Cutaneous Friction Injuries and Blister Prevention in Athletes: From Stratum Corneum Mechanics to Smart-Textile Solutions: A Systematic Review

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ABSTRACT

BACKGROUND

Friction blisters and chafing are among the most common dermatologic causes of time loss and performance decline in sports; however, preventive practices often lag behind emerging tribological and textile science.

OBJECTIVE

To synthesize contemporary evidence on the pathophysiology, epidemiology, and prevention of frictional dermatoses in athletes, with emphasis on engineered fabrics and barrier interventions.

METHODS

We conducted a narrative review of MEDLINE via PubMed, SPORTDiscus Web of Science (1980–May 2025) with manual reference tracking. Inclusion focused on randomized controlled trials (RCTs), prospective cohorts, bench-tribology studies, and technology reports.

RESULTS

Incidence varies from 20–60% in marathoners and >70% in ultradistance hikers. Shear stress ≥ 30 N/cm^{-2} applied to a hydrated stratum corneum initiates intra-epidermal clefting; anatomical hotspots differ by sport (plantar foot in running, palmar digits in rowing, perineum in cycling). Acrylic or synthetic-blend socks reduce blister risk compared to cotton in RCTs of soldiers and marathoners, while double-layer and toe socks reduce skin-to-skin shear. Tribological tests revealed that the knit architecture modulates the coefficient of friction (COF) more significantly than the raw fiber type. Topical petrolatum-based lubricants reduce blister incidence by 30–40% when reapplied every 4 hours. Hydrocolloid dressings and kinesiology tape offer about 50% protection during multi-day marches. Early prototypes of smart socks integrate pressure-heat sensors to detect "hot spots" before vesiculation.

CONCLUSIONS

A multimodal regimen, including an optimized sock/footwear interface, targeted lubricants or dressings, moisture control, and athlete education, remains best practice. Research should converge bench COF thresholds with athlete-centered outcomes and explore sustainable, self-lubricating yarns paired with real-time wearable analytics.

Keywords: Friction blisters, Smart textiles, Tribology, Moisture management, Athletic dermatology

Introduction

Friction blisters, which are fluid-filled, intra-epidermal vesicles generated by repetitive shear, are among the most common skin injuries in athletes, military personnel, and outdoor enthusiasts.[1] Chafing, or superficial erosions in intertriginous zones, follows the same pathophysiology but presents as diffuse macerations and erythema.[2] Friction blisters and chafing remain understudied relative to their impact on performance and training continuity. Long-term surveillance of a major U.S. marathon series found that roughly two in five runners who sought medical care did so for friction blisters, making blistering the single most frequent cutaneous reason for finish-line treatment[3] and up to 69% of soldiers develop blisters on forced marches (5–10% dropping out of duty).[4] Blisters cause pain and thus compromise proprioception, alter gait, and promote secondary infection.[5]

Mechanistically, blister formation occurs when shear forces exceed the tolerance of the hydrated stratum corneum, leading to intraepidermal cleavage and the accumulation of serous fluid.[6] Chafing and superficial erosions in intertriginous areas share this pathophysiology but often present with more diffuse maceration and erythema.[2] Despite clear biological mechanisms, preventive guidelines for athletes remain inconsistent and often anecdotal, covering fabric choice, topical lubricants, adhesive dressings, and emerging "smart" textiles.[7]

Despite ubiquitous prevalence, preventive guidelines are inconsistent and often rely on anecdotal evidence. This review integrates current biomechanical understanding with textile technology and evidence-based barrier strategies to guide physicians, dermatologists, coaches, and kit designers.

Methods

We performed a structured narrative review of frictional dermatoses in athletic and military populations by searching MEDLINE (via PubMed), SPORTDiscus, Web of Science, and Cochrane CENTRAL for English-language articles published between January 1980 and May 2025. Search strings combined terms related to blistering ("blister*," "friction dermatos*," "chafing") with activity keywords ("athlete*," "runner*," "military," "hiker*," "sports") and intervention concepts ("sock*," "textile*," "lubrican*," "antiperspirant*," "tape," "hydrocolloid," "smart fabric"). We also hand-searched reference lists of key reviews to identify additional studies. Our focus was on randomized controlled trials (RCTs), prospective cohorts, bench-tribology experiments, and technology reports that evaluated either the mechanisms or prevention of friction injuries in healthy, physically active humans, excluding case reports, non-English publications, and studies limited to diabetic or neuropathic foot

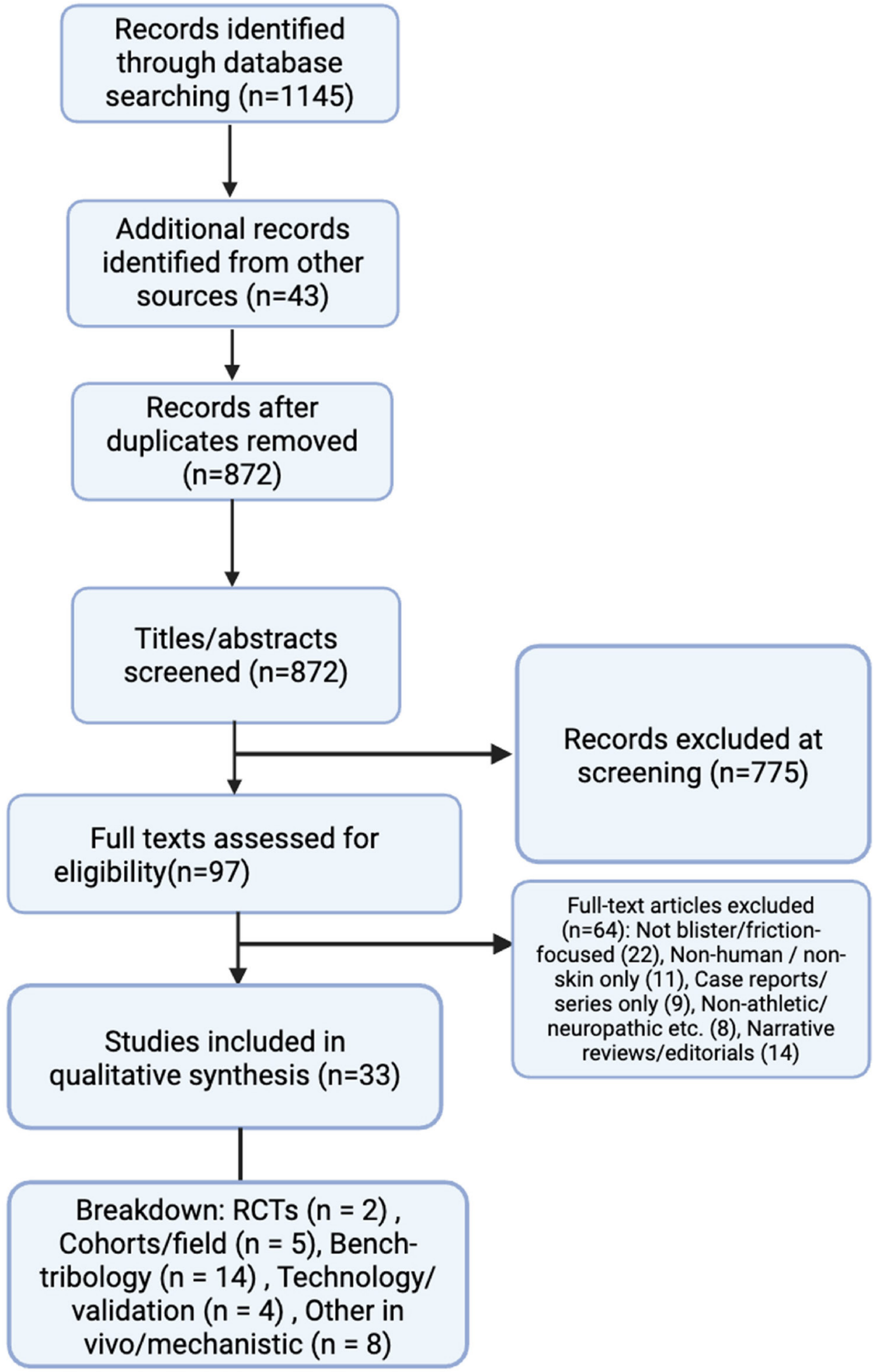

Fig 1 | PRISMA-style flow diagram of study selection for this narrative review of friction injuries and blister prevention (1980–May 2025)

disease. Titles and abstracts were screened, full texts reviewed, and data extracted on study design, participant characteristics, the intervention or device tested, outcome measures (e.g., blister incidence or coefficient of friction [COF]), and key effect estimates (risk ratios, p-values, confidence intervals). Due to the diversity of methodologies and outcomes, we synthesized results qualitatively, organizing findings into three domains: textile innovations, topical/barrier strategies, and emerging sensor-based technologies, while tabulating RCT effect sizes and tribological metrics where available.

Figure 1 depicts the selection process. Of 1,188 records identified (1,145 database hits; 43 additional sources), 872 remained after de-duplication. Titles and abstracts were screened, and 775 were excluded, leaving 97 full texts for assessment. Sixty-four studies were excluded for various reasons (Figure 1), resulting in 33 studies included in the qualitative synthesis.

Since the designs were heterogeneous and no meta-analysis was planned, we qualitatively assessed bias. RCTs were small (median n ≈ 70), unblinded, and used surrogate outcomes (hot-spot counts). Cohort or field studies relied on convenience samples with short follow-up (<4 weeks). Bench experiments used simplified skin surrogates and static loads, which limited ecological validity. These factors guided how we weighted evidence in the narrative synthesis.

This review is reported following the PRISMA 2020 guidelines.[8] The risk of bias was assessed independently by two reviewers. We used the RoB 2 tool for randomized trials and the ROBINS-I for non-randomized field or cohort studies. Bench tribology and technology validation reports were evaluated using an adapted three-domain checklist (ecological validity, measurement reliability, reporting completeness). Disagreements were resolved by consensus. Risk-of-bias assessments are provided in Tables 1–3.

Skin Biology and Tribology

From a tribological standpoint, the COF between skin and textile surfaces dictates blister risk more than raw force alone.[9] At the skin-textile interface, COF (μ) equals shear force divided by normal load.[10] Tribometer studies, which vary normal load, humidity, and temperature, consistently demonstrate that wet cotton can exhibit a COF of up to 0.85, more than double its dry value of 0.37.[11] Conversely, synthetic fibers such as acrylic or polyester blends maintain lower COFs when moist, in part due to their hydrophobicity and filament geometry.[11] Moreover, knit architecture has a significant impact: increasing stitch density reduces the depth of fiber protrusions, lowering shear peaks by nearly 20% even when fiber chemistry remains constant.[11] Thus, fabric architecture may outweigh fiber type in blister biomechanics.

Emerging biomechanical models emphasize that blister formation is not solely determined by cumulative shear cycles but also by the interplay between normal load distribution and localized moisture gradients.[12] Areas of intermittent pressure, such as the metatarsal heads during toe-off, experience spikes in shear that coincide with peak sweat buildup, creating "hot spots" predisposed to injury (Figures 2 and 3).[12] Understanding these microenvironmental factors has paved the way for targeted interventions, from hydrophobic yarns that wick sweat away from the skin-textile interface to seamless garment designs that eliminate abrupt transitions in surface topography.[13] In the sections that follow, we build on this mechanistic foundation to

Table 1 | RoB 2 assessments for randomized trials

Study (Citation)	Randomization Process	Deviations from Intended Interventions	Missing Outcome data	Outcome Measurement	Selective Reporting	Overall RoB
COMPEED® hydrocolloid vs. regular plasters, 604 military marchers[32]	Low	Some concerns (open-label)	Low	Some concerns (self-reported hot spots/blisters)	Low	Some concerns
Paper tape vs. control, Pre-TAPED II, 128 ultramarathoners[32]	Low	Some concerns	Low	Some concerns (self-report)	Low	Some concerns

Table 2 | ROBINS-I assessments for non-randomized field/cohort studies

Study (Citation)	Confounding	Selection of Participants	Classification of Interventions	Deviations from Intended Interventions	Missing Data	Measurement of Outcomes	Reporting Bias	Overall
203 hikers; wet socks ↑ blister risk (RR 1.94)[20]	Serious (hydration, terrain not controlled)	Low	Low	Low	Low	Moderate (self-report)	Low	Serious
Acrylic socks vs. cotton in runners[22]	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate
Petrolatum/silicone lubricant field trials in runners[14]	Moderate	Low	Low	Some concerns (reapplication adherence)	Low	Moderate (self-report)	Low	Moderate
Double-sock system in Army recruit[4]	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate
Antiperspirant crossover trial in hikers (RR 0.55)	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate

Table 3 | Adapted 3-domain checklist for bench/tribology/technology studies

Study (Citation)	Ecological Validity	Measurement Reliability	Reporting Completeness	Overall
DeBois et al. 2022 sock-skin tribology DOE (10 fabrics)[10]	Some concerns (static rig)	Low concern	Low concern	Some concerns
Eun et al. 2022 static COF method for socks[18]	High concern (static only)	Low concern	Some concerns	High
Prototype in-shoe sensor vs. F-Scan and FLIR, n = 5[24]	Some concerns (short treadmill test)	Low concern	Low concern	Some concerns
Hashmi et al. (2016) anti-blister product lab trial[30]	Some concerns	Low concern	Some concerns	Some concerns
Phase-change microcapsule yarn concept[25]	High concern (concept only)	Some concerns	Some concerns	High

Domains: (1) Ecological validity (loads/moisture/temperature realistic?), (2) Measurement reliability (calibrated devices, repeats), and (3) Reporting completeness (methods, stats). Scale: High concern/Some concerns/Low concern.

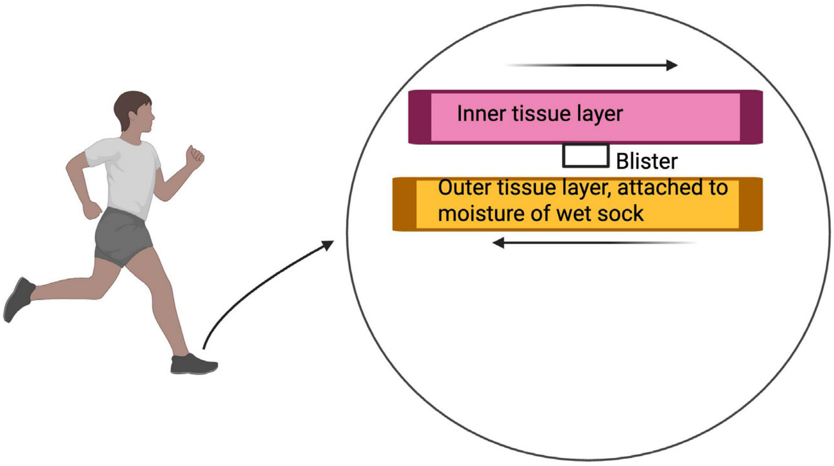

Fig 2 | Blister formation schematic. The inner tissue layer experiences normal movement, whereas the outer tissue layer sticks to the wet insole, creating a blister
Source: Created in BioRender. Islam, R. (2025) https://BioRender.com/44m4byc

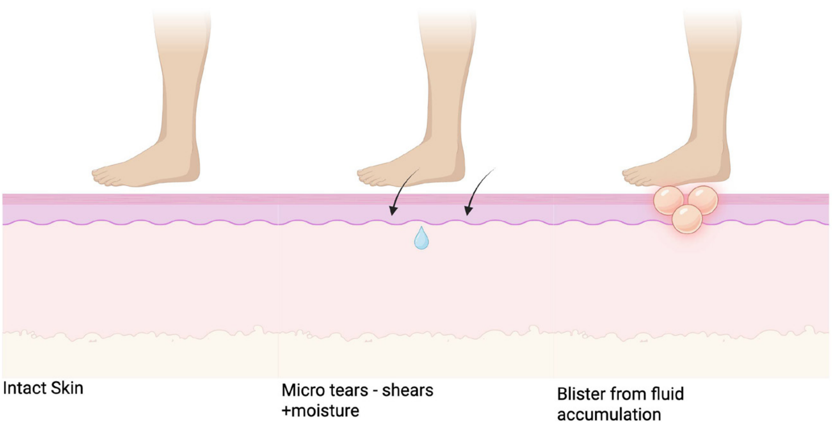

Fig 3 | Schematic showing shears and fluid accumulation causing blisters
Source: Created in BioRender. Islam, R. (2025) https://BioRender.com/lzy0kbg

evaluate how specific textile innovations and barrier strategies modulate these biomechanical forces and decrease the occurrence of frictional dermatoses in athletic settings.

Epidemiology and Sport-Specific Patterns

Frictional dermatoses affect athletes across virtually all disciplines, but the anatomical sites and incidence rates vary markedly by sport and environmental conditions. In long-distance running events, plantar forefoot and heel blisters are most common, with prospective data indicating that 20–60% of marathon and ultramarathon participants develop at least one blister per race. The incidence rises sharply once the cumulative mileage exceeds 25 km, as sweat accumulation and repetitive shear converge to overwhelm the skin's tolerance. In cutting sports such as soccer and basketball, rapid changes of direction and abrupt deceleration impose high shear stresses on the hallux and mid-foot, resulting in blisters in 15–25% of players during competitive matches.

Rowers, whose palms endure continuous friction from oar handles, report blister rates of 30–45% over 2,000-m training sessions, with a peak incidence on the proximal phalanges and metacarpal heads. Weightlifters and gymnasts similarly experience digital pulp lesions, often exacerbated by the application of chalk, which increases surface roughness when dry. Cyclists and triathletes face a related but distinct issue: "saddle sores," which are essentially friction-induced follicular occlusions and deep-tissue chafing in the perineal region. Rates of saddle soreness approach 40% during multi-stage events unless specialized padded shorts and chamois creams are used.

Taken together, these epidemiological and sport-specific insights underscore the need for tailored prevention strategies that account for both the mechanical demands of each activity and the modifiable environmental and anatomical factors that contribute to injury risk. In the next section, we examine how intrinsic and extrinsic risk factors can be conceptualized within a unified framework to inform targeted interventions.

Risk-Factor Framework

Frictional dermatoses arise from a complex interplay between intrinsic skin and anatomical characteristics and extrinsic environmental and equipment-related factors. Intrinsic factors include individual foot morphology, skin properties, and physiological responses.[14] For example, excessive pronation or cavus foot deformities alter normal load distribution, concentrating shear forces along the medial or lateral borders of the foot and increasing blister risk.[15] Hyperhidrosis, whether genetically determined or exercise-induced, elevates local skin hydration, weakening corneocyte cohesion and lowering the threshold for intra-epidermal cleavage.[16] Callus formation provides mechanical reinforcement but can be a double-edged sword, whereas a uniform callus can distribute pressure evenly, thick or uneven calluses may "catch" on sock seams or footwear irregularities, creating focal shear hotspots.[17]

Extrinsic factors encompass all external elements that influence the skin-textile interface. Footwear fit is paramount: shoes that are too tight increase normal load and shear, whereas overly loose shoes allow excessive foot movement, both of which exacerbate blister formation.[15] Rapid mileage increases (e.g., >10% per week) outpace skin adaptation and heighten incidence, especially in novice runners.[18] Sock selection, such as fiber type, knit density, seam placement, and liner systems, further modifies the COF at the interface.[19] Moisture management is critical; wet socks exhibit COFs up to 0.85 compared to dry values near 0.37, which directly correlates with blister incidence. Improper tape application or benchtop dressings can also backfire: wrinkles or adhesive edges become new shear foci if not applied smoothly.[11]

Environmental variables such as ambient temperature and humidity play an enabling role. High heat and humidity increase skin moisture content, soften the stratum corneum, and elevate COF by 20–30%, doubling blister rates in wet conditions. Conversely, arid, cold conditions may reduce maceration but increase

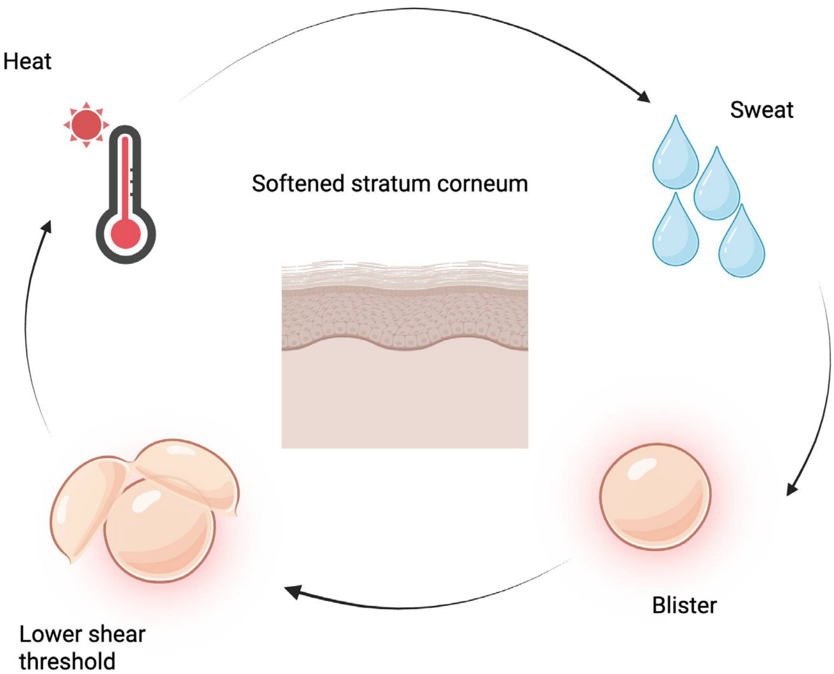

Fig 4 | Increased temperatures leading to blister formation
Source: Created in BioRender. Islam, R. (2025) https://BioRender.com/c484nkf

the risk of fissuring and cracking under shear.[20] A study of 203 hikers found that 68.5% presented with blisters from long-distance hiking (average~253.7 km). It was reported that hiking in socks that were deemed wet was associated with a 1.94 times greater risk of foot blisters (95%CI:1.04–3.61) ($p = 0.035$) (Figure 4).[21]

Textile Innovations and Mechanical Prevention

Textile-based interventions target the skin-textile interface to reduce shear forces and manage moisture, two key factors that contribute to blister formation.[22] Among these, sock design has received the most rigorous study. In the largest randomized controlled trial to date, Knapik and colleagues assigned 357 U.S. Army recruits to wear either cotton or acrylic socks during basic training marches; those wearing acrylic socks experienced a 48% relative reduction in new blisters (25 vs. 48%; RR:0.52, 95%CI:0.38–0.71).[4] Similar findings emerged in civilian settings: marathon runners randomized to acrylic-polyester blends reported 32% fewer plantar blisters compared with cotton controls.[23] These synthetic fibers combine hydrophobicity, which limits moisture uptake, with filament geometries that slide more readily over one another and across skin.

Beyond fiber chemistry, sock architecture exerts a pronounced effect on friction. Socks reduce the moisture content of the surface of the foot, thereby reducing the COF.[15] Laboratory tribology work shows that knit structure and stitch density influence friction more than fiber chemistry: in a 12-fabric DOE, shifting from terry to single-jersey architecture cut dynamic friction by ≈15–30%, whereas swapping polyester for cotton had minimal impact.[11] Modern performance socks often incorporate double-layer constructions, wherein a thin, nylon-based liner sock sits beneath an outer cushion sock; the liner absorbs shear through inter-sock movement, sparing the skin from the bulk of frictional cycles.[24] In Knapik et al.'s study, a dense double-sock system (polyester liner + wool-polypropylene outer) reduced overall blister incidence to 40% compared with 69% in the standard single-sock group ($p < 0.001$) and halved severe blister cases.[4] Toe socks, separating each digit, offer another strategy to minimize interdigital shear, though evidence remains limited, and user compliance varies.

Moisture management is equally critical. Hydrophobic, multi-filament polyester blends (e.g., Coolmax®) promote horizontal sweat wicking, maintaining lower in-shoe relative humidity. Laboratory and small-field studies consistently show that synthetic, moisture-wicking yarns lower in-shoe humidity; however, only one clinical trial has directly linked the choice of fiber to a reduction in blisters. In long-distance runners, the use of acrylic socks reduces blister counts by approximately half compared to cotton (13% vs. 23%; $p = 0.032$).[23] Coolmax-type polyester blends improve perceived dryness and lower sock moisture in field tests, yet no randomized study has quantified their impact on blister incidence.[24]

The frontier of textile innovation lies in smart and sensor-embedded fabrics. Early prototypes integrate thin-film thermistors and pressure sensors into the sock sole, transmitting real-time data to a wrist-worn display. In a dynamic laboratory validation study, Smith et al. tested a novel single-sensor in-shoe device in five healthy adult volunteers, directly comparing its measurements to those of the F-Scan™ in-shoe pressure system (gold standard) and a FLIR® T630sc infrared camera for skin temperature. During a 13-minute treadmill walk, wearing 100% cotton socks and their own sports shoes, the prototype was superimposed over the reference sensors inside each shoe. Paired analyses demonstrated no statistically significant differences between the prototype and F-Scan™ in peak plantar pressure ($p > 0.05$) or between the prototype and FLIR® T630sc in skin temperature readings ($p > 0.05$), with no systematic bias or drift observed over time.[25]

Other approaches embed microcapsules of phase-change materials or silicone lubricants within yarns; in the context of blisters, under increased frictional heat, these capsules could rupture and release slip agents directly at high-stress zones, sustaining low COF without reapplication.[26] While promising, these technologies await larger field trials to validate durability, washability, and user acceptability.

Beyond socks, seamless garments reduce abrupt transitions in surface topography that can catch on skin.[27] Compression shorts with bonded rather than stitched seams minimize intertriginous chafing in the groin and posterior thigh, whereas wraparound sports bras employ wide, soft-edge bands to prevent under-bust shear in female athletes.[28]

Barrier Products and Adjunct Strategies

Beyond optimizing textiles, topical and adhesive barriers play a critical role in preventing frictional dermatoses by directly modifying the skin-environment interface.[29] These products fall into four main categories: lubricants, antiperspirants, absorbent powders, and adhesive dressings or tapes.

Lubricants

Petrolatum-based and silicone-based balms are among the most widely studied friction-reducing agents. In tribological bench tests, these lubricants decrease the COF between skin and textile surfaces by approximately 20–30%, delaying the onset of microtear formation.[30] Field trials in half-marathon and marathon runners demonstrate that applying a thin layer of petrolatum or a commercial silicone balm (e.g., Body-Glide®) to high-risk sites, such as the heels, forefoot, and medial arch, before activity and reapplying every 3–4 hours, reduces blister incidence by 30–40%.[15] Importantly, compliance with reapplication schedules is key: one study found that skipping a single reapplication doubled blister rates, underscoring the need for event planning and athlete education.

Antiperspirants

Reducing sweat production can indirectly lower COF by limiting skin hydration. Aluminum-chloride hexahydrate formulations (20% spray or roll-on) applied nightly for 3 days before prolonged activity reduce sweat output by up to 40%. In a randomized crossover trial of 96 hikers, the antiperspirant arm showed a 45% reduction in new foot blisters compared to the placebo (RR:0.55; 95%CI:0.37–0.83), although 12% of participants reported mild irritant dermatitis at high-concentration sites. Lower-strength roll-on products (<10% aluminum) show variable efficacy and are better tolerated but may require more frequent application.

Powders and Absorbents

Talc, cornstarch, and zinc-oxide powders absorb moisture and can create a drier microenvironment; however, they may also introduce abrasive particulates if overapplied. Limited open-label studies in endurance athletes suggest modest benefits. A randomized trial involving 30 adults, divided into three groups that received different topical anti-blister treatments, was conducted to determine which product was most effective in reducing the risk of blisters. The participants underwent standardized compressed-air–driven cycles of heel compression and shear at their untreated baseline. Skin temperature increases did not differ between any product and no treatment (p = 0.767, p = 0.767, p = 0.515) nor among the three products themselves (p = 0.551). Conversely, application of the powder produced a significant decrease in near-surface skin hydration (mean Δ = −8.53 arbitrary units versus baseline; p = 0.01), whereas the film-former (Δ = −1.47 AU; p = 0.26) and the antiperspirant (Δ = −1.00 AU; p = 0.80) each yielded non-significant hydration changes.[31]

Adhesive Dressings and Tapes

Moleskin, hydrocolloid dressings (e.g., Compeed®), and athletic tapes provide a physical barrier that redistributes shear away from vulnerable skin. In a prospective, non-comparative clinical trial, Parish et al. evaluated a novel adhesive gelling foam dressing in 23 patients with exuding pressure ulcers recruited from seven North American centers. Subjects received the foam dressing, which was applied at least weekly alongside standard pressure-relief measures and optional secondary bandaging, and they were followed for up to 28 days or until ulcer healing occurred. At the final assessment, mean ulcer area had decreased by 13%, and 61% of patients demonstrated either complete healing or reported subjective improvement in ulcer condition.[32] This gelling-foam dressing's ability to offload shear forces, manage moisture, and cushion vulnerable skin in pressure ulcers suggests that a similar approach could be translated to blister prevention by redistributing frictional stress and maintaining an optimal microenvironment at high-risk sites.

Furthermore, in a randomized field investigation of 604 military athletes, COMPEED® hydrocolloid patches reduced the occurrence of hot spots/blisters from 25.5 to 14.5% (RR 0.57; p = 0.0001), allowing 85% of participants to complete a 40-km march uninterrupted.[33] Similarly, a multisite RCT of 128 ultramarathoners found that pre-taping blister-prone areas with Micropore paper tape reduced new blisters by 40%, with a number-needed-to-treat of 1.3.[34]

Denting the friction cycle at the skin interface through the use of lubricants, sweat-reducing agents, absorbent powders, and adhesive barriers adds a potent layer of protection, especially when combined with optimized textile selection. For optimal effect, athletes should adopt a multi-modal approach: apply an antiperspirant regimen several days before events, use lubricants pre- and during activity, dust high-sweat areas with powder, and pre-tape or patch known hotspots with hydrocolloids or specialized tape.

Discussion

Integrated Prevention Protocols

Preventing friction injuries most effectively requires combining textile choices, topical barriers, and behavioral strategies into a cohesive protocol. First, pre-event skin preparation is essential: athletes should inspect and debride uneven calluses several days before competition, smoothing edges that might catch on socks or seams.[35] Nightly application of an aluminum-chloride antiperspirant to the feet for 2–3 days prior can reduce sweat production, lowering baseline skin hydration and baseline COF.[36]

On the day of the activity, the selection of high-density, synthetic double-layer socks is critical. A thin, hydrophobic liner sock (made of acrylic or polyester) worn under a cushioned outer sock absorbs inter-sock shear and wicks moisture away from the skin.[24] Shoes should be sized with approximately a half-size of extra room in front to accommodate foot swelling and blister dressings, and laced using a heel-lock configuration to minimize slippage.[37] For sports involving upper-body friction, such as rowing, weightlifting, or under-bust shearing in female athletes,

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Table 4 | Summary of blister-prevention interventions. Rating Key: Cost: $ (<$10), $$ ($10–30), $$$ (>$30/device). Durability Judged for a Marathon/Ruck (>4–6 hours) or Multi-Day Hike, Where Noted

Category	Primary Mechanism	Key evidence and Effect Size	Field Durability (hours/days of activity)	Cost/Availability	Common Downsides
Socks (double-layer synthetic/polytetrafluoroethylene blend/toe socks)	Lowers COF, wicks moisture, and redistributes shear	Acrylic/double-layer socks RR ~0.52 vs. cotton; toe socks cut interdigital blisters ~40–50% in ultramarathons	High (last entire event; no reapplication)	$$ (still inexpensive per pair; specialty > basic cotton)	Can retain heat if too thick; sizing/fit issues
Lubricants (petrolatum, silicone gels)	Reduces COF acutely; fills skin-textile asperities	Petrolatum ↓ blister incidence ~30–40%; silicone gels similar magnitude in small RCTs	Low–Moderate (needs reapply q3–4 hours)	$ (very cheap, widely available)	Greasy feel, attracts grit; can macerate if overused
Antiperspirants (20% aluminum chloride)	Lowers sweat→ moisture→ COF; toughens SC	Small trials show ~30–50% reduction in blister hot-spots; strongest in feet with hyperhidrosis	High if started 2–3 nights pre-event; once daily	$ (OTC)	Irritation/dry cracking if overused; stings on broken skin
Dressings/Tape (hydrocolloid, paper/kinesio tape, moleskin)	Physical barrier to shear; redistributes load	Hydrocolloid RR ~0.57; paper tape NNT ≈1–2 in thru-hikers; kinesio tape mixed bench data	Moderate–High (24–72 hours if applied well; sweat may loosen)	$–$$	Can peel in sweat; allergic adhesive reactions
Smart-textile sensors (moisture/temp/pressure)	Real-time monitoring to trigger preventive action	Prototype studies only; no blister outcome RRs yet	Variable (depends on battery/washability)	$$$ (early-stage tech)	Cost, bulk, and data management require user adherence

seamless, bonded garments and sports bras with wide, soft-edge bands are advised to eliminate abrupt topographical transitions.[38]

Immediately before donning socks, athletes should apply a thin layer of silicone-based lubricant (e.g., BodyGlide®) to identify "hot spots" (commonly the heel, medial arch, and fifth metatarsal head), reapplying every 3–4 hours for events exceeding two hours. For multi-day expeditions, hydrocolloid dressings or prophylactic adhesive tape should be pre-cut to cover blister-prone areas. Patches should be applied smoothly without wrinkles and reinforced around the edges with paper or kinesiology tape to prevent edge lift. Powders can be lightly dusted into shoes to absorb excess moisture, but overapplication should be avoided to prevent abrasion on the shoe interior.[15]

During prolonged activity, athletes should periodically check their footwear fit and replace or adjust socks if moisture levels rise, as wet socks can double the risk of blisters. During rest breaks, feet can be briefly exposed to air, and shoe interiors can be dried with portable dryers or by rotating between two pairs of shoes.[12]

Finally, education and self-monitoring underpin all interventions. Athletes and support staff should be trained to recognize early signs of "hot spots" (localized warmth or discomfort) and carry a compact blister-prevention kit containing lubricants, powder, tapes, and patches. A simple checklist covering pre-event skin prep, sock selection, lubricant timing, dressing application, and mid-event shoe inspection can ensure consistency and reduce reliance on memory under stress (Table 4).[39]

By integrating these measures: optimized textiles, barrier applications, environmental controls, and athlete education, into a standardized prevention protocol, teams and individuals can dramatically reduce the incidence of friction blisters and chafing, maintain performance continuity, and minimize downtime due to skin injuries (Figures 5 and 6).[15]

Controversies and Research Gaps

Despite growing interest in friction-blister prevention, several controversies and evidence gaps hinder the translation of laboratory findings into field practice. First, bench-to-field correlation remains imperfect: tribological rigs can precisely measure the COF under controlled loads and humidity, yet their static conditions fail to replicate dynamic gait patterns, varying pressure distributions, and cyclic moisture fluctuations experienced in real-world activities.[40] As a result, materials that perform optimally in vitro may offer less protection on trail runs or multi-day marches.

Second, heterogeneity in outcome definitions complicates cross-study comparisons. Some trials define a blister as any fluid-filled vesicle regardless of size or pain, while others exclude minor deroofed erosions or confluent chafing lesions. This inconsistency hinders meta-analyses and obscures the true effect sizes of interventions such as hydrocolloid dressings or antiperspirants.

Third, the underrepresentation of diverse athlete populations limits the generalizability of the findings. The RCTs included in our review focus on male military recruits or endurance runners, leaving female athletes, particularly those in sports with upper-body chafing, and youth or adaptive sports participants poorly studied.[4] Hormonal differences, skin thickness variations, and sport-specific biomechanics may alter blister risk and intervention efficacy in these groups.

Lastly, the environmental sustainability of synthetic fibers and disposable dressings raises ethical and ecological concerns. Acrylic and polyester blends excel at moisture management and low COF but contribute to microplastic shedding during washing and disposal. Similarly, single-use hydrocolloid patches and tapes generate significant medical waste. Biodegradable hydrophobic yarns and reusable barrier technologies are currently in early development, yet lack rigorous performance and life-cycle assessments.[41]

Addressing these gaps will require standardized blister definitions, pragmatic field trials that simulate

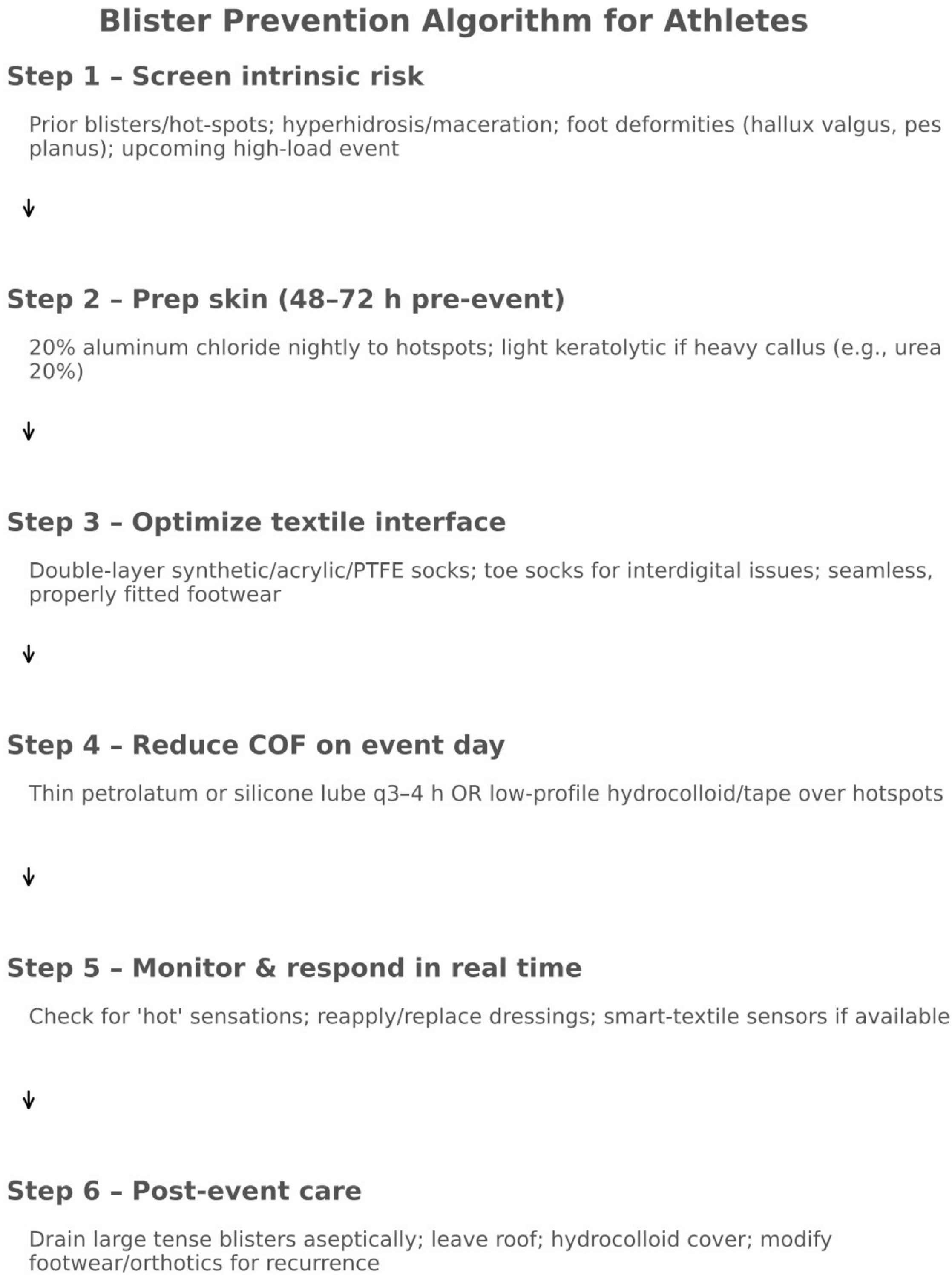

Fig 5 | Algorithm for prevention and acute management of friction blisters in athletes. COF, coefficient of friction

athletic conditions, the inclusion of diverse cohorts, and research into eco-friendly materials that strike a balance between performance and environmental responsibility.

The evidence base is limited by small, unblinded trials and laboratory studies that may not reflect in-field conditions. Consequently, recommendations should be viewed as provisional pending larger pragmatic trials. Overall, most trials had a high or "some concerns" risk of bias due to a lack of blinding and surrogate outcomes, while cohort/field studies were at a moderate risk from confounding and incomplete follow-up; bench studies frequently lacked ecological validity.

Future Directions

Innovations in materials science and wearable technology hold promise for advancing blister prevention beyond current textile and barrier strategies.

"Quick pick: socks vs lubricant vs dressing"

1. **Event duration?**
   - **< 4 h / single bout** → go **lubricant** first; reapply q3–4 h.
   - **≥ 4–6 h or multi-day** → prioritize **sock choice + antiperspirant**; add dressing for known hotspots.
2. **Anatomical site?**
   - **Interdigital / toe web** → **toe socks** ± thin hydrocolloid strip.
   - **Plantar / heel / Achilles** → **double-layer/PTFE socks** ± paper tape/hydrocolloid.
   - **Upper trunk/thigh (chafing)** → **silicone/petrolatum lubricant**; breathable fabric.
3. **Sweat rate / maceration risk?**
   - **High sweat / wet environment** → **antiperspirant 2–3 nights prior** + moisture-wicking socks; avoid over-occlusion.
   - **Low sweat / dry skin** → **lubricant or dressing**; monitor for cracking.
4. **History of hotspot?**
   - **Yes** → pre-tape or hydrocolloid on that site regardless of other choices.
   - **No** → monitor only; intervene at first "hot" sensation.

Abbrev: PTFE, polytetrafluoroethylene.

Fig 6 | Decision tree. PTFE, polytetrafluoroethylene

Self-lubricating yarns, incorporating microencapsulated silicone or phase-change materials, could release slip agents in response to frictional heat, maintaining a low COF without repeated topical applications. Early bench models demonstrate up to 25% additional COF reduction compared with standard silicone balms; however, human trials are needed to validate durability through laundering and extended wear.

Wearable sensor integration represents another frontier: thin-film pressure and thermal sensors embedded within socks can transmit real-time data on "hot-spot" formation, as pilot studies have shown 90% sensitivity for blister prediction in ultramarathoners. Coupling these sensors with haptic or app-based alerts could enable athletes to preempt blister onset with targeted interventions, but challenges remain in ensuring sensor adhesion, battery life, and data accuracy under high-sweat conditions.

On the sustainability front, biodegradable hydrophobic fibers, such as polylactic acid blends and bio-based polyesters, offer eco-friendly alternatives to acrylic and nylon, potentially reducing microplastic shedding during wash cycles. Preliminary lab tests indicate comparable moisture-wicking performance, though long-term wear and COF metrics require further investigation.

Military health agencies already issue practical blister-prevention guidance (for example, U.S. Army Public Health Center factsheets recommending synthetic socks, taping, and antiperspirants).[42] Meanwhile, environmental regulation is reshaping material choices: the EU's 2023/2055 REACH restriction on intentionally added microplastics and emerging U.S. laws (California AB1628 on microfiber filtration; the proposed federal Fighting Fibers Act of 2024) are pushing textile developers toward low-shedding, bio-based yarns. These shifts mean future sock and dressing designs must balance friction performance with sustainability mandates.

Finally, establishing standardized outcome measures and dynamic field-testing protocols will be crucial. Future studies should harmonize blister definitions (in terms of size, pain threshold, and lesion type), employ wearable tribometers to capture real-time shear cycles, and include diverse cohorts across various demographics, including gender, age, and adaptive sports. Such efforts will bridge the gap between laboratory innovation and athletic application, ultimately empowering personalized, data-driven prevention of frictional dermatoses.

Conclusion

Frictional dermatoses, encompassing localized intra-epidermal blisters to widespread chafing erosions, arise from the interaction of shear forces, moisture, and individual skin biomechanics. Evidence supports a multimodal prevention paradigm: selecting high-density, hydrophobic double-layer socks and moisture-wicking textiles; applying topical lubricants and antiperspirants; and using adhesive dressings or tapes at known hotspots. Emerging smart-textile solutions and self-lubricating yarns promise real-time, personalized protection, while biodegradable fibers offer sustainable alternatives to traditional synthetics. However, translating findings from the bench to the field remains constrained by inconsistent outcome definitions, limited diversity in study populations, and ecological concerns. Standardizing blister metrics, expanding pragmatic field trials, and integrating wearable sensor data will be key to refining interventions. By combining mechanistic insights with athlete-centered strategies, clinicians, coaches, and product developers can markedly reduce friction injuries, maintain performance, and minimize downtime, ensuring friction blisters become a preventable nuisance rather than a recurrent barrier to athletic success.

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