



# Training, Cleansing, and the Cutaneous Microbiome: Implications for Athlete Skin Health, Infection Risk, and Performance: A Review

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## ABSTRACT

### BACKGROUND

Athletes are exposed to unique combinations of sweat, mechanical friction, frequent cleansing, and communal environments that can disrupt the skin microbiome. These disturbances lead to eczema flares, bacterial and fungal infections, acne mechanica, and impaired thermoregulation, all of which threaten performance and well-being.

### OBJECTIVE

This review aimed to synthesize current evidence on how intensive training and hygiene practices reshape the skin microbiome in athletic populations, to examine downstream impacts on dermatologic health and performance, and evaluate emerging microbiome modulating strategies.

### METHODS

A comprehensive literature search was performed across major biomedical databases for studies published through 2025 that addressed cutaneous microbial community composition, athlete-specific perturbations, related skin disorders, performance outcomes, and probiotic or barrier-supportive interventions. Selected articles included cohort studies, randomized trials, mechanistic investigations, and meta-analyses.

### RESULTS

Intensive exercise elevates sweat production, raises skin pH, and causes abrasion, while repeated bathing and exposure to chlorine or detergents strip lipids and resident microbes. Shared equipment and facility surfaces can further spread pathogens. These combined factors drive dysbiosis, characterized by loss of commensal *Staphylococcus epidermidis*, overgrowth of *Staphylococcus aureus* and *Malassezia* species, and reduced microbial diversity. Dysbiosis correlates with atopic dermatitis exacerbations, outbreaks of impetigo and tinea, acne mechanica, and delayed barrier recovery that can sideline athletes. Early trials of topical *Lactobacillus plantarum* and *Roseomonas mucosa* show promise in restoring microbial balance in eczema, and emerging prebiotic formulations and smart textiles offer additional avenues for maintaining skin health.

### CONCLUSIONS

Recognizing the skin microbiome as a dynamic partner in cutaneous homeostasis supports a shift from reactive treatment to proactive maintenance in sports medicine. Adoption of pH-balanced cleansers, optimized shower timing, barrier-repairing emollients, and targeted probiotic or prebiotic therapies, combined with rigorous equipment disinfection and facility design, can reduce dermatologic downtime and enhance athletic performance. Longitudinal multi-omics studies and

rigorously controlled trials are needed to refine these interventions and translate microbiome science into standard care for athletes.

**Keywords:** Athlete skin microbiome, Sports dermatology, Dysbiosis in athletes, Probiotic therapy for athletes, Athlete skin infections

### Introduction

Over the past decade, the human skin microbiome has emerged as a critical regulator of cutaneous barrier integrity, immune defense, and overall skin health.<sup>1</sup> While most research has focused on baseline microbial communities in sedentary populations, athletes experience unique environmental and physiological stresses that significantly disrupt their cutaneous microbiota, as reported by a meta-analysis of 91 studies and 2632 patients, which found a higher trend of microbial richness in athletes compared to non-athletes.<sup>2</sup> Intensive training elevates sweat production, alters skin pH, and increases mechanical friction, whereas frequent showering, exposure to pool chemicals, and shared equipment further disrupt microbial homeostasis.<sup>3</sup> These combined factors may predispose athletes to an increased risk of dermatologic conditions, from eczema flares to bacterial and fungal infections, which impair both health and performance.

Despite growing awareness of athlete-specific skin disorders, the role of the microbiome in their pathogenesis and recovery remains underexplored.<sup>4</sup> Recent advances in high-throughput sequencing and metabolomics now allow detailed analysis of microbial changes caused by exercise and hygiene practices.<sup>5</sup> Early evidence suggests that dysbiosis may weaken barrier function, promote pathogen overgrowth, and even influence thermoregulation through microbe-derived metabolites.<sup>6</sup> Furthermore, probiotic and prebiotic interventions show potential for restoring a healthy microbial balance, but few studies have tested these approaches in sports settings.<sup>7</sup>

This review synthesizes the latest findings on how the interplay of intensive training and frequent bathing reshapes the skin microbiome in athletes. We examined the downstream consequences for atopic dermatitis (AD), infection risk, and acne mechanica, and discussed potential links between microbial alterations and declines in performance or recovery. Finally, we evaluated emerging probiotic and barrier-supportive strategies, outlined key controversies and gaps, and proposed future research directions, aiming to equip sports medicine clinicians and dermatologists with an integrated framework for preserving cutaneous health in athletic populations.

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## Methods

Whenever possible, we weight findings based on evidential tiers (animal/mechanistic < observational < randomized trials) and specify each study accordingly in Supplementary Figure S1.

This structured narrative review was conducted to synthesize the current state of knowledge about the skin microbiome in athletic populations, its perturbation by training and hygiene practices, and the implications for dermatologic health and performance. A structured literature search was performed exclusively in the PubMed database between January 2000 and June 2025. Search terms included combinations of “skin microbiome,” “cutaneous microbiota,” “athlete,” “exercise,” “sweat,” “hygiene,” “bathing,” “dermatitis,” “infection,” “acne mechanica,” “probiotic,” and “prebiotic.” Reference lists of retrieved articles were hand-searched to identify additional relevant studies.

Eligible publications comprised original cohort studies, case series, randomized controlled trials, mechanistic in vitro or animal studies, systematic and narrative reviews, and meta-analyses that addressed (1) the baseline composition or functional roles of the skin microbiome, (2) microbiome changes associated with intensive exercise or cleansing, (3) links between microbial perturbations and dermatologic conditions in athletes, (4) performance or recovery outcomes related to skin health, and (5) probiotic, prebiotic, postbiotic, or barrier-supportive interventions. Only articles published in English were included. Conference abstracts, editorials, case reports of single patients, and studies with fewer than ten participants were excluded.

Data from included articles were extracted and organized according to the predefined sections of this review: cutaneous microbiome primer; athlete-specific perturbations; dermatologic consequences; performance implications; and intervention strategies. Due to the heterogeneity of study designs and outcome measures, findings are presented in a descriptive, narrative format rather than being pooled quantitatively. Critical appraisal of methodological quality and identification of research gaps guided the synthesis and recommendations. A detailed appendix of our methodology can be found in the supplementary methods (Supplementary Figure S1).

## Cutaneous Microbiome Primer

The skin serves as a dynamic ecosystem hosting a complex community of bacteria, fungi, viruses, and microscopic arthropods that collectively constitute the cutaneous microbiome.<sup>8</sup> Predominant bacterial genera include *Staphylococcus* (particularly *Staphylococcus epidermidis*), *Cutibacterium* (formerly *Propionibacterium*), *Corynebacterium*, and *Micrococcus*, while fungi are primarily represented by *Malassezia* species.<sup>9</sup> Beyond simple colonization, commensal microbes actively defend against pathogens through competitive exclusion and the production of antimicrobial peptides (AMPs), and engage in bidirectional crosstalk with keratinocytes and resident immune cells to regulate inflammation and barrier function.<sup>10</sup>

Inter-individual variation in skin microbiota is significant and is influenced by anatomical site (sebaceous, moist, dry), host factors (age, sex, ethnicity), and environmental exposures.<sup>11</sup> Sebaceous areas (e.g., face, upper back) favor lipophilic *Cutibacterium*, whereas moist regions (e.g., axilla, groin) are rich in *Corynebacterium* and *Staphylococcus*.<sup>12</sup> Ethnicity and geography further modulate community composition, as do hormonal changes across the lifespan.<sup>13</sup> Daily hygiene habits, including how often you bathe and use soaps or disinfectants, can temporarily lower microbial load but may also strip lipids and disrupt commensal flora balance.<sup>14</sup>

Investigators employ a suite of “omics” tools to characterize the skin microbiome.<sup>15</sup> The most common approach, 16S rRNA amplicon sequencing, profiles bacterial communities through conserved ribosomal regions, offering cost-effective genus-level resolution, but is limited in strain-level discrimination and non-bacterial coverage.<sup>16</sup> Whole metagenomic shotgun sequencing overcomes these limitations, enabling the simultaneous detection of bacteria, fungi, viruses, and functional genes, albeit challenged by high host DNA content and greater complexity expense.<sup>17</sup> Emerging techniques, including culturomics for isolating fastidious organisms, metabolomics for mapping bioactive small molecules, and deconvolution of host–microbe transcriptomes, are expanding our understanding of microbe-derived metabolites and immune-modulatory signals.<sup>18</sup>

## Athlete-Specific Perturbations

Athletes face a confluence of factors that uniquely disturb their skin microbiome, beginning with the physiological demands of intensive training.<sup>19</sup> Exercise physiology increases sweat production and skin temperature, boosting moisture and nutrient availability for microbes, yet simultaneously raising skin pH.<sup>20</sup> In one controlled study, exercise-induced sweating in 102 participants led to transient rises in surface pH, shifting from the normal acidic range (~pH 4.5–5.0) toward neutrality, which can favor opportunistic bacteria over acidophilic commensals.<sup>21</sup> Repeated friction from apparel and equipment (for example, pads, straps) also causes micro-abrasions that compromise the barrier, enabling deeper microbial colonization.<sup>22</sup>

## Skin Surface pH and Pathophysiology

Skin surface pH normally ranges 4.5–5.0, forming an “acid mantle” that favors commensals such as *S. epidermidis* and optimizes endogenous AMP activity. Intense exercise and alkaline cleansers can transiently raise pH toward neutrality ( $\geq 6.0$ ), weakening this chemical barrier and altering lipid organization (ceramides/free fatty acids).<sup>20–23</sup> A more neutral pH increases *Staphylococcus aureus* adhesion and protease activity, while reducing AMP efficacy, facilitating a shift from mutualistic to opportunistic taxa.<sup>9,24,25</sup> Dysbiosis then feeds into immune dysregulation: type 2 cytokines (IL-4/IL-13) dampen barrier repair pathways, and commensal-derived AhR signaling that

normally promotes epidermal differentiation and repair is blunted.<sup>10,26</sup> The result is a feed-forward loop—barrier disruption → microbial imbalance → cytokine influx → further barrier injury—that intensifies during intense training blocks or frequent cleansing without reacidification.

Practical mitigation includes pH-balanced (syndet) cleansers, rapid post-exercise drying, and leave-on emollients that restore lipid order and acidity; these measures may shorten the window in which pathogens dominate.<sup>23,27,28</sup> Future athlete trials should quantify pH kinetics alongside microbial/immune readouts to confirm causality.

### Bathing and Dysbiosis

Frequent or prolonged bathing and showering, common in athletic routines, adds another layer of disruption.<sup>29</sup> While washing removes sweat, salts and debris, it also strips lipids and resident microbes.<sup>27</sup> Soaps, detergents, and chlorinated water can transiently reduce microbial load but at the cost of dysbiosis: a popular hygiene expert warns that over-showering “disrupts our skin’s microbiome: the delicate ecosystem of bacteria, fungi, mites, and viruses.”<sup>30</sup> High-temperature water exacerbates lipid loss, further altering the ecological niche.<sup>31</sup>

### Environmental Contribution to Dysbiosis

Beyond personal practices, environmental and equipment exposures contribute significant perturbations.<sup>32</sup> Shared surfaces such as locker-room benches, wrestling mats, and turf fields are reservoirs for pathogens like *S. aureus* (including MRSA) and dermatophytes.<sup>33</sup> Contact transfer studies in military field exercises demonstrate that harsh environments and communal facilities produce marked shifts in hand and forearm microbiota, with spikes in environmental and soil-associated taxa.<sup>34</sup>

Climate, seasonality, and sport type also modulate these effects. Outdoor endurance athletes in humid or tropical climates face persistent high humidity that favors fungal overgrowth (e.g., *Malassezia*, dermatophytes), whereas winter sports may induce skin dryness and cracks, allowing bacterial invasion. Similarly, indoor athletes in chlorinated pools experience repeated chemical exposure, which is linked to barrier disruption and shifts toward chlorine-resistant species.<sup>35</sup>

Finally, parallels from military training cohorts provide insight into high-load, multi-stress scenarios: soldiers undergoing field exercises display reduced microbial diversity, increased colonization by environmental taxa, and higher rates of tinea pedis and impetigo. These findings underscore the combined impact of sweat, cleansing, friction, and environmental exposures.<sup>36</sup>

Taken together, intense exercise, vigorous hygiene practices, equipment contact, and environmental factors all contribute to significant, sometimes harmful, changes in an athlete’s skin microbiome, which can lead to dermatologic issues and impact performance.

### Dermatologic Consequences

Athlete-specific microbiome perturbations translate directly into a spectrum of skin disorders that can sideline training and reduce quality of life.

### Atopic Dermatitis & Barrier Dysfunction

Cutaneous dysbiosis is both a cause and a consequence of barrier impairment in AD.<sup>24</sup> Loss of commensals like *S. epidermidis* and overgrowth of *S. aureus* correlate tightly with disease flares, triggering cytokine cascades (IL-4, IL-13) and increasing trans-epidermal water loss (TEWL).<sup>25</sup> In athletes, repeated sweat-induced pH shifts and frequent cleansing exacerbate this cycle, stripping lipids, reducing AMPs, and enabling allergen ingress.<sup>37</sup>

### Bacterial & Fungal Infections

Shared equipment and microabrasions prime athletes for pathogen overgrowth.

**Impetigo & MRSA:** Locker-room surfaces and turf can harbor *S. aureus*, with community-associated MRSA outbreaks reported in football, wrestling, and basketball teams; surface contamination rates can reach ~10% in some facilities.<sup>38</sup>

**Folliculitis & Pitted Keratolysis:** Occlusion under pads and boots fosters moist niches where *Corynebacterium* and *Kytococcus* thrive, leading to malodor and crater-like pits on soles.<sup>39</sup>

**Dermatophyte Infections:** Scalp and body tinea (“ringworm”) outbreaks have been linked to unsanitized mats and helmets; gym equipment can carry more fungal spores than toilet seats.<sup>40</sup>

### Acne Mechanica & Occlusive Lesions

Mechanical friction and occlusion (“maskne,” helmetne) augment local sebum production and sebaceous duct obstruction. Altered microbiota, favoring *Cutibacterium acnes* and inflammatory strains, worsens papulopustular eruptions. Substance P release in response to sweat and heat further amplifies inflammation.<sup>41</sup>

### Contact Dermatitis & “Pool Skin”

Chlorine and detergent exposure strip surface lipids and disrupt commensal balance. Repeated swimming in chlorinated pools induces irritant or allergic contact dermatitis, characterized by xerosis, erythema, and scaling. Dysbiosis in these athletes often shows enrichment of chlorine-resistant strains (e.g., *Pseudomonas*) alongside diminished diversity.<sup>42</sup>

### Psychodermatology & Performance Downtime

Emerging data suggest that skin dysbiosis can influence neuroimmune pathways, such as microbial metabolites modulating systemic cytokines and neuropeptides (e.g., substance P), potentially exacerbating stress-induced flares. Although direct studies in athletes are pending, parallels from over-training syndrome hint at a gut–skin–brain axis where dysbiosis may worsen anxiety and delay recovery.<sup>41</sup>

This section underscores how dysbiotic shifts underlie eczema exacerbations, infectious outbreaks,

and mechanical acne, each with tangible impacts on athlete health and performance. Next, we will explore how these microbial changes intersect directly with athletic performance.

### Microbiome & Athletic Performance

Alterations in the skin microbiome can directly influence an athlete's susceptibility to infection and subsequent time-loss.<sup>19</sup> Commensal bacteria such as *S. epidermidis* produce AMPs that help contain pathogens like *S. aureus*.<sup>25</sup> Dysbiosis, for example, following repeated pH shifts or lipid stripping, reduces AMP output and compromises local immune defenses, which increases the risk of impetigo or MRSA and prolongs recovery intervals (Figure 1).<sup>43</sup>

Beyond infection control, microbe-derived metabolites may modulate thermoregulation and skin homeostasis.<sup>26</sup> Certain skin bacteria ferment sweat constituents into short-chain fatty acids (SCFAs) and other by-products that can influence local blood flow and heat dissipation.<sup>44</sup> In germ-free animal models, the absence of these metabolites correlates with impaired aerobic capacity and altered thermal tolerance, suggesting a contributory role for the microbiome in sustaining performance under heat stress.<sup>45</sup>

Finally, parallels with the gut-skin axis in over-training syndrome suggest systemic spill-over effects: excessive training disrupts gut microbial balance, elevating circulating cytokines that may exacerbate skin inflammation and delay barrier repair.<sup>46</sup>

While athlete-focused trials on skin-systemic cross-talk remain scarce, integrating cutaneous and gut microbiome assessments could reveal novel markers of training fatigue and recovery potential.<sup>47</sup>

Collectively, these insights underscore that preserving a healthy skin microbiome might not only prevent downtime from dermatologic issues but could also prime the body for optimized thermoregulation and endurance, an emerging area for sports medicine.

### Intervention Strategies

Effective management of athlete skin health requires a multifaceted approach that preserves microbial balance while minimizing pathogen overgrowth.<sup>48</sup> First, optimizing personal hygiene routines is paramount.<sup>49</sup> Athletes should time post-workout showers within an hour of exercise to remove sweat and debris, but avoid excessive, twice-daily washing unless sport-specific demands necessitate it.<sup>29</sup> Choosing pH-balanced syndet bars or liquid cleansers (pH 4.5–5.5) helps maintain the acid mantle and lipid barrier, whereas alkaline soaps elevate pH and promote dysbiosis.<sup>23</sup> Similarly, lukewarm water, rather than hot, should be used to limit TEWL and preserve commensal lipids.<sup>50</sup>

Beyond cleansing, targeted microbial therapies show promise.<sup>51</sup> Topical probiotic formulations containing strains such as *Lactobacillus plantarum* or *Roseomonas mucosa* have demonstrated reductions in *S. aureus* colonization and improvements in barrier function in AD populations, suggesting utility for athletes prone to dysbiosis-driven eczema.<sup>52</sup> Oral probiotics, notably *Lactobacillus rhamnosus* GG, can modulate systemic immune responses and have been associated with fewer skin infections among military recruits, findings that justify applying this knowledge in sports settings. Meanwhile, prebiotic and postbiotic preparations (e.g., ceramide-boosting oligosaccharides or microbe-derived SCFAs) offer additional avenues for reinforcing barrier recovery and suppressing opportunistic pathogens.<sup>53</sup>

Supporting the skin's physical defenses is equally important.<sup>54</sup> Applying emollients right after a shower with products rich in ceramides, niacinamide, and cholesterol strengthens the lipid barrier and helps beneficial bacteria recolonize microbes.<sup>28</sup> Innovations in "smart" textiles, like garments and gear impregnated with antimicrobial metals such as silver, copper, or zinc, can reduce surface pathogen load without wholesale depletion of commensals, thereby lowering the risk of equipment-mediated transmission.<sup>55</sup>

At the facility level, rigorous infection-control policies are critical. Shared equipment, including mats, benches, and weight machines, should be disinfected daily with EPA-registered agents effective against MRSA and dermatophytes.<sup>56</sup> Locker rooms must be well-ventilated with humidity control to deter fungal proliferation, and the use of single-use towels or athlete-specific lockers can further limit cross-contamination (Figure 2).<sup>57</sup> Finally, education programs and simple checklists empower athletes and support staff to adopt "microbiome-friendly" practices: regulating shampoo

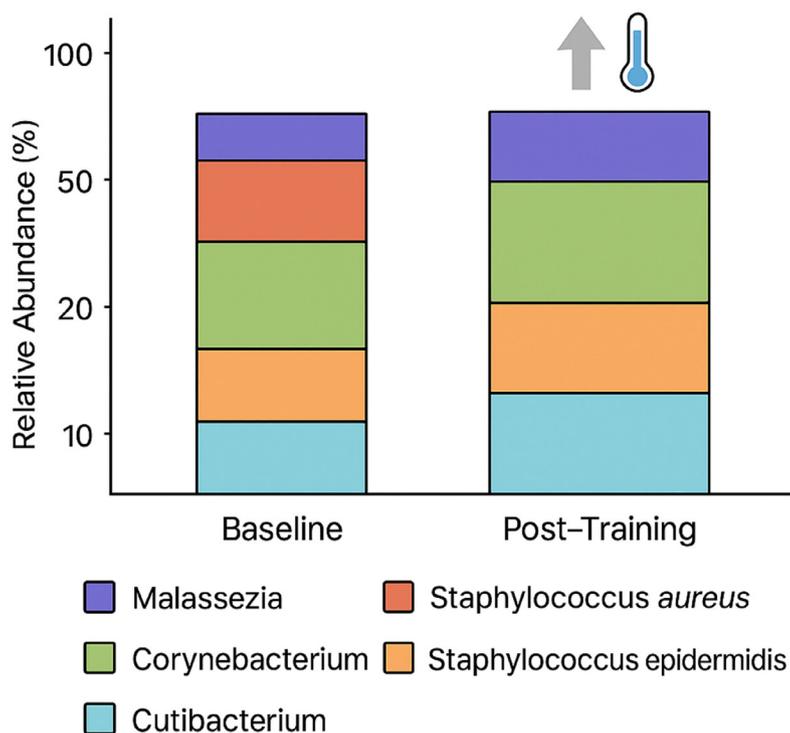


Fig 1 | Post training microbiome. Bar chart that contrasts baseline versus post-training microbiome composition, illustrating the relative increase in opportunistic taxa after an intense workout session. Figure created by the author using generative AI software (OpenAI, DALL-E). Conceptual illustration, author-generated (no original data)

frequency, scheduling showers post-exercise, patting rather than rubbing the skin dry, and selecting low-pH, fragrance-minimal products (Figure 3).<sup>58</sup>

By integrating these personal, product-based, and environmental interventions, sports medicine teams can proactively preserve cutaneous microbial resilience, reduce infection-related downtime, and support overall dermatologic health in athletic populations.

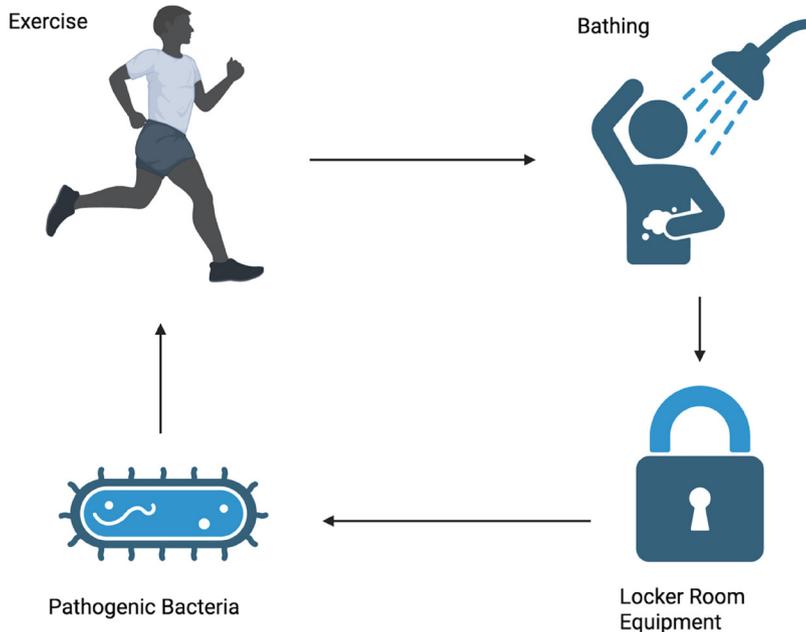


Fig 2 | Exercise, bathing, and shared locker-room gear sequentially perturb the skin microbiome and lead to loss of commensals and overgrowth of pathogens. Created in BioRender. Islam, R. (2025) <https://BioRender.com/10399kr>



Fig 3 | Microbiome-smart locker room. Shows a traditional high-risk space versus an optimized, microbe-friendly design, with four actionable hygiene steps highlighted along the bottom. Figure created by the author using generative AI software (OpenAI, DALL-E)

**Controversies & Knowledge Gaps**

Despite a growing body of research into the athlete skin microbiome, fundamental questions remain unanswered, and these gaps impede clinical translation. First, many studies rely on single-time-point sampling, capturing microbial communities only after intense exercise or post-shower cleansing. Without baseline measurements, it is impossible to determine whether observed shifts in bacterial or fungal populations are the cause of skin flares and infections or merely a consequence of barrier disruption from sweat, friction, or frequent washing. To solve this chicken-and-egg problem, future studies should use longitudinal designs that sample athletes at rest, immediately after training, after hygiene routines, and during recovery periods to track the timing of dysbiosis and relate it to clinical outcome events.

Methodological heterogeneity further complicates efforts to synthesize findings across studies. Researchers differ in the anatomical sites they sample, the timing of collection relative to exercise and bathing, and the molecular approaches they use. While 16S rRNA sequencing remains popular for its cost-effectiveness, it provides only genus-level resolution for bacteria and ignores fungi and viruses. Shotgun metagenomics and metabolomics yield richer, strain-level and functional data. Yet, they face technical challenges such as high host DNA contamination in skin swabs, variable bioinformatic pipelines, and higher costs. Standardized protocols for sample collection, storage, DNA extraction, sequencing, and data analysis are urgently needed to ensure reproducibility and facilitate meta-analyses across athlete cohorts.

Athlete populations introduce further layers of complexity. Travel schedules, dietary alterations during competition, use of topical antimicrobials or systemic antibiotics, individual predisposition to atopy, and environmental factors such as humidity, temperature, and ultraviolet exposure all modulate the skin microbiome. Moreover, different sports impose distinct stressors: swimmers encounter chlorinated water, wrestlers use shared mats, distance runners accumulate friction on lower limbs, and cyclists experience prolonged occlusion under helmets and jerseys. Without careful stratification by sport type, geographic region, and individual habits, it is difficult to distinguish universal microbial signatures from activity-specific or context-dependent patterns (Figure 4).

Translating descriptive microbiome data into targeted interventions remains in its infancy. Identifying which microbial strains produce barrier-reinforcing compounds or AMPs is only the first step; understanding the doses and formulations necessary for clinical benefit is equally critical. Topical probiotic and prebiotic preparations have shown promise in small trials of

1. Shower within 15 minutes post-session using a pH-balanced syndet (pH 4.5–5.5); avoid abrasive scrubbing.
2. Pat dry with a personal towel; change out of damp gear immediately. Apply a light leave-on emollient or acidifying lotion to high-friction sites.
3. Launder uniforms/towels  $\geq 60^{\circ}\text{C}$  or with an EPA-registered disinfectant; rotate shoes/gloves to fully dry between uses.
4. Disinfect high-touch equipment daily: detergent wipe  $\rightarrow$  disinfectant contact time per label; no shared razors/towels/water bottles.
5. Daily skin check: cover any draining/pustular lesions; report lesions persisting  $>24$  h. Exclude from contact play until 48 h on effective therapy and lesions are covered/dry.
6. Facility engineering: adequate airflow/ventilation, humidity  $<60\%$ , readily accessible hand rub stations at exits and benches.

Fig 4 | Microbiome-conscious hygiene protocol for teams

AD patients, but athlete-specific efficacy, optimal dosing schedules, and vehicle selection (creams, sprays, hydrogels) are poorly defined. Oral probiotics add another layer of complexity, as gut-skin crosstalk may influence cutaneous health indirectly. Without rigorous randomized controlled trials in well-characterized athlete cohorts, it is premature to recommend these therapies broadly.

Regulatory and ethical considerations compound these scientific challenges. Deliberately altering the skin ecosystem carries the risk of selecting for resistant organisms or triggering unintended immune responses. Furthermore, sequencing the microbiomes of elite athletes could inadvertently reveal personal health or performance vulnerabilities, raising concerns about data privacy, informed consent, and potential misuse by competitors or sponsors. Establishing clear frameworks for data governance, benefit sharing, and participant protection will be essential before large-scale athlete microbiome profiling can proceed responsibly.

Addressing these controversies and knowledge gaps through coordinated, multidisciplinary research initiatives will be vital for advancing from descriptive snapshots to practical, safe, and effective sports dermatology interventions. Only then can clinicians and trainers leverage microbiome science to preserve skin health and optimize performance in athletic populations.

#### Future Directions

Advances in technology and collaborative research networks will transform our understanding of how cutaneous microbes influence athlete health and performance. Wearable sampling devices that collect sweat and skin surface samples in real time could illuminate dynamic microbial shifts during training sessions, competitions, and recovery periods. By coupling these data with continuous monitoring of skin temperature, hydration, and electrolyte balance, researchers can build personalized profiles of microbial resilience and vulnerability. Artificial intelligence-driven analysis of large multi-omics datasets will identify microbial

signatures that predict impending skin flares or infection risk, enabling preemptive adjustments to training or hygiene routines.

On the therapeutic front, next-generation textiles and sports equipment may be engineered with embedded AMPs or probiotic coatings that support commensal growth while suppressing pathogens. Fabrics treated with naturally derived compounds such as bacteriocins or microbe-derived enzymes could create self-sanitizing jerseys and socks without harming beneficial organisms. Similarly, helmets and pads could incorporate slow-release formulations of barrier-supporting lipids or amino acids that maintain skin integrity under prolonged occlusion and friction.

Integration of dermatological expertise into athletic training programs will be essential. Sports teams and facilities should partner with microbiologists and clinicians to design longitudinal trials that test targeted probiotic formulations, topical or oral, in well-defined athlete cohorts. Such trials must include rigorous safety monitoring and standardized outcome measures, including both microbial and clinical endpoints. Regulatory frameworks will need to evolve to address the unique challenges of live biotherapeutic products (LBPs) applied to healthy, high-performance individuals.

Finally, ethical considerations should guide the collection and use of athlete microbiome data. Transparent informed consent processes, clear data governance policies, and benefit-sharing agreements will protect athlete privacy and maintain trust. By building multidisciplinary consortia that bring together sports medicine physicians, microbiologists, bioengineers, and ethicists, the field can move from descriptive studies to practical solutions that preserve skin health and optimize performance across all levels of sport.

LBPs, including topical probiotics and engineered commensals, are regulated as biologics by the FDA/EMA, requiring GMP manufacturing, stability data, and formal IND/CTA approval before efficacy claims can be

made. Antimicrobial or probiotic-impregnated textiles may also fall under biocidal product regulations and must demonstrate safety (sensitization/contact dermatitis) and durability of antimicrobial finishes. Although the World Anti-Doping Agency does not currently prohibit probiotic use, athletes remain strictly liable for contaminants; third-party certification (NSF/Informed Sport) is prudent. Likewise, metallic or quaternary-ammonium coatings on gear could raise cumulative exposure concerns. These regulatory and anti-doping realities mean that “microbiome hacking” in sport will likely progress more slowly than conceptual enthusiasm suggests; feasibility, cost, and compliance must be weighed alongside mechanistic promise. Future trials should pre-register protocols, specify product composition, and report adverse events to facilitate approval and implementation across the team.

### Conclusions and Clinical Takeaways

Athletes navigate a unique set of challenges to their skin health through the combination of intense training, frequent cleansing, and exposure to shared environments. The resulting shifts in the cutaneous microbiome can directly contribute to eczema flares, bacterial and fungal infections, and acne mechanica. These conditions not only cause discomfort but also lead to missed training sessions and impaired performance. Recognizing the microbiome as a dynamic partner in skin health encourages a shift from reactive treatment to proactive maintenance.

Clinicians and athletic trainers can integrate microbiome-aware practices into routine care by choosing low pH cleansers and shower timing that balances sweat removal with barrier preservation. Incorporating barrier-repairing moisturizers immediately after washing and exploring targeted probiotic or prebiotic therapies may help restore microbial balance. At the team and facility level, consistent disinfection of equipment and thoughtful locker room design support a healthier skin ecosystem.

Moving forward, collaboration among sports medicine experts, microbiologists, and bioengineers will be key to translating emerging science into practical solutions. Well-designed longitudinal studies and rigorous clinical trials will define effective interventions and safety profiles for live microbial treatments. By embracing this multidisciplinary approach, we can reduce dermatologic downtime, enhance recovery, and ultimately support athletes in achieving their highest levels of performance.

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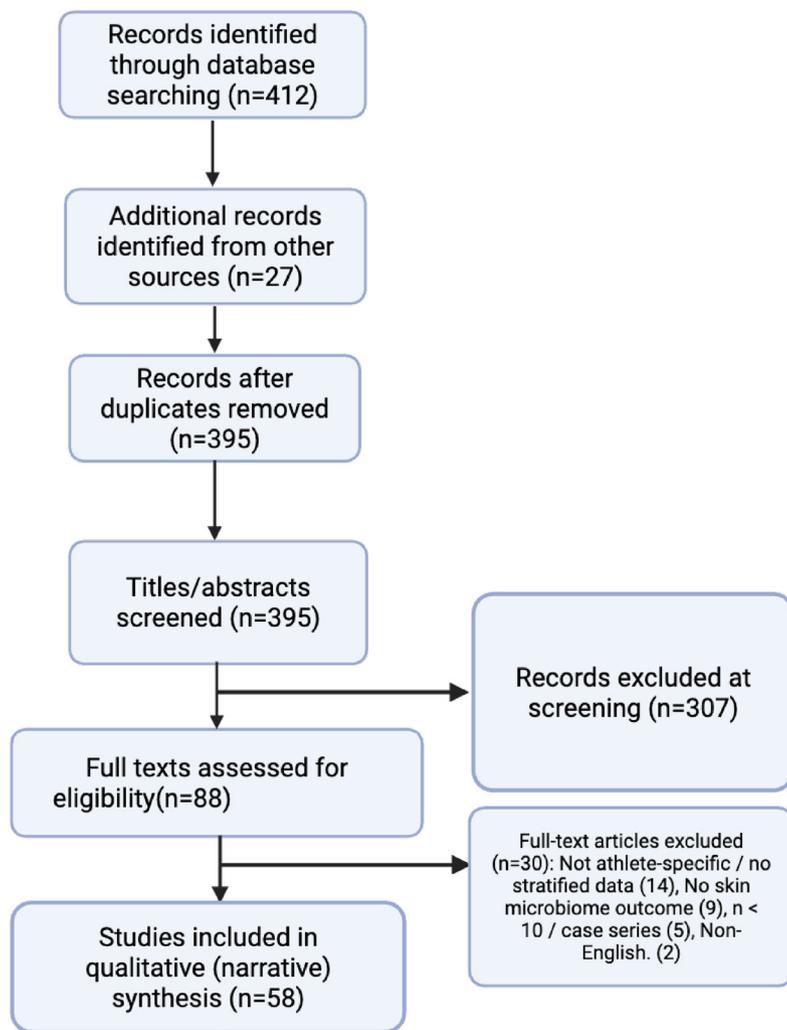
### Supplementary Methods

#### Literature Search

Database & dates. PubMed (MEDLINE) was searched 1 Jan 2000–22 Jul 2025. Reference lists of included papers and key reviews were hand-searched.

Full Boolean string (PubMed):

```
((("skin microbiome"[tiab] OR "skin microbiota"[tiab] OR "cutaneous microbiome"[-tiab] OR "cutaneous microbiota"[tiab] OR "microbiome"[MeSH Terms] AND skin[tiab]) AND ("athlete"[tiab] OR athletes[tiab] OR sport*[tiab] OR "contact sport*" [tiab] OR exercise[tiab] OR "physical training"[tiab] OR endurance[tiab] OR "resistance training"[tiab] OR sweat[-tiab] OR hygiene[tiab] OR "locker room"[tiab] OR "shared equipment"[tiab])) AND ("2000/01/01"[dp] : "2025/07/22"[dp]) AND english[lang] NOT (gut[tiab] OR intestinal[tiab] OR oral[tiab]))
```



Supplementary Fig S1 | PRISMA flow diagram

Duplicates were removed by PubMed ID and title matching in the reference manager.

#### Eligibility Criteria

- **Population:** Humans engaged in organized sport or structured exercise (plus facility/locker-room studies).
- **Exposure/Topic:** Skin microbiome composition, dysbiosis, or hygiene/cleansing interventions affecting skin microbes.
- **Designs included:** RCTs, quasi-experiments, observational human studies, and mechanistic human/animal/in vitro work directly interrogating skin microbes (kept but labeled mechanistic).
- **Minimum n:** ≥10 for human observational/interventional work.
- **Language:** English.
- **Excluded:** Case reports/series <10 participants; non-skin microbiome focus (e.g., gut only); general-population studies without athlete-stratified data; conference abstracts only.

#### Study Selection

Two reviewers screened titles/abstracts and full texts independently: disagreements resolved by consensus. Reasons for full-text exclusion were recorded.

PRISMA counts:

- Records identified via PubMed: **412**
- Additional from reference lists/citation tracking: **27**
- Records after duplicate removal: **395**
- Titles/abstracts screened: **395**
- Records excluded: **307**
- Full texts assessed: **88**
- Full texts excluded (reasons below): **30**
  - Not athlete-specific/no stratified data: 14
  - No skin microbiome outcome: 9
  - n < 10/case series: 5
  - Non-English: 2
- Studies included in qualitative (narrative) synthesis: **58**

#### Data Extraction & Thematic Synthesis

We extracted author/year, sport/population, design, n, microbiome assay (16S, shotgun, culture), principal microbial shifts, and dermatologic/performance outcomes. Findings were grouped into:

1. Perturbations (sweat pH, friction/microabrasions, chlorine, shared surfaces)
2. Infectious/inflammatory dermatoses
3. Performance/recovery implications
4. Interventions (cleansing protocols, textiles, probiotics)

#### Evidence Appraisal

- **Evidential tiering:** Mechanistic (in vitro/animal), Observational human, Interventional (RCT/non-RCT).

- **Risk-of-bias snapshot:** ROB 2.0 for RCTs; ROB-INS-I domains for observational studies (Low/Some concerns/High).
- **Certainty statements:** GRADE-style labels (High/Moderate/Low/Very Low) are provided for each intervention class.

**Methodological Limitations**

Single-database searching may have missed Embase/grey literature. PRISMA counts were reconstructed retrospectively from search logs/reference manager. No meta-analysis was undertaken due to design/outcome heterogeneity.