, hiking, and ultramarathon, found blister incidence was at its highest earlier rather than later in the event. This finding may verify that skin can adapt to mechanical strain. Foot-blister risk factors were assessed in military cadets who underwent abrupt increases in walking, running, and general physical activity during 6 weeks of summer Army Reserve Officer Training Corps training.[24] Blisters occurred in 42.1% of cadets, with 95% of all cases occurring in the first 3 weeks (week 1 = 34.6%, week 2 = 51.2%, week 3 = 9.3%). In an examination of the blister incidence in 357 male US Marine recruits undergoing basic training over 12 weeks,[36] the highest incidence was in weeks 1 through 3 compared with weeks 4 through 6, 7 through 9, and 10 through 12. Among 142 Korean college student volunteers who undertook a 21-day, 580-km road march, most blisters occurred on the second day.[14] Just over 95.1% of students developed their first foot blister in the first 5 days, with few blisters occurring after that time.

For preventive strategies, a role appears to exist for familiarity with the activity and footwear that may affect the overall blister incidence. Previous hiking or military experience offered some protection against blister formation in 189 recruits going through basic military training.[37] Blisters were most noticeable early in recruit training in 1 study,[36] and troops who did not break in their boots were more likely to sustain blisters during a 12-month deployment in Iraq according to another study.[38] In research involving 2617 cadets at Army Reserve Officer Training Corps training, those who wore their boots >20 hours per week in the 2 weeks immediately before training were less likely to develop foot blisters than those who did not (29.70% versus 44.41%; $P = .001$).[24] Gardner and Hill[21] found that hikers who had not preconditioned their footwear were more likely to develop blisters (32% versus 25%). Finally, in a group of 221 male lieutenants taking part in their first training hike, the likelihood of blister formation depended on the running habits of the individual.[39]

The incidence of blisters was highest in the early stages of training, suggesting that adaptive changes took time.

In summary, preventive strategies focusing on the skin's ability to undergo structural adaptive changes should be maximized to increase its resistance to mechanical fatigue, including gradual familiarization with the activity and terrain.[36,37,39] Familiarization with footwear should also be considered.[21,24,38] However, we highlight 2 cautionary notes. First, although some level of thickened stratum corneum appears advantageous, excessive hyperkeratosis is generally accepted as counterproductive in blister prevention.[11,40,41] Shear deformation continues to occur in the soft tissue under a thickened stratum corneum. Certainly, if blisters occur in the presence of thickened stratum corneum, the aim should not be to promote further thickening to the point of callus formation. In this case, shear deformation is likely to be greater due to increased focal pressure and, therefore, friction force and shear stress. Second, many well-conditioned, seasoned competitors in sport and experienced hikers during wilderness activities develop friction blisters.[26,42] Whether the cause is low intrinsic shear resistance, an exceptionally long-duration or unaccustomed activity, unfavorable climatic conditions, preexisting structural abnormalities, or altered gait patterns due to pain avoidance or injury, sometimes additional blister-prevention strategies are needed.

Reduce the Magnitude of Shear Deformation

Decreasing the magnitude of shear deformation imparted to the skin is the aim of most blister-prevention products and techniques. Shear-deformation magnitude can be reduced in 4 ways: reduce friction force, apply shear-absorbing materials, spread shear load over a larger area, and reduce bone movement (Figure 1).

Reduce Friction Force. Friction is the force that opposes the movement of one surface over another at an interface. An interface exists between 2 materials in parallel contact. Sliding or rubbing can occur at an interface, which is resisted by a friction force. The likelihood of sliding or rubbing motion depends on 2 factors: (1) the coefficient of friction (COF) between the 2 surfaces and (2) the compressive force pressing them together.

Reduce the COF. The COF (μ) is the common expression for frictional behavior at a material interface. It is dimensionless and represents the ratio of friction force to the normal force pressing 2 surfaces together. A low COF corresponds to a low force required for sliding to occur, whereas a high COF requires a higher force for sliding to occur. Examples of low, medium, and high COFs include polished oiled metal surfaces ($\mu < 0.1$), glass on glass ($\mu = 0.4$), and rubber on tarmac (close to $\mu = 1.0$).[43] The COF determines the sliding capacity or the stickiness between 2 surfaces that form an interface. Common interfaces related to blister prevention are the skin-sock interface, the sock-shoe lining interface, the skin-skin interface within the interdigital spaces, the sock-sock interface in the case of double socks, and the shoe-ground interface.

Akers and Sulzberger[44] described COF management by the purposeful selection of materials in footwear design and manufacturing to reduce friction over the most at-risk points. Carlson[6] suggested that materials placed between the skin of the foot at various interfaces can change friction. Indeed, Veijgen[45] noted that the study of skin friction combines tribology, materials science, dermatology, product development, and rehabilitation.

Blister-prevention techniques that focus on reducing the COF target either the surface of the skin or the various interfaces that exist between the foot and the shoe. By lowering the COF, these interventions encourage slippage at a specific interface. The end result theoretically allows increased motion across the interface so the superficial integument can move in response to, or in synch with, the movement of the underlying bone, thereby decreasing the magnitude of the shear deformation within the skin. Techniques include the use of lubricants; powders; all moisture-management strategies, including moisture-wicking socks; double-sock systems; polytetrafluoroethylene (PTFE) patches; and some dressings.

Reduce pressure. Pressure-management strategies potentially lessen blister formation by reducing friction force. With less friction force, slippage at various material interfaces theoretically enables the skin surface to move in synch with the underlying bone. The most well-known examples of pressure-reduction blister-prevention strategies are cushioned insoles, pressure-deflective padding, thick socks, and toe socks for the interdigital spaces.

Pressure by itself is not the primary deforming force in the pathomechanics of the friction blister.[6,46–49] Naylor[2] showed that when friction loads were doubled, skin damage occurred 3 times as fast without any increase in vertical force, indicating that friction force had a greater role in blister injury than vertical compression force. However, friction force is directly proportional to normal force (compression force) and the COF between 2 surfaces. Therefore, higher friction forces are found in areas of the foot that have more pressure against the skin. Elevated compressive force against the skin occurs in areas of bony prominences, where the compressive force is concentrated over a smaller surface area. In relation to the foot, plantar pressures are generally higher in the forefoot than the rearfoot.[50,51] This pattern is further amplified in cases of pes cavus and equinus deformity.[52–58]

Pressure-mapping technologies are primarily limited to measuring compressive forces on the plantar surface of the foot. However, other situations in which bone deformity concentrates compressive force include the apices and dorsal interphalangeal joints of claw toes, interdigital contact points from adductovarus digital deformity, and the posterior calcaneus (Haglund deformity). In summary, the higher the compressive force, the greater the resistance to synchronous movement between the skin surface and the underlying bone.

Apply Shear-Absorbing Materials. Most cushioning materials not only reduce pressure but also absorb shear strain by undergoing shear deformation themselves. In so doing, these materials allow the skin surface to move in synch with the underlying bone, limiting shear strain within the soft tissues.[6,11,44] A material's ability to resist shear deformation is known as the *shear modulus*, which is a measure of the elastic shear stiffness of a material. A low shear modulus indicates the material easily deforms when a shear force is applied.

Shear-absorbing materials investigated in the prevention of foot blisters include insole materials such as Spenco (Implus Footcare LLC, Inc) and Poron (Rogers Corporation).[59–61] Thick socks have been presumed to afford a level of blister

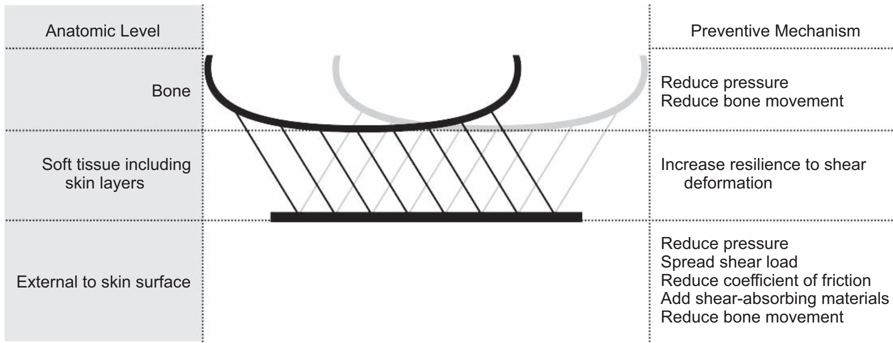

Figure 2. A diagrammatic representation of the opportunities for blister prevention.

protection via shear absorption.[62] Although clinical testing to date is lacking, gel toe devices might prevent toe blisters because of the apparent low shear modulus of the material. The challenge in applying shear-absorbing materials is matching the shear modulus of the material with the functional requirements of the area in question.

Spread the Shear Load. A purely speculative mechanism of action of adherent tapes, moleskin, and dressings in preventing blisters is spreading the shear load while not necessarily reducing the COF or compression force. Blisters occur at discrete locations, usually at bony prominences where both compressive and shear forces are concentrated over a small surface area. Researchers[11,63] have postulated that adhesive materials affixed to an area of skin larger than the bony prominence itself may broaden the area of skin subjected to shear deformation. In this way, shear deformation per unit area is decreased. To date, no research and very little commentary on this mechanism of blister prevention exist.

Reduce Bone Movement. At initial contact during ambulation, the foot strikes the ground at a tangential angle rather than in a purely vertical direction. This angle creates shear forces exerted on the foot, resulting in anteriorly directed shear deformation of the soft tissues. Similarly, during push-off, the forefoot experiences a second shear event in the opposite direction to the shear force at initial contact, creating shear strain that is also in the opposite direction to that at initial contact. The force of friction keeps the skin surface and external footwear material interfaces in stationary contact for maximum efficiency as the bones move and press into the ground for push-off. Because of the compliance and various physical properties of the epidermis, dermis, and subcutaneous layers, this bone movement does not cause immediate or uniform motion of the soft tissue located beneath. Temporospatial gait and foot biomechanical factors cause excessive joint mobility to influence the overall movement of bone.[64]

Bone movement and its critical influence on shear force and resultant shear deformation occurring in the multilayered overlying soft tissue "sandwich" are overlooked contributing factors to blister formation. Evaluating excessive bone movement at specific locations in the foot offers the potential for implementing preventive methods and yet remains underappreciated. For example, digital deformities, such as hammertoes and claw toes, compromise the plantar purchase or load-bearing capacity of the affected digit.[65] With claw toes, the action of the flexor digitorum longus (FDL) to directly plantar flex the digit to the supportive surface is compromised due to reverse buckling of the toe at the proximal and distal interphalangeal joints.[66] In the healthy intact toe, these joints remain in full extension, enabling the action of the FDL to exert a pure plantarflexion moment at the metatarsophalangeal joint.[67] With the loss of the extensor apparatus of the toes, the FDL does not plantar flex the digits at the metatarsophalangeal joint and instead pulls the phalanges in a plantar and proximal direction, accentuating shear forces at the apices of the toes during push-off.[68]

On a more global level, kinetic and kinematic variables may create gait abnormalities that increase the shear forces at various locations of the foot. For instance, some individuals demonstrate an "abductory twist" or "medial whip" during the heel-rise phase of walking or running. This transverse-plane motion of the foot creates shear forces that can manifest along the medial border of the first metatarsal head as well as the hallux. Excessive pronation of the foot during midstance has been speculated to cause the abductory twist motion during heel rise.[69]

The take-home message is that clinicians should evaluate the location of recurrent blisters in patients and consider the contribution of biomechanical mechanisms that may have increased the shear load at the site of skin injury. Instead of focusing solely on reducing friction at the skin surface, providers should address the abnormal motion of the bones beneath the skin, which is the fundamental element of the pathomechanics of the friction blister (Figure 2).

INDIVIDUAL BLISTER-PREVENTION STRATEGIES TO REDUCE SHEAR-DEFORMATION MAGNITUDE

Antiperspirants

Even mild to moderate hydration levels of the feet are known to increase skin friction and the likelihood of blisters.[1–3,49,70–74] Naylor[1] recognized the protective effect of dried skin against blister formation, confirming that moisture reduced the number of shear applications the skin could withstand before blister damage. Therefore, antiperspirants have been proposed to potentially have an indirect COF-reduction blister-prevention effect by reducing skin-surface friction.

In military settings, antiperspirants that reduced blister incidence concurrently caused significant irritant dermatitis.[22,75,76] Formulations included aluminum chlorohydrate,[75] aluminum zirconium tetrachlorohydrex glycine,[75] and 20% aluminum chloride hexahydrate in anhydrous ethyl alcohol.[22] To reduce this adverse effect, researchers added emollient additives to 20% aluminum zirconium tetrachlorohydrex glycine concentration plus water.[76] Although irritant dermatitis was not noted, the blister incidence was not different among groups.

More recently, investigators[73] observed the rate of temperature change during shear loading of the skin at the posterior heel on dry and hydrated skin in 20 healthy participants. One foot was soaked in water to hydrate the skin. The contralateral foot acted as a control. Intermittent loading was applied until an observable change of 3°C was evident. A 3°C increase in temperature was used as the endpoint of testing because this value had earlier been identified as the temperature change indicative of imminent blister formation.[5] The rate of temperature change of the hydrated foot group was greater than that of the nonhydrated foot group ($P = .001$) and showed a strong positive correlation ($r = 0.520$) with skin-surface hydration.[73]

Later authors[77] found that an antiperspirant (Boots Anti-Perspirant Foot Spray [The Boots Company, PLC]) did not affect foot-skin hydration or the rate of temperature change, which was thought to predict imminent blister formation. Overall, the evidence indicates that nonirritating antiperspirants do not prevent blisters.

Moisture-Wicking and -Absorbing Socks

Socks can potentially prevent blisters by reducing moisture content on the surface of the foot, thereby reducing the COF. In addition, sock-fiber properties and construction that may affect friction blister rates include moisture regain, swelling properties, water transport, heat transfer, and the COF.[78]

Cotton is a hydrophilic fiber that inhibits moisture-wicking ability.[78] Cotton fibers absorb 3 times as much moisture as synthetic acrylic fibers.[78] When wet, cotton has a 10-fold greater drying time than synthetic fibers.[79] Conversely, synthetic fibers such as acrylic, polypropylene, and polyester are hydrophobic and facilitate wicking by transporting moisture along the fiber surfaces.[80] A specialized polyester fiber known as Coolmax (The LYCRA Company) has a scalloped oval cross-sectional fiber geometry designed to increase its surface area by 20% to facilitate moisture transport.[81] When comparing synthetic fibers, Bagherzadeh et al[81] found that polyester fibers (Coolmax) dried 15% faster than acrylic fibers.

Herring and Richie[82] compared blister incidence in 35 long-distance runners wearing padded socks of identical construction but different materials—100% cotton or 100% acrylic fibers. The cotton-sock group developed twice as many blisters and 3-times larger blisters than those in the acrylic-sock group, suggesting that acrylic fibers were beneficial over cotton fibers in athletic socks. The authors proposed that the results were explained by a lower friction force on the skin surface due to the superior moisture management of acrylic. However, in their follow-up study of socks with reduced padding (contrary to the dense padding in the first study), they demonstrated no difference in blister frequency between cotton- and acrylic-fiber socks.[62] The investigators concluded that the superior blister-prevention capacity of acrylic fibers over cotton fibers depended on sock construction. They speculated that the wicking capacity of acrylic fibers was enhanced by denser padding within the sock, promoting better moisture movement from the skin surface. Alternatively, they suggested that a sock's ability to prevent blisters could depend on some other mechanism related to its thickness, such as pressure reduction or shear force absorption.

Athletic hosiery dissipates pressure against the skin of the foot, depending on the fiber composition as well as the thickness or density of the fibers in the sock. Howarth and Rome[83] studied the plantar shock attenuation over 72 hours of 5 types of athletic socks (cotton socks, wool cushion-sole sport socks, acrylic cushion-sole hiking socks, double-layer cotton socks, and toweling cushion-sole sport socks) compared with that of barefoot participants. Only the wool cushion-sole sport socks and acrylic cushion-sole hiking socks displayed more shock attenuation than barefoot walking. The cotton socks, double-layer cotton socks, and toweling cushion-sole sport socks did not demonstrate attenuation. In other studies,[84–88] padded hosiery reduced peak plantar pressures in the forefoot of patients with rheumatoid arthritis and diabetic neuropathy.

Although socks can affect moisture management to reduce the COF, the inherent frictional properties of the sock itself should also be considered.[7] Burns[89] assessed whether polytetrafluoroethylene (PTFE or Teflon; Chemours) could reduce friction blisters when incorporated into the heel, forefoot, and toe area of an athletic sock. Among 77 university students participating in aerobics classes over 4 weeks, the PTFE sock provided no protective effect against blisters. Dai et al[90] used a 3-dimensional finite-element model to simulate the foot-sock-insole interfaces and investigated the effects of wearing socks with different combinations of frictional properties on plantar foot contact. Wearing socks with low friction against the skin of the foot more effectively reduced plantar shear force than wearing socks with low friction against the insole.

Knapik et al[7] recognized the multiple mechanisms by which socks may reduce blister formation, including moisture reduction and the ability to resist compression and undergo deformation. This conclusion underscores the fact that socks can be part of 3 strategies that can reduce the risk of foot blisters: COF reduction, pressure reduction, and shear absorption.

Several laboratory studies have been conducted to measure friction force and the COF of various sock fabrics and sock fibers.[78,91–93] Although examining friction force at the sock-skin interface might offer insight into how fabric structure and sock fibers affect the COF, relating these factors to blister formation in the feet should be done cautiously. Laboratory methods do not fully replicate the in vivo condition of a sock worn in a shoe. Even though the authors of these investigations suggested that fabric structure was more important than fiber composition in terms of friction force, other factors such as wicking, thermal dissipation, and pressure reduction by socks must also be considered. The wicking capacity of socks demonstrated in laboratory evaluations has not always been replicated in research on sock performance in footwear during actual physical activity. Without exposure of the entire sock to the outside ambient environment, its moisture-absorptive capacity may be more important than wicking for keeping the skin of the foot dry. Sweat production by the foot has been estimated to range between 381 and 447 g/h, which can often overwhelm the simple wicking capacity of the sock fibers.[94,95]

Bogerd et al[96] performed a field study with 37 military recruits marching over 4 consecutive days to measure the moisture content on the skin surface of the feet and retained by the socks after marching. They also measured participants' perceptions of skin temperature, overall dampness, friction, and comfort via a questionnaire. Inexplicably, they proposed that these variables were critical to the formation of friction blisters on the feet but did not document blister events. Of the 2 socks tested, a 50% Merino wool and 33% polypropylene blend was rated as cooler, less damp, and more comfortable than a 99% polypropylene sock. Surprisingly, in these soldiers wearing prototype military boots equipped with a GORE-TEX (W.L. Gore and Associates) membrane, the wool-blend sock kept the surface of the foot drier than the polypropylene sock in 2 locations (dorsal metatarsals and posterior calcaneus), whereas the entire plantar surface of the foot showed no difference in moisture content when the 2 socks were compared. The wool-blend sock absorbed 2.9 times the moisture of the polypropylene sock. The authors speculated that the superior moisture-storage benefits of the wool-blend sock outweighed the wicking capacity of a polypropylene sock inside a closed boot, where moisture evaporation is compromised. Thus, to reduce the moisture content on the skin surface, the absorptive capacity of a sock becomes most important when the footwear is resistant to vapor evaporation.[96]

Finally, the thermal-conductive properties of sock fibers are important considerations for blister prevention. Reducing or evacuating heat from the skin surface depends on the thermal conductivity of the sock fibers. Cotton fibers have a low thermal conductivity of 0.07 W/m·K. Polyester has an average thermal conductivity of 0.14 W/m·K, and polyamide (nylon) has a high thermal conductivity of 0.25 W/m·K but a 6-fold greater moisture regain than polyester.[78]

Overall, even though many hosiery products are advertised as preventing blisters, scientific evidence for this therapeutic effect is lacking. The only confirmation came from the combined results of 2 double-blind studies in which acrylic socks reduced the blister risk when they were dense and padded rather than thin.[62,82]

Socks Versus No Socks

When individuals place their foot in a sock and then in a shoe, multiple interfaces are established. Each interface has its own COF, and slip will occur where the COF is the lowest. Sanders et al[97] compared the COFs of the skin-material, sock-material, and skin-sock interfaces. They chose materials used in the orthotic and prosthetic profession (Spenco, Poron, nylon-reinforced silicone, soft pelite, medium pelite, firm Plastazote [Zotefoams], regular Plastazote, and NickelPlast [AliMed]), and the sock material was wool. The COFs at the skin-material interfaces were higher than those at the skin-sock interfaces. This result supported the beneficial effect of wearing socks, which provide a skin-sock interface, versus wearing shoes without socks, which provide only a skin-material interface. Most running and walking athletes wear socks, but triathlon athletes, many of whom prefer the time-saving aspect of forgoing socks (skin-material interface) during the transition from the swimming to the running leg of the race, have a high blister incidence.[98]

Double-Sock Systems

Double-layer sock systems are a COF-reduction strategy used to create an additional material interface. The intention is for the sock-sock interface to exhibit a lower COF than both the skin-sock and shoe-sock interfaces so that slippage occurs between the sock layers. Various military organizations have indicated considerable interest in determining how these sock systems can prevent friction blisters on the feet of marching soldiers.

Blister incidence and severity were investigated in 357 Marine recruits participating in basic Marine Corps training.[99] Training took place 6 days per week for 12 weeks and included road marches, endurance activities, combat courses, and drills. Recruits wore either standard-issue socks or 1 of the following 2 double-sock systems: a standard-issue sock plus a thin polyester inner sock or a very thick, dense, wool-polypropylene prototype outer sock over a thin polyester inner sock. The standard-issue sock was described as a 1-twist-per-inch sock, thicker at the heel and sole where the fabric composition was 50% wool and 50% cotton with spandex, with the remainder of the sock being 50% wool, 30% cotton, and 20% nylon. The authors provided no information about the white polyester liner sock other than describing it as thin. The prototype sock was characterized as a uniformly thick 50% wool and 50% polypropylene sock with a thread density of 7 twists per inch. Blister incidence was 69% for the standard group, 77% for the standard-plus-inner-sock group, and 40% for the prototype-plus-inner-sock group. Severe blisters requiring medical attention occurred in 24%, 9%, and 11% of the groups, respectively. The double-sock systems were somewhat more protective against blisters than a single sock. The standard-issue sock plus liner reduced blister severity, but the dense prototype wool sock combined with a polyester liner reduced both overall blister incidence and severity.

Jagoda et al[39] compared blister incidence and severity in a group of 221 male lieutenants on their first training hike using 1 of 3 sock and powder conditions: standard-issue sock only, white athletic sock plus nylon sock plus powder, and standard-issue sock plus white athletic sock plus powder. Blister incidences were 59%, 41%, and 22%, respectively. Blister severity was highest with the standard-issue sock only. Van Tiggelen et al[37] addressed the effect of different sock systems in 189 Belgian military recruits undergoing basic military training. The control group wore the standard-issue military sock (70% combing wool and 30% polyamide). A second group wore padded polyester socks (88% polyester, 11% polyamide, and 1% elastane), and a third group wore a double-sock combination of a thin inner sock (45% polyester, 45% viscose, 8% polyamide, and 2% elastane) under a thick cotton-wool sock (40% cotton, 40% wool, 18% polyamide, and 2% elastane). Blister incidences were 51%, 16%, and 32.3%, respectively, showing that the single-sock condition of the padded polyester sock offered greater blister protection than the double-layer sock system. This increased level of blister protection may suggest that the hydrophobic polyester fibers created lower friction conditions at the skin-sock, sock-shoe, or both interfaces than the lower friction conditions between the layers of the double-sock system. Separately, the protective effect may have reflected the thickness of the sock, providing a pressure-reduction or shear-absorption mechanism.

Overall, the evidence for double-sock systems is equivocal. In 1 study, 2 double-sock systems reduced the blister incidence versus a single sock.[39] Other researchers found that only 1 of 2 double-sock systems decreased the blister incidence compared with a single sock.[99] In a third study, a single-sock condition was more protective than a double-sock system.[37] The material composition and thickness of the 2 socks likely affected the outcome and varied considerably in the 3 examinations.

Toe Socks

Toe socks have become popular in endurance running and hiking. Their most obvious mechanism of action is pressure reduction by adding cushioning bulk to the interdigital space. Of importance, any pressure relief from this interdigital padding depends on the available room in the toe box of the shoe. Alternatively, toe socks can potentially offer a reduction in the COF via the double-sock layers in the interdigital space.

To date, the effectiveness of toe socks has not been established. However, while testing the effectiveness of paper tape on all toes on the experimental foot, Lipman et al[100] found that the simultaneous use of Injinji (Injinji Inc) toe socks was associated with an increased blister occurrence. Specifically, 34% of feet that were taped and wore toe socks sustained blisters, whereas 27% did not incur blisters.[100] They did not explicitly state that these blisters occurred on the toes and did not comment on an increased blister incidence with the simultaneous use of paper tape and toe socks in the follow-up study 2 years later.[101] Overall, toe socks have not been adequately tested to enable any conclusions to be drawn.

Lubricants

Lubricants reduce the COF between surfaces and are usually applied to the skin, targeting the skin-sock interface. The 2 types of wet lubrication are boundary and fluid. *Boundary lubrication* describes the separation of 2 surfaces by a lubricant film. In this case, friction is influenced by the nature of the underlying surfaces as well as by the lubricant. *Fluid lubrication* describes the separation of 2 surfaces by a thick lubricant film. In this case, friction depends entirely on the physical properties of the lubricant itself. Of the 2, fluid lubrication appears to reduce friction more effectively.[2]

Fluid lubrication depends on the amount of lubricant applied and its ability to stay in situ on the skin. Highley et al[72] added 50 µL (50 mL^3) of mineral oil to 1 square inch (6.4516 cm^2) of skin and measured friction against a rotating nylon head. A substantial and prolonged decreased friction level occurred. Nonetheless, when the rotating nylon head was cleaned at 1-minute intervals with hexane-treated tissue, friction levels initially decreased and then gradually increased, reaching a maximum after 15 minutes.

Investigators studying boundary lubrication of the skin of the abdomen[102] and volar forearm[103] and its effect on skin friction showed that water and both mildly and moderately greasy moisturizers increased friction levels. Only viscous lubricants (petrolatum, mineral oil, and glycerin) reduced friction levels, for approximately 90 minutes. At 3 hours, friction levels rose 35% above baseline.[103]

Although numerous lubricant products are aimed at the blister-prevention market, their use in preventing foot blisters is unknown.[41] Only skin-friction studies, such as those mentioned earlier, exist, and none included foot skin. However, it is intuitive that the friction-reducing effect of lubricants is limited, owing to absorption and the dissipation of the product in active situations.[7] If lubricants are identified as effective, the requirement to reapply them to the feet to provide ongoing blister protection limits their use in many situations, including running events and military settings.

Powders

Powders have been used in skin-friction studies based on a strategy of producing a drier integument.[2,104] They offer 2 COF-reduction effects to reduce friction force at the skin surface. First, powders absorb moisture to dry the skin.[1,2] Second, powders work as a dry lubricant.[104] Yet in British Army participants using talcum powders, either no difference (when compared with a control group) or a higher blister incidence among those using the powder was noted.[7] When powder becomes wet, frictional forces increase.[77,104] Investigators[7,104] have also suggested that, when sweat and powder combine, the material clumps and becomes abrasive.

The effectiveness of self-chosen prevention strategies was determined in 50 participants pursuing two 5-day, 219-km multistage ultramarathons.[20] At the end of each day, blister frequency and severity were recorded, as well as the preventive measures used. Two runners used talcum powder alone. Five runners used talcum powder with combinations of lubricants, antiperspirants, and taping. Blister formation was not reduced in the runners using talcum powder, antiperspirants, lubricants, or any combination of these. Still, the sample size may have been too small to show any difference.

Other researchers[77] tested 3 topical agents for their effect on skin-surface hydration and rate of temperature change while shear cycles were imparted to the posterior calcaneal skin. These products were Flexitol Blistop (a film-forming compound), Boots Anti-Perspirant Foot Spray (an aerosol antiperspirant spray), and 2Toms BlisterShield powder (PTFE and polyethylene wax). The powder decreased skin-surface hydration, suggesting a possible blister-preventive effect. However, it did not affect the rate of temperature change, which the authors thought would predict blister formation. The other products did not affect skin-surface hydration or the rate of temperature change.

Current evidence indicates that powders are either ineffective or increase the blister risk.

Tape, Moleskin, and Dressing

The application of adhesive tape on the feet to prevent blisters is a common intervention used by clinicians and individuals.[11,20,63,100,101] Brennan[105] and Richie[8] stated that the scientific evidence behind using adhesive tape for blister prevention was lacking. Since then, 2 prospective randomized comparative studies have been performed on the use of paper tape to prevent blisters in ultramarathon runners.[100,101]

In the first study of 136 participants during a series of 6-stage ultramarathons, paper tape was applied to "the majority of common blister sites" on 1 randomly selected foot, with the untreated foot acting as the control.[100] All 90 athletes who completed the study developed blisters. No protective effect of paper tape was demonstrated. In fact,

Product	Manufacturer	Average CoF†	Difference, %‡	Thickness, mm	No. of tests
Bursatek bandage	Advanced Wound Systems, Newport, OR	0.57	—	6	3
Dr Scholl's Moleskin Plus	Schering-Plough Corp, Kenilworth, NJ	0.69	+21	31	3
Moleskin	PPR Inc, Brooklyn, NY	0.94	+64	26	3
Band-Aid	Johnson & Johnson, New Brunswick, NJ	1.01	+77	22	3
Band-Aid Plastic	Johnson & Johnson	1.03	+80	18	3
2nd Skin Blister Pads	Spenco Medical Corp, Waco, TX	1.04	+82	35	3
New-Skin	Medtech, Jackson, WY	1.05	+84	9	4
Nexcare Comfort	3M Health Care, St Paul, MN	1.08	+89	35	3
Dr Scholl's Blister Treatment	Schering-Plough Corp	1.20	+110	32	3
Blister Block (Compeed)	Johnson & Johnson	1.37	+139	40	3
Tegaderm	3M Health Care	1.54	+169	1.5	3

†CoF indicates coefficient of friction. 237-g normal applied load to end probe.
‡Compared with the Bursatek device.

Figure 3. Laboratory product comparisons using a custom-made friction measurement apparatus. Used with permission of Elsevier, from Polliack and Scheinberg.[46] A new technology for reducing shear and friction forces on the skin: implications for blister care in the wilderness setting. *Wilderness Environ Med*. 2006;17(2):109–116; permission conveyed through Copyright Clearance Center, Inc. Abbreviation: CoF, coefficient of friction.

the blister incidence was higher for the experimental foot, with 47 runners (52%) sustaining blisters on the taped foot versus 35 runners (39%) sustaining blisters on the control foot. Eight participants experienced blisters on both feet.

In the second study of 128 participants competing in a series of 6-stage ultramarathons, paper tape was applied to a randomly selected foot, either to participants' self-reported blister-prone areas or to 1 randomly selected location if the participant had no blister history.[101] The untaped areas of the same foot, not the contralateral foot, served as the control. Eighty-three percent (n = 106/128) developed blisters. Of the 109 participants who completed the study, 8 participants sustained blisters on taped areas, 74 participants sustained blisters on untaped areas, and 7 participants remained blister free. Therefore, paper tape effectively reduced the blister incidence when applied to areas of the foot that the participant deemed blister prone, with an absolute blister reduction of 40% and a number needed to treat of 1.31.

The mechanism by which paper tape prevents friction blisters is worth considering. Tape may be assumed to prevent blister formation through a COF-reduction strategy.[7] Nonetheless, although the COF of the tape-sock interface may be lower than that of the skin-sock interface, friction data for tapes used in blister management are lacking. Some friction data exist for other adhesive products, including moleskin and blister dressings. Polliack and Scheinberg[46] determined the frictional properties of 11 bandages used to treat blisters, including Compeed (Johnson & Johnson), 2 types of moleskin, 2 Band-Aid (Johnson & Johnson) products, and their own bandage called Bursatek (Advanced Wound Systems LLC). The mean COF ranged from 0.57 to 1.54 (Figure 3). The authors also evaluated the thickness of the bandages, recognizing that thick products may add pressure to the blistered area. They reported that thickness and COF were not proportional, as the thinnest bandage, Tegaderm (3M Health Care), exhibited the highest COF. Bursatek was the second thinnest bandage but exhibited the lowest COF, a presumably desirable combination in blister treatment.

A friction-reducing blister-prevention effect may be assumed of tapes, moleskin, and certain dressings.[7] However, questions exist about how effectively some of these materials reduce friction.[63,106] Moleskin is a durable cotton fabric, and many tapes are made from cotton, including RockTape (Implus LLC), KT Tape, and some athletic tapes.[106–109] Cotton is known for poor moisture-management capabilities.[79,110]

A theoretical mechanism of shear-load spreading has been proposed as a strategy to lessen the magnitude of shear deformation using adhesive products applied to the skin, including tapes, moleskin, and dressings.[11,63,106,111] Although lacking any substantiating research, the concept assumes that, when adhering a material to an area of skin larger than the bony prominence or blister site itself, shear gradients are reduced as the shear load is spread over a wider area. Theoretically, a rigid tape would perform this function more effectively than a flexible tape.[63] Note that the paper tape used by Lipman et al[100,101] was nonelastic and, thus, would be considered a rigid tape.

Overall, the only evidence that exists is for paper tape. That evidence is drawn from 2 high-quality prospective randomized comparative studies.[100,101] However, the evidence is equivocal, with 1 study showing a higher incidence of blisters and the other showing a strong preventive effect. Further research is needed to determine the effectiveness of paper tape. In addition, clinical trials that involve tests of other tapes commonly used in blister prevention are required.

Callus

We have discussed shear-induced epidermal adaptations that increase the skin's resilience to shear load. A protective shear-load spreading effect from a thickened stratum corneum, as described for taping, may also provide a level of blister protection.[30] Sanders et al[30] postulated that the increased epidermal volume through which shear load is distributed results in lower shear-stress gradients and, therefore, may reduce the risk of intraepidermal failure. Yet a thickened stratum corneum can reach a point at which it forms a callus, which is a known risk factor for a friction blister on the foot.[11,40] Presumably, a middle ground exists between moderate and excessive stratum corneum thickening.

Polytetrafluoroethylene Patches

Focusing on COF reduction, investigators[112–114] have tested laboratory friction in 5 materials frequently used in the orthotics and prosthetics profession: ShearBan (PTFE; Tamarack Habilitation Technologies, Inc), russet leather, Poron, Spenco,

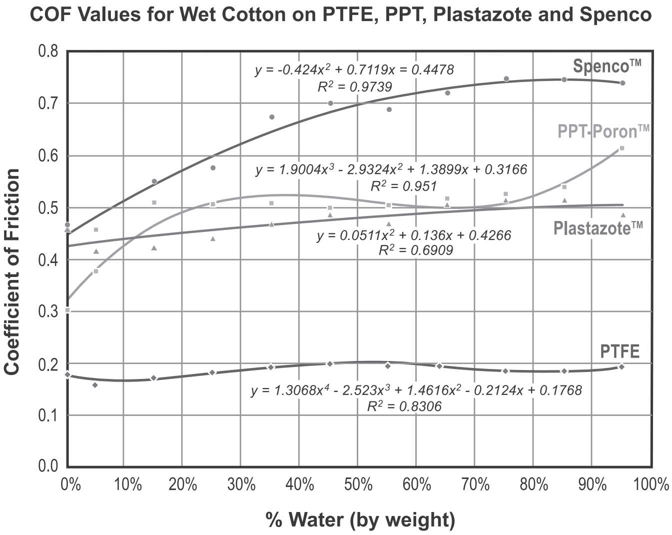

Figure 4. Coefficient of friction (COF) between cotton and 4 different support surface materials. The moisture content of the cotton sock is the independent variable and varies between 0% and 100% by weight. The COFs of the sock against polytetrafluoroethylene (PTFE) and against Plastazote are approximately 0.17 and 0.47, respectively, and those values are not significantly affected by increases in sock moisture content. Spenco, an insole material, shows a rather continuous COF increase as the sock gains moisture, and PPT-Poron showed a significant jump in COF to a moisture content of about 35% and then little further increase. Spenco, Implus Footcare LLC, Inc. PPT-Poron, Langer Biomechanics. Plastazote, ZOTEFOAMS. From Carlson[6] JM. Functional limitations from pain caused by repetitive loading on the skin: a review and discussion for practitioners, with new data for limiting friction loads. *J Prosthet Orthot.* 2006;18(4):93–103. https://journals.lww.com/jpojournal/pages/default.aspx. and republished with permission. The Creative Commons license does not apply to this content. Use of the material in any format is prohibited without written permission from the publisher, Wolters Kluwer Health, Inc. Please contact permissions@lww.com for further information.

and Plastazote, interfaced with either cotton or polyester Coolmax socks in both dry and 30% moisture conditions. According to Payette,[114] all orthosis materials exhibited lower COFs under dry conditions than under moist conditions except for the Plastazote-cotton sock interface. Overall, ShearBan had the lowest COFs under both dry and moist conditions compared with leather, Poron, Spenco, and Plastazote.[114]

Carlson[6] measured the COF between cotton and 4 of the same materials: ShearBan (PTFE), Poron, Spenco, and Plastazote. The moisture content of the cotton sock was the independent variable and varied from 0% to 100% by weight. The COFs of the sock against PTFE and Plastazote were 0.17 and 0.47, respectively, and those values were not affected by increases in sock-moisture content (Figure 4). Spenco, an insole material, showed a rather continuous COF increase as the sock gained moisture, and PPT-Poron (Langer Biomechanics) displayed an increase in COF to a moisture content of about 35% and then little further rise. Although these laboratory investigations were favorable, no blister-incidence research has been conducted with clinical trials testing this product.

Cushioned Insoles

Cushioning materials present a pressure-reduction strategy for blister prevention. Friction force is directly proportional to pressure (compression force) and the COF between 2 surfaces. Therefore, higher friction forces occur in areas of the foot that have higher compressive forces against the skin. Cushioning materials and fixed-volume gel materials limit peak pressures by expanding the area of contact, thereby spreading the vertical load.[6] This concept can be applied to cushioning at any anatomic location of the foot, including insoles used under the feet and toe cushions. The effectiveness of the material depends on its thickness versus its effects on mechanical efficiency: excessive cushioning can negatively affect the energy expenditure of locomotion.[6]

Tong and Ng[115] studied the ability of 4 Poron-cushioned or Poron and Plastazote-cushioned insoles to reduce peak pressure at plantar locations of the foot. A combination of Poron and a firm Plastazote material was most effective. House et al[116] compared the effectiveness of 2 insoles for preventing blisters. A group of 1416 Royal Marine recruits used standard flat 3-mm coarse-weave polyvinylidene chloride insoles aimed at thermoregulation, and 1338 recruits received 3-mm shock-absorbing insoles. The shock-absorbing insoles consisted of a 3-mm-thick layer of cellular polyurethane foam with a felt top sheet, an underlay of 99% polyester and 1% polyethylene, and a 3-mm-thick cellular polyurethane foam heel pad. The shock-absorbing insoles did not protect against blisters, with incidences of 17.2% (polyvinylidene chloride insoles) and 18.6% (shock-absorbing insoles).

Cushioning materials can also provide a shear-absorption strategy for blister prevention based on their ability to deform and rebound, a physical property defined as the *shear modulus*.[11,44] Spence and Shields[59,60] described the shear-absorption function of closed-cell cushioned insole materials as a *ball-bearing effect*. As opposed to open-cell materials, closed cells in rubbers or foams are independent and allow lateral movement of 1 cell relative to adjacent cells. They discussed a new closed-cell neoprene that absorbed 1 cm of fore, aft, and lateral shear and 25° of rotary shear, as well as vertical forces. The insole developed by Spence and Shields[59,60] was one-eighth–inch (0.3175-cm) thick and had a stretch nylon top cover to lower the surface friction force and aid the sock-clad foot's sliding into the shoe. This insole was used in 1 shoe, with the other foot serving as the control, for a period of 3 to 12 months, among 200 athletes with self-reported blister concerns or general foot discomfort; only 1 athlete sustained a blister with the insole. Thus, 99.5% of feet with the neoprene insole remained blister free, whereas 75% of feet without the insole were blister free.

The same closed-cell neoprene polymer rubber (Spenco) was compared with an open-cell polyurethane (Poron) for blister and callus formation in 90 recruits from the US Coast Guard Training Center undergoing an 8-week training regime.[61] Among the 30 participants in each of the 3 groups (control group, Poron insoles, and Spenco insoles), most blisters and calluses occurred in the control group (8 participants) compared with the Poron (4 participants) and Spenco (1 participant) groups.

Spence and Shields[59,60] also assessed a silicone gel material that prevented decubitus ulcers in patients who were bedridden. They performed preliminary experiments using the same material for blister prevention. Although it reduced shear within the skin, its high elasticity (low shear modulus) produced instability under the foot.

Overall, the evidence supports the use of neoprene or Spenco insoles for blister prevention.

Footwear Fit

Ill-fitting shoes are often cited as a primary cause of foot blisters.[41,117] Tightly fitted shoes may increase compressive forces against bony prominences and thereby increase friction forces. Alternatively, loosely fitted shoes may allow excessive sliding of the foot, which could increase shear. No scientific studies have been conducted to verify the role of properly fitted footwear or lacing techniques in blister prevention.

Pressure-Deflective Padding

Deflective padding in the form of donut pads is a common blister-management technique using a pressure-reduction strategy.[41,105] This padding typically contains moleskin with an aperture cut in the middle and is placed over the "hotspot" or blister-susceptible area of skin. Presumably, the thicker the padding, the better the pressure decrease. The effectiveness of felt deflective paddings of different thicknesses to reduce peak pressure has been documented as follows:

- 5-mm felt padding reduced pressure by 24% to 31%[118]
- 7-mm felt padding was more effective than 5-mm felt padding at reducing peak pressure[119]
- 7-mm felt modified donut pad reduced pressure by 25%[120]
- 20-mm felt padding reduced peak plantar pressure by 49%[121]

These results indicate that a thicker material can potentially reduce peak plantar pressures better than thinner materials. However, the relevance and effectiveness of pressure reduction with deflective pads for preventing friction blisters have not been investigated.

Loose-Packed Wool

Another strategy for blister prevention that has not been verified is the use of loose-packed wool. Although the hiking community has predominantly used loose-packed Merino wool to prevent blisters around the toes, no research exists on its true effectiveness. Similar to the incorporation of wool fibers into hosiery, the application of loose-packed wool around the toes may locally lessen pressure against the integument, acting as a pressure-reduction strategy. Another expected benefit of wrapping wool around the toes would be lowering the moisture content of the skin and acting as a friction-reduction strategy. Alternatively, loose-packed wool around the toes may be a shear-absorption strategy, with the wool fibers moving independently across one another. In doing so, the wool sample would undergo shear deformation, decreasing the shear force applied to the foot. Whether the intervention prevents blisters during physical activity needs to be verified in future clinical trials.

Biomechanical Alterations

Shear-stress distribution on the plantar surface of the forefoot and toes was evaluated in 3 groups of 11 volunteers each while they walked barefoot over a shear and pressure platform: adult runners with frequent blisters, an adult control group who were moderately active and without blisters, and a pediatric control group (aged 10 to 17 years) who were typically physically active and without blisters.[26] The blister group demonstrated increased pressure and shear-stress magnitudes compared with the control groups, and the authors suggested that contact time might play a role in blister formation. They postulated that these disparities may be due to differences in the frictional properties of the skin, intrinsic muscle activity, or higher pressure magnitudes. Contrary to this notion, researchers[37,122] in 2 studies found no differences in blister incidences among participants with self-reported (via questionnaire) pes cavus (high arches), pes planus (flat feet), or normal feet.

Clinicians typically implement biomechanical interventions to address pressure and shear-induced conditions in the human foot. These interventions include the following:

- Foot orthoses with specific design features[123–127]
- Footwear with specific design features[128,129]
- Gait alterations and athletic taping[130,131]
- Digital orthoses[132,133]
- Stretches, strengthening, manual therapies, and surgical procedures to reduce joint stiffness and increase range of motion[134–139]

Currently no published studies have verified that any type of foot orthosis, taping technique, shoe, digital device, manual therapy, or gait pattern can prevent blister formation on the foot, and this knowledge gap offers opportunities for future research. At the same time, interventions such as inserts and taping intended to treat other conditions of the foot may inadvertently contribute to blistering events.

Miscellaneous Blister-Prevention Strategies

Environmental debris that enters the shoe, such as sand, pebbles, and rubber from synthetic turf fields, can cause blisters. Even though bulky detritus increases focal pressures and subsequently friction force, it is more likely to cause a superficial-to-deep abrasion injury. Regardless, preventing entry into the footwear is important. Gaiters are frequently used in hiking, trail running, and desert ultramarathons for this reason.[41]

Creases in socks should be avoided, as they intensify focal pressure. Similarly, folds and excess bulk after applying athletic tape to the foot and ankle should be minimized with appropriate tape selection, appropriate application technique, and the use of an adhesive enhancer product to prevent loosening. Regular inspection of socks, insoles, and footwear linings should be performed for signs of excessive compaction and wear. These areas of material degradation will be less able to absorb shear strain and increase friction force by raising either focal pressure or the COF, predisposing the individual to blister formation if not abrasion injury.

Summary of Clinical Evidence

Many of the interventions commonly used to prevent friction blisters lack evidence. Some have been tested in the laboratory, but few have been tested for effectiveness in real-life situations. Evidence exists for use of the following:

- Strategies that allow adaptive skin changes, including familiarity with footwear and the activity[21,24,36–39]
- Neoprene or Spenco insoles[59,61]
- Densely padded acrylic socks[62,82]

Evidence does not support use of the following:

- Antiperspirants, as they do not reduce the blister risk[75,76,140]

- Talcum powder, as it either has no effect or increases the blister risk[7,20]

Evidence is equivocal for use of the following:

- Double-sock systems, with inconsistent blister outcomes shown in 3 studies[37,39,99]
- Paper tape, with only 2 similar studies performed, including 1 that showed blistering was worse[100] and the other that showed a strong preventive effect[101]

Finally, many strategies have theoretical benefit, but they have either insufficient or no evidence to support their use. These strategies include optimized footwear fit; lubricants; BlisterShield powder; PTFE patches; tapes other than paper tape; pressure-deflective padding; gel materials; loose-packed wool; toe socks; socks of specific yarn or fiber composition or construction technique; and biomechanical interventions including stretches, strengthening, physical therapy, foot orthoses, digital orthoses, specific footwear properties, and gait alterations.

More research is needed to support or disprove often used, theoretically coherent, and anecdotally successful blister-prevention strategies. Furthermore, investigators should focus on the primary mechanism of friction-blister pathomechanics, the asynchronous motion of bones relative to the overlying integument. In addition, determining if particular strategies are useful at specific anatomic sites would be helpful.

CONCLUSIONS

Few blister-prevention products, methods, or practices are backed by clinical evidence. Current evidence supports the use of densely padded acrylic socks, neoprene insoles, and strategies that promote adaptive skin changes, including familiarity with the footwear and the activity. Conversely, antiperspirants and powder have been found to be nonprotective. The evidence for paper tape and double-sock systems is equivocal. The value of other strategies, even those that make intuitive sense or are in popular use, such as optimized footwear fit, most athletic tapes, lubricants, and biomechanical improvements, has not been confirmed sufficiently with clinical research or at all.

Finally, the aim of every blister-prevention strategy is to prevent shear-induced mechanical fatigue from resulting in intraepidermal tear. As such, effective opportunities for blister prevention involve maximizing the intrinsic resilience of the skin to shear deformation, reducing the number of shear-deformation episodes, and reducing the magnitude of shear deformation. These goals can be achieved by reducing the friction force via decreasing the COF and pressure at the various skin and footwear interfaces, absorbing shear with materials external to the body, spreading the shear load over a larger area with products adhered to the skin, and limiting the motion of the bones adjacent to the blister location.

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