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Endurance Athletes and Skin Aging: Mechanisms, Risks, and Protective Strategies

Guang Orestes[1], Mary Grace Hash[2], Tyarah Trias[3], Afreen Hussaini[4], Alejandra Sataray-Rodriguez[5], Stefany Acosta[6], Kelly Frasier[7]*

[1]Kirk Kerkorian School of Medicine at UNLV, Las Vegas, NV, USA

[2]Edward Via College of Osteopathic Medicine, Auburn, AL, USA

[3]California Health Sciences University, Clovis, CA, USA

[4]A.T. Still University School of Osteopathic Medicine in Arizona, Mesa, AZ, USA

[5]University of Nevada, Reno School of Medicine, Reno, NV, USA

[6]Michigan State University College of Osteopathic Medicine, East Lansing, MI, USA

[7]Department of Dermatology, Northwell Health, New Hyde Park, NY, USA

[*]Corresponding author:

Kelly Frasier, DO, MS,
Department of Dermatology, Northwell Health,
New Hyde Park, NY, USA, Phone: 3105956882,
Email: kellymariefrasier@gmail.com

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ABSTRACT

With the growing popularity of endurance sports in recent years, endurance athletes are uniquely vulnerable to premature skin aging due to prolonged environmental exposures, high physical exertion, and training demands. This review explores factors contributing to skin aging in endurance athletes, including ultraviolet radiation, oxidative stress, chronic dehydration, and nutritional deficits. Key mechanisms such as photoaging and reactive oxygen species production are examined alongside the impacts of training intensity and insufficient recovery on skin health and aging. Strategies to mitigate these effects, including photoprotection, antioxidant supplementation, and hydration optimization, are highlighted, emphasizing their relevance to athlete-specific skincare practices. By addressing the gaps in current research and prevention, this review underscores the importance of integrating dermatologic care into endurance training to enhance both skin health and athletic longevity.

Keywords: Skin Health, Injury, Aging, Ultraviolet Radiation.

INTRODUCTION

Skin aging is a multifaceted physiological process influenced by both intrinsic and extrinsic factors, resulting in visible, structural, and functional changes in the skin. Intrinsic factors involve the natural senescence of skin cells, while external factors include environmental factors such as ultraviolet (UV) radiation and pollution [1]. This complex process results in a

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gradual decline in skin integrity, elasticity, and regenerative capacity. Clinical manifestations of skin aging include fine lines, wrinkles, reduced skin elasticity, altered pigmentation, increased fragility, and heightened susceptibility to dermatological disorders [2-4]. While intrinsic aging occurs slowly, extrinsic factors, particularly UV radiation, significantly accelerate visible aging. Photoaging, defined as premature skin aging caused by chronic UV exposure, presents with characteristics such as skin coarseness, deep wrinkles, mottled hyperpigmentation, telangiectasia, and may include premalignant and malignant neoplasms [5,6]. The cumulative impact of all these processes not only alters appearance but also compromises the skin's protective barrier, making it more prone to injury and carcinogenesis. Endurance athletes represent a unique demographic that is more vulnerable to premature skin aging due to prolonged and repetitive environmental exposure and the physiological demands of intense physical exertion.

Endurance athletes engage in sports that demand sustained physical effort over extended periods. In this paper, "endurance athlete(s)" and "athlete(s)" are used to describe all individuals involved in endurance sports, regardless of their experience or skill level. Endurance sports include various activities, such as marathons, triathlons, ultramarathons, long-distance cycling, cross-country skiing, and long-distance swimming [7]. These activities focus on endurance and stamina - the ability to sustain performance over long periods instead of short bursts of activity. Participation in endurance sports has grown increasingly popular worldwide, with a notable rise in participation in events like marathons and triathlons. For instance, the coveted Boston Marathon received 36,393 qualifying applications to participate in the 2025 race, marking a significant increase compared to prior years [8]. This trend reflects the health benefits and personal challenges associated with these sports, attracting a diverse range of participants, from casual enthusiasts to elite competitors [9]. Endurance sports require prolonged training and competitive racing, often under harsh environmental conditions, exposing athletes to prolonged outdoor elements such as UV radiation, extreme temperatures, wind, and water. Moreover, the physical and metabolic demands of endurance training can lead to oxidative stress and dehydration, further exacerbating cumulative skin damage.

Although numerous studies have examined the benefits of endurance exercises, high-intensity endurance sports pose some risks. Concerns about general health issues in endurance sports, including cardiovascular, respiratory, musculoskeletal, nutritional, hydration, and mental health challenges, are on the rise [10-14]. However, the aspect of dermatological health among these athletes has not been thoroughly researched, leaving significant gaps in our understanding and preventive strategies. This review aims to address the multifaceted nature of skin aging in endurance athletes by examining key mechanisms such as UV-induced photoaging, oxidative stress, chronic dehydration, nutritional imbalances, and mechanical stress. It highlights the risk factors unique to endurance athletes, such as high-intensity training and inadequate recovery, and ultimately provides evidence-based strategies for prevention and intervention. By integrating dermatological considerations into endurance sports training, athletes can be well-equipped to protect their skin from premature aging and diseases, enhance their performance longevity, and improve their overall well-being.

Mechanisms of Skin Aging in Endurance Athletes

UV Radiation

Chronic exposure to UV radiation (UVR) induces cell damage, leading to immune system remodeling andsubsequent immunosuppression, accelerating photoaging of the skin [15]. UVR damages various cellular structures, primarily nuclear DNA and components of the extracellular matrix (ECM). Prolonged UVR exposure results in the covalent linking of adjacent pyrimidine bases to generate cyclobutane pyrimidine dimers (CPD) and 6-4 pyrimidine-pyrimidone photoproducts (6-4 PP) [16]. Additionally, chronic UVR exposure generates oxidative stress, which induces selective guanine oxidation, thereby leading to the formation of 8-oxo-7,8-dihydroguanine (8-oxo-G), further compromising the skin [15,17]. These mutagenic photoproducts compromise the integrity of the DNA backbone and inhibit cellular transcription [16,17]. Furthermore, prolonged UVR exposure leads to increased expression of matrix metalloproteinases (MMPs), resulting in degradation of ECM proteins and loss of structural integrity, further contributing to photoaging [15,18]. Specifically, MMP-1, MMP-3, and MMP-9 are implicated in the destruction of collagen and elastin fibers, accelerating skin laxity and wrinkle formation [16]. Moreover, ECM damage promotes the accumulation of senescent cells that express the Senescence-Associated Secretory Phenotype (SASP) and secrete pro-inflammatory cytokines. This inflammatory cascade stimulates

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the expansion of immunosuppressive cells, such as Treg, DCreg, and myeloid-derived suppressor cells that downregulate the immune response. This process drives chronic inflammation and ECM damage, thereby accelerating skin aging [15]. These processes create a self-perpetuating cycle of ECM breakdown, immune dysfunction, and chronic inflammation, further emphasizing the consequences of prolonged UVR exposure on skin health.

Endurance athletes who participate in outdoor sports are chronically exposed to UVR damage. Wolf et al. found that endurance athletes participating in hiking, tennis, and running reached the maximum acceptable limit of UVR exposure recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in less than 20 minutes, with total UVR exposure reaching up to eight times greater than the acceptable limit (Wolf et al., 2020). Chronic UVR exposure in these athletes resulted in damage to the tumor suppressor gene p53, resulting in cell cycle arrest, tumorigenesis, and apoptosis [19]. Furthermore, the high training loads associated with endurance sports contribute to exercise-induced immunosuppression, inhibiting adequate repair following stress on the body, further contributing to tumorigenesis [19]. These findings demonstrate the cellular damage incurred by the skin barrier accompanied by an impaired regenerative capacity, which ultimately results in photoaging of the skin. Furthermore, it highlights the increased risk of developing skin cancer in endurance athletes as prolonged UVR exposure compromises cellular integrity by causing damage to the p53 gene while also hindering the body's ability to repair and appropriately detect cancer cells due to immunosuppression. A study by Richtig et al. investigating risk factors for malignant melanoma (MM) in endurance athletes, specifically marathon runners, found an increased prevalence of lentigines and atypical nevi on sun-exposed areas of skin when compared to unexposed areas [20]. These findings are known markers of MM, suggesting that chronic UVR exposure significantly increases the risk of developing MM in this demographic.

Oxidative Stress

Endurance athletes experience a greater burden of oxidative stress due to the increased production of reactive oxygen species (ROS) in skeletal muscles. During endurance training, athletes demonstrated a 20-30 times greater consumption of whole-body oxygen, leading to a substantial production of ROS that can overwhelm the body's antioxidant capacity [21]. The accumulation of ROS drives oxidative modification of membrane lipids, initiating lipid peroxidation. In this process, membrane lipids incur damage as ROS molecules interact with polyunsaturated fatty acids (PUFAs), generating radical intermediates that ultimately produce 4-hydroxynonenal (4-HNE) byproducts [22], a byproduct capable of causing cell damage, accelerating skin aging, and contributing to the development of skin cancer. Oxidative damage to lipids can be measured by F2-isoprostanes, a biomarker of oxidative stress in endurance athletes, which has been found only to be elevated during physical activity [21]. Additionally, damage to membrane lipids can lead to the release of ceramides from the stratum corneum, thereby compromising the integrity of the skin barrier [18]. The loss of ceramide consequently results in decreased moisture retention in the skin, promoting the formation of wrinkles and causing premature aging of the skin. As muscle contraction occurs, phospholipase A2 (PA2) activates and catalyzes a reaction that cleaves arachidonic acid (AA) from membrane phospholipids and generates ROS downstream [23]. Furthermore, PLA2 activates the isoform, NOX2 of NADPH oxidase, which generates ROS in contractile muscles [23]. This exercise-induced oxidative stress in endurance athletes contributes to DNA damage, exacerbating cellular aging and increasing susceptibility to diseases. Furthermore, excessive accumulation of ROS levels may overwhelm the body's antioxidant capacity, impair sodium-potassium ATPase activity, and disrupt ion gradients, leading to decreased muscle contractility and fatigue [15]. Mitigating oxidative stress through skin protection and antioxidant strategies is important for maintaining athletic performance and long-term skin health.

Chronic Dehydration and Skin Barrier Integrity

Endurance athletes often experience chronic dehydration due to their intense training routines and rigorous training, which compromises the integrity of the skin barrier and increases the risk of premature aging. Factors such as the intensity and duration of exercise, along with environmental conditions, contribute to significant fluid loss and inadequate replenishment of fluid stores, worsening dehydration [24]. The stratum corneum, a critical component of the epidermis, is particularly vulnerable under these conditions, as it is crucial for skin maturation and desquamation. Increased transepidermal water loss (TEWL) disrupts vital enzymatic processes for desquamation, resulting in dry, flaky skin [25]. Proper desquamation and subsequent regeneration of skin cells are fundamental for maintaining a youthful and healthy

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appearance. Interestingly, individuals aged 65 and older tend to show lower TEWL levels compared to those aged 18 to 64, highlighting age-related variations in skin hydration and barrier function [26]. Therefore, it is critical to maintain proper hydration to support healthy skin regeneration processes.

Water is vital for preserving the skin barrier's integrity; thus, dehydration can have detrimental consequences. Skin elasticity, defined as the ability of the skin to return to its original shape after being stretched, is heavily dependent on hydration. Sufficient water intake improves both the elasticity and resilience of the skin [27]. The physiological importance of elastin illustrates the adverse effects of dehydration on its function. Elastin's structure, composed of tropoelastin subunits stabilized by hydrophobic interactions, relies on water molecules to interact with its nonpolar residues to preserve its structure during stretching. Consequently, reduced hydration results in increased skin stiffness [28]. The recoil properties provided by elastin are fundamental to maintaining youthful skin. Degradation of elastin fibers in the dermis is strongly associated with wrinkle formation, as observed in smokers and individuals exposed to excessive UV light, underscoring elastin's critical role in skin integrity and wrinkle development [29]. Moreover, endurance athletes who lose substantial amounts of fluid through perspiration and fail to replenish their water stores place their skin at risk of dehydration, compromising its integrity and function.

Nutritional Deficiencies

Endurance athletes, both male and female, have significant nutritional demands to replenish the stores depleted during intense physical exertion. However, many fail to meet the necessary intake of both macronutrients and micronutrients required for optimal performance and recovery [30]. Carbohydrates, a crucial macronutrient, provide sustained energy throughout physical activity. Within the skin, glucose is a fundamental component for the glycosylation of proteins and lipids, contributing to the formation of the extracellular matrix. However, excessive glucose levels can inhibit the proliferation of keratinocytes in the epidermis, potentially impeding skin regeneration [31]. Given glucose's critical role in supporting keratinocyte function, fluctuations in glucose levels—especially those resulting from physical activity—may negatively impact overall skin health. During periods of intense exercise, glucose depletion can lead to short-term hyperglycemia after meals and hypoglycemia, particularly during the night [32]. Consequently, the depletion of carbohydrate stores in endurance athletes can adversely affect not only the structural integrity of the skin but also the regenerative processes crucial for keratinocyte formation.

In addition to macronutrients, micronutrients play a critical role in maintaining skin integrity. Vitamin E, for instance, is a micronutrient that is often not sufficiently replenished in endurance athletes [30]. Since Vitamin E cannot be synthesized by the body, it must be obtained through dietary sources. This micronutrient serves several essential functions, including its protective role in safeguarding lipid molecules within the stratum corneum, its antioxidant properties, and its involvement in the synthesis of collagen, elastin, and glycosaminoglycans [33]. When endurance athletes deplete their Vitamin E stores during prolonged training sessions, they compromise their skin's ability to perform these vital functions. Supplementation with Tocotrienols, a specific form of Vitamin E, may help mitigate the effects of skin aging by reducing inflammation, inhibiting melanin accumulation, and limiting UV-induced damage [34]. To prevent premature signs of aging, endurance athletes should consider incorporating supplements to address micronutrient deficiencies in their diet.

Mechanical Stress

The use of specific equipment or the repetitive friction forces experienced during physical activity can lead to the accumulation of skin microtrauma, potentially accelerating the risk of premature aging. For instance, long-distance runners often develop skin lesions such as chafing, abrasions, calluses, and blisters due to repetitive skin-to-skin or skin-to-equipment contact [35]. These repetitive injuries not only compromise the skin's structural integrity but also act as a stimulus for initiating localized immune responses. Mechanical deformation of the skin triggers the release of cytokine IL-1α, activating endothelial selectin and promoting extravasation of leukocytes within the dermis [36]. Elevated cytokine levels contribute to a state of chronic inflammation, leaving the body more susceptible to long-term inflammatory damage. This systemic low-level inflammatory state associated with increased serum cytokine levels is thought to play a role in the aging processes of the skin, as it is observed in aged individuals [37]. The heightened inflammatory response caused by repetitive microtrauma underscores the importance of protecting the skin barrier to mitigate the risk of prematurely aged skin.

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Risk Factors Specific to Endurance Athletes

Environment

As previously mentioned, cumulative ultraviolet (UV) exposure is a significant environmental factor influencing skin aging, further accelerated by UV-induced reactive oxygen species (ROS) production, which damages skin cells and disrupts the extracellular matrix (ECM). Athletes in outdoor sports like running, cycling, and triathlons face heightened vulnerability due to prolonged exposure [38,39]. Training at high altitudes intensifies this risk, with UV levels rising 10–20% per 1000 meters of elevation [38-40]. Reflective surfaces like snow, water, and pavement further amplify UV exposure, as seen in skiing, where athletes endure both direct and reflected rays, increasing their risk of photodamage, skin cancer, and premature aging. Cold, dry air at high altitudes reduces humidity, increasing transepidermal water loss (TEWL) and leaving the skin prone to dehydration and irritation [41]. Wind exposure exacerbates this by stripping the skin of moisture and causing microabrasions that impair its barrier function. For example, cross-country skiers face combined cold and wind impacts, which disrupt the skin's integrity and accelerate aging. UV and extreme weather conditions at high altitudes also raise the risk of seborrheic dermatitis, UV keratitis, and skin cancer [42]. High-altitude training highlights the importance of consistent skin protection, even in colder climates.

Athletes in aquatic sports also face considerable chemical exposures contributing to skin aging, particularly from chlorinated pools. Chlorine disrupts the skin's natural barrier, causing dryness, irritation, and an increased risk of chemical dermatitis [43]. Over time, repeated exposure strips natural oils, leading to roughness, discoloration, and wrinkle formation. Chlorination by-products (CBPs), like trihalomethanes and haloketones, further penetrate the skin, increasing oxidative stress and degrading the collagen matrix, which impairs elasticity [44]. Open-water swimmers encounter additional risks from pollutants in agricultural runoff, industrial waste, and saltwater. These contaminants weaken the skin barrier, promote inflammation, and accelerate aging [39,42]. Fluctuations in aquatic environments further heighten skin permeability, increasing susceptibility to harmful chemical absorption [43]. Protective strategies such as showering after swimming, using barrier creams, and moisturizing regularly help minimize damage and preserve skin health.

Wind exposure, though less studied, is a potentially significant contributor to skin aging. Prolonged wind exposure depletes skin moisture, causing dryness, irritation, and a weakened barrier [45]. Athletes such as cyclists, sailors, and cross-country runners often face abrasive wind, which induces microtears and exacerbates TEWL, leaving the skin more susceptible to UV radiation and environmental pollutants [41]. Wind increases the risk of chapped skin, redness, and inflammation, contributing to fine lines and wrinkle formation over time [43]. In cold, windy environments, such as high-altitude locations, the combined effects of wind and low temperatures crack the skin and accelerate collagen and elastin breakdown. Wind exposure also strips protective oils, intensifying sunburn and photodamage risk [46]. Incorporating antioxidants into skincare routines can help combat oxidative damage caused by wind exposure. Additionally, regularly assessing skin health and consulting dermatologists can ensure early intervention for any adverse effects.

Training Intensity and Chronic Low-Level Inflammation

Regular physical activity plays a significant role in protecting against chronic low-grade inflammation, particularly the type associated with aging, known as "inflammaging." Moderate-intensity exercises, such as brisk walking, steady cycling, or swimming, have been shown to reduce inflammatory markers, including C-reactive protein (CRP), tumor necrosis factor-alpha (TNF-α), and interleukin-6 (IL-6). These reductions are attributed to improved adipokine profiles, decreased visceral fat, and enhanced mitochondrial function [47]. Additionally, muscle contractions during exercise stimulate the release of anti-inflammatory myokines, including IL-10 and brain-derived neurotrophic factor (BDNF), which actively suppress pro-inflammatory cytokines [47]. These myokines exert systemic effects, helping to regulate inflammation across the body. Exercise also boosts the production of antioxidant enzymes, reducing oxidative stress, a critical factor in the development of inflammaging [48]. These processes collectively contribute to the anti-inflammatory benefits of low to moderate-intensity physical activity.

Furthermore, regular moderate exercise has been found to enhance endothelial function and vascular health, which further mitigates inflammatory responses. The balance between exercise intensity, frequency, and adequate recovery is crucial for optimizing the anti-inflammatory effects of physical activity. Resistance training complements

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aerobic exercise by preserving muscle mass, improving insulin sensitivity, and reducing inflammation in adipose tissue [49,50]. Physical activity also enhances regulatory T-cell function, reduces pro-inflammatory macrophage infiltration, and improves gut microbiota composition, which in turn promotes the production of anti-inflammatory short-chain fatty acids [49,51]. However, excessive high-intensity training without sufficient recovery can temporarily elevate inflammatory markers, highlighting the importance of balancing exercise intensity and recovery to fully harness the anti-inflammatory benefits of exercise.

Impact of High-Intensity Training on Inflammation

High-intensity training (HIT), when performed excessively or without proper recovery, leads to a temporary increase in inflammatory markers, potentially exacerbating inflammation. Research has demonstrated that intense exercise significantly raises cytokines such as IL-6, IL-8, and TNF-α immediately following the activity, with peak levels ranging from 1.59 to 26.79 times higher than baseline [52,53]. While IL-6 and IL-8 levels typically return to baseline within hours, the increase in these markers after high-intensity exercise is more pronounced compared to moderate exercise. Furthermore, IL-10 increases significantly after intense exercise, contributing to a transient immune response that may last several hours [49]. These elevated inflammatory markers, particularly after prolonged or ultra-endurance intense exercise, may exacerbate inflammation, especially if the body is not allowed adequate time for recovery. The transient nature of these responses emphasizes the importance of recovery periods in preventing potential negative outcomes of excessive HIT.

Emerging evidence suggests that low-to-moderate intensity training is effective in reducing systemic inflammation while also minimizing the risk of injury or overtraining. Resistance training, when combined with aerobic exercise, offers a unique approach to combating inflammaging by preserving muscle mass, improving insulin sensitivity, and reducing inflammation in adipose tissue [49,50]. Regular physical activity also induces beneficial adaptations in the immune system, including enhanced regulatory T-cell function and reduced pro-inflammatory macrophage infiltration in tissues [49]. Exercise further improves gut microbiota composition, leading to the production of short-chain fatty acids that exert anti-inflammatory effects [51]. Conversely, excessive physical activity, especially in untrained individuals, can result in transient immunosuppression and increased vulnerability to infections [48]. Therefore, finding the appropriate balance in training intensity is essential to maximizing the health benefits of exercise while minimizing the risks associated with chronic inflammation and immune dysregulation.

Inadequate Recovery: Effects of Sleep, Overtraining, and Sleep Deprivation on Skin Health

Sleep is crucial for recovery, influencing cognitive function, tissue repair, and hormonal regulation, including growth hormone and cortisol. Sleep deprivation disrupts metabolic processes, weakens the immune system, and impairs tissue repair, increasing the risk of overtraining syndrome (OTS) [54]. OTS is characterized by excessive training without sufficient rest, leading to fatigue, decreased performance, and a higher risk of injury. Collegiate athletes are especially vulnerable to OTS due to irregular sleep patterns and academic pressures [54,55]. Gender differences also play a role in recovery, with female athletes experiencing hormonal fluctuations that can influence recovery outcomes. Diagnosing OTS is challenging, though biomarkers such as creatine kinase levels and hormonal changes offer some insight. Prevention and treatment emphasize balanced training, rest, nutrition, and managing psychological stressors, which help enhance recovery and reduce OTS's impact. Research also shows that sleep deprivation can disrupt skin barrier function and immune responses, increasing inflammatory markers like IL-1β and TNF-α, which affect skin integrity and healing [54]. Chronic sleep deprivation exacerbates immune system imbalances and collagen metabolism, contributing to skin aging and impairing wound healing. Ensuring adequate sleep is vital for preserving skin health, especially for endurance athletes, and can improve overall athletic performance by supporting both skin and immune recovery.

Prevention and Intervention Strategies

Photoprotection

Daily photoprotection is essential in combating prolonged sun exposure and preventing photoaging caused by ultraviolet (UV) radiation. In the United States, broad-spectrum sunscreens protect against ultraviolet B (UVB) and short-wavelength ultraviolet A (UVA) radiation, although their effectiveness against long-wave UVA and visible light remains limited [56]. While appropriate sunlight is essential for health, the use of topical sunscreens allows individuals to mitigate the negative effects of UV radiation, including photoaging and

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skin cancers. Recent advancements in sunscreen formulations have addressed visible light by incorporating inorganic UV filters such as zinc and titanium oxide. These formulations also feature increased water resistance properties to maintain the same sun protective factor (SPF) after water exposure [57,58]. Moreover, regular and appropriate use of sunscreen is crucial for its protective effects. Forsea [57] advises applying a high-SPF sunscreen of 2 mg/cm^2 (SPF 50 or higher) to the entire body 20 minutes before sun exposure and reapplying every 2 hours while outdoors.

Furthermore, many people underutilize sunscreen by applying insufficient amounts, such as less than the size of a palm's worth, thereby reducing the efficacy of sunscreen. For athletes who sweat heavily, the frequency of sunscreen application may pose challenges. Photoprotective clothing is another valuable tool for optimizing sun protection in conjunction with sunscreens. Sun-protective clothing, such as hats and long-sleeved shirts, is graded on the ultraviolet protection factor (UPF) scale. A fabric with a minimum of UPF 30, which blocks 96.7% of UV radiation, qualifies for the Seal of Recommendation from The Skin Cancer Foundation [59]. UPF clothing shows promise as a practical option for individuals who underutilize or incorrectly apply sunscreen. Additionally, UPF clothing can be essential to protect endurance athletes who may have difficulty adhering to the recommended reapplication protocol for topical sunscreens.

Antioxidant Supplementation and nutrition

Nutrition has long been closely connected to skin health, providing another avenue for preventing skin aging. Free radical formation from environmental insults, such as UV radiation, is pivotal in signs of premature skin aging. A diet rich in fruits and vegetables offers a source of antioxidants, including vitamins A, C, E, D, and carotenoids, all fundamental for skin health [60]. Moreover, dietary carotenoids have potent antioxidant properties that act synergistically with sunscreens to enhance photoprotection and reduce photodamage. Foods such as mangos, almonds, soybeans, and cocoa are rich in vitamin C, carotenoids, and polyphenols, all of which have been shown to possess strong antioxidant capabilities, improving skin elasticity while reducing wrinkles and hyperpigmentation [61]. Similarly, topical antioxidants can help prevent damage imposed by UV exposure and other environmental factors. Topical application of vitamins C and E and trace mineral selenium have been shown to contribute to the prevention and reversal of extrinsic skin damage. Effective topical formulations containing L-ascorbic acid, α-tocopherol, ferulic acid, and phloretin counteract the depletion of vitamins C and E on the skin's surface, attributed to sunlight and pollution [62]. Furthermore, the loss of essential antioxidants impacting aging highlights the importance of direct delivery through topical application to help replenish skin integrity. These products may offer significant benefits in preventing skin aging, particularly for endurance athletes exposed to numerous environmental pollutants and UV radiation.

Hydration Strategies

Given the external disruptors to the skin barrier faced by endurance athletes, maintaining hydration throughout training may offer benefits in preventing skin aging and preserving barrier function. Cutaneous water loss is influenced by hydration imbalances and defects in the stratum corneum, the uppermost layer of the skin, which serves as the barrier to water homeostasis. Significant water loss occurs through sweating, which can be mitigated through the use of humectants, such as glycerol and hyaluronic acids, and occlusive agents, such as petroleum jelly, waxes, and perhydrosqualene, to enhance water retention in the skin [63]. Endurance athletes who experience extensive water loss due to sweat and heat exposure may benefit from products that reinforce the skin barrier enforcers. Furthermore, insufficient systemic hydration and sweat-induced deficits can lead to electrolyte imbalances and barrier function. Long-duration training in certain sports may lead to substantial water deficits of 2-4 liters, which may require up to 1 liter per hour of water and electrolyte-rich drinks for athletes to offset body water deficits during training [64,65]. Additionally, elite endurance athletes often employ experience-based, pre-planned drinking and cooling strategies to maintain hydration and regulate body temperature during competitions [65]. However, no standardized hydration protocol currently exists to guide these athletes. Further research is needed to develop protocols for appropriate hydration that minimize barrier dysfunction and water deficits during athletic training that address the unique needs of endurance athletes.

Advance skincare

Endurance athletes can enhance their skincare routine with advanced products that include topical ingredients known for their anti-aging effects in the broader population. Retinoids, vitamin A derivatives, are considered the gold standard in topical skin rejuvenation treatment. They promote

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keratinocyte proliferation, resulting in a thicker epidermis and improved skin texture, helping to reduce fine lines and wrinkles by promoting skin renewal [66,67]. Additionally, retinoids stimulate collagen synthesis to enhance skin elasticity and counteract the thinning of the dermal layer associated with aging [68]. They also help to even skin tone by reducing hyperpigmentation and promoting a more uniform complexion, giving the appearance of more rejuvenated skin [69]. However, retinoid use is linked to skin sensitivity, necessitating athletes to use more rigorous sun protection [70]. On the other hand, bioactive peptides such as carnosine, palmitoyl tripeptide-5, and acetyl hexapeptide-3 have been shown to enhance collagen production and skin elasticity, reducing wrinkles [71]. Hyaluronic acid improves skin hydration and elasticity, maintaining moisture and reducing wrinkle appearance [72]. These products show promising efficacy in reducing the appearance of skin aging and can be adopted by endurance athletes; however, specific studies on endurance athletes are limited.

Given the skin barrier disruptions experienced by athletes due to environmental exposure and physical stress, products containing ceramides and other emollients may provide potential benefits in repairing and maintaining the integrity of the skin barrier to combat premature aging [73]. Ceramides are part of the lipid matrix in the stratum corneum, which helps in restructuring damaged lipid arrangements to repair the skin barrier [74,75]. Ceramide-containing formulations can also reduce inflammation and offer photoprotection, benefiting athletes exposed to increased ultraviolet (UV) radiation [75]. Natural-based emollients, such as Perseae americana (avocado) oil, Oenothera biennis (evening primrose) oil, and Vitellaria paradoxa (shea butter), have demonstrated efficacy in restoring barrier function and hydration while minimizing transepidermal water loss [76]. This evidence suggests that consistent application of ceramides and emollients, combined with photoprotection strategies, helps endurance athletes mitigate environmental damage, including UV, wind, and saltwater exposure during training and racing. Fragrance-free and hypoallergenic options are preferable to prevent irritation.

Aesthetic and cosmetic interventions provide additional avenues for athletes to combat skin aging. Non-invasive treatments such as Platelet-Rich Plasma (PRP), neuromodulators like botulinum toxin, and tissue bio-stimulators effectively diminish wrinkles, expression lines, and skin pigmentation with minimal downtime, enabling athletes to maintain their training schedules with few interruptions [77]. These treatments, guided by a dermatologist, provide options for athletes to preserve skin health and appearance, effectively balancing performance with their aesthetic goals.

Behavior Change

Behavior and training modifications are essential for comprehensive and holistic skin health management in endurance athletes. Minimizing ultraviolet (UV) exposure by training during lower UV-intensity periods– such as early morning or late afternoon– and utilizing weather services to monitor real-time UV indices can help in safer outdoor sessions. Establishing pre-, during-, and post-training skincare routines is critical. This involves applying and reapplying a board-spectrum, water-resistance sunscreen, wearing adequate physical coverage using UPF-related fabrics, cleansing and removing sweat, dirt, and chemicals, followed by the use of hydrating, fragrance-free, hypoallergenic emollient-based moisturizers. Quality sleep and intentionally structured recovery are vital for supporting collagen synthesis and reducing systemic inflammation [78]. Athletes can implement techniques to improve sleep hygiene and structure rest days intentionally to reduce chronic inflammation, further supporting their skin health.

Future Directions

Need for longitudinal studies on skin aging in endurance athletes

Dermatological health in endurance athletes remains a largely underexplored area, with significant gaps in research on the long-term effects of intense physical exertion and environmental exposure on skin aging. While existing studies have highlighted risks associated with endurance sports, such as cardiovascular, respiratory, and musculoskeletal challenges, there is a lack of focused investigations into the cumulative impact on skin health [10]. Longitudinal studies are needed to examine the progression of skin aging in endurance athletes, identifying patterns and risk factors that emerge over years of training and competition. These studies should specifically investigate how prolonged UV exposure, oxidative stress, chronic dehydration, nutritional deficiencies, and mechanical stress contribute to premature aging over time in this unique population. Such studies would provide critical insights into the unique dermatological risks faced by endurance athletes, allowing for the development of evidence-based prevention

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strategies and interventions. Addressing this gap would not only improve skin health outcomes but also enhance the overall performance, longevity, and well-being of athletes engaged in these demanding sports.

Development of athlete-specific skincare products and protocols

Creating athlete-specific skincare products and protocols is critical for addressing the unique dermatological needs of endurance athletes and mitigating premature skin aging caused by prolonged environmental exposure and intense physical exertion. The development of tailored skincare solutions should focus on broad-spectrum, water-resistant sunscreens designed specifically for athletes, incorporating features such as sweat-resistance, non-comedogenic properties, and easy reapplication during long training sessions. High-performance UPF-rated exercise clothing, moisture-wicking UV-blocking fabrics, and aerodynamic, lightweight UV-protective sunglasses and hats should be prioritized. While existing products serve these needs to some extent, further advancements can include smart gear embedded with UV monitoring sensors to enhance functionality [79]. Collaborations with athletic apparel brands could drive the creation of durable, breathable, and practical products that offer comprehensive protection against UV exposure while supporting performance. Investing in research and testing would ensure these solutions meet the specific needs of endurance athletes, providing both immediate sun protection and long-term strategies to combat skin aging.

In addition to the development of products, creating standardized athlete-specific skincare protocols is equally critical for preventing premature skin aging. These protocols should be designed and tested to address the unique needs of athletes at the pre-, during-, and post-training levels. Pre-training routines should emphasize applying broad-spectrum, sweat-resistant sunscreen daily, reapplying every two hours during prolonged exposure [80]. Additionally, deep moisturization before cold-weather events or barrier creams for water-based sports can be recommended to help mitigate environmental damage [81]. During training, protocols should explore methods to minimize UV exposure, such as incorporating real-time UV monitoring devices and promoting hydration strategies [79]. Post-training protocols should focus on cleansing the skin with gentle products to remove sweat and pollutants, followed by antioxidant-rich serums like vitamin C to combat oxidative stress and moisturizing with ceramides and hyaluronic acid to restore the skin barrier [82,83,73,74]. Regular mole checks should also be integrated to promote early detection of melanoma, along with education on the importance of quality sleep and recovery for optimal skin repair [79]. By aligning these protocols with athlete-specific products, endurance athletes can adopt holistic and practical strategies to protect their skin and reduce the effects of premature aging.

Integration of Wearable Technology

Emerging wearable technologies offer promising strategies for real-time skin monitoring in endurance athletes. Advanced biosensors track hydration, sweat rate, electrolyte, and metabolite levels, including glucose and lactate, in real-time, providing valuable data through app-based platforms [84]. Devices like the Gx Sweat Patch® and the Epicore Discovery Patch®, highlight how wearable technologies can seamlessly integrate physiological data with actionable recommendations, making them indispensable tools for athletes seeking to optimize both performance and recovery [85,86]. Similarly, wearable UV sensors offer innovative solutions for monitoring UV exposure and helping athletes protect their skin from photoaging and damage caused by prolonged outdoor activity [80]. By offering continuous monitoring of these key metrics, wearables address the challenges of adequate hydration, nutrient fluctuations, metabolic demands, and UV protection, enabling athletes to manage their skin health and overall performance proactively. Integrating these capabilities into a single platform would provide a comprehensive approach to optimizing both skin protection and athletic recovery.

Additionally, integrating wearable sleep technology and smart sleep solutions is essential for athletes, as quality sleep is crucial for both performance and skin health. Newer sleep trackers, such as the Oura Ring and Whoop Strap, monitor sleep stages, recovery, and physiological metrics like heart rate variability [87,88]. In contrast, Eight Sleep's Pod Pro not only performs the same functions but also optimizes sleep through temperature regulation and real-time adjustments [89]. These tools not only enhance athletic recovery and performance but also support skin health by promoting deep, restorative sleep, which is vital for cellular repair and reducing inflammation [54]. By integrating these technologies, athletes can ensure that their sleep routines align with the demands of their training, ultimately improving their overall well-being and longevity in their sport.

CONCLUSION

Endurance athletes are at a higher risk of early skin aging due to prolonged exposure to environmental factors, vigorous physical activity, and the physiological stress that accelerates skin damage. Factors such as UV radiation, oxidative stress, dehydration, improper nutrition, and repetitive mechanical injuries weaken the skin's structure and its protective functions. To mitigate these challenges, targeted education, personalized skincare routines, and innovative products specifically for athletes are crucial. This includes advanced sunscreens, hydration-centric formulations, and products rich in antioxidants. Additionally, wearable technology allows athletes to monitor their hydration levels, UV exposure, and recovery processes in real-time, which supports skin health management and enhances performance. Ongoing research is essential to understand the skin-related effects of endurance sports and to develop effective intervention strategies. By prioritizing skin health through research, education, and technological advancements, endurance athletes can safeguard their skin, enhance their overall well-being, extend their athletic longevity, and improve their quality of life.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

REFERENCES

1. Farage MA, Miller KW, Elsner P, Maibach HI. (2013). Characteristics of the Aging Skin. Adv Wound Care (New Rochelle). 2(1):5-10.
2. Farage MA, Miller KW, Berardesca E, Maibach HI. (2009). Clinical implications of aging skin: cutaneous disorders in the elderly. Am J Clin Dermatol. 10(2):73-86.
3. Papaccio F, D Arino A, Caputo S, Bellei B. Focus on the Contribution of Oxidative Stress in Skin Aging. Antioxidants (Basel). 2022 Jun 6;11(6):1121.
4. Paliwal G, Saxena K, Koti V, Shukla P, Dutt S, Usmani S, et al. (2019). Study of clinical patterns and frequency of cutaneous manifestations in the elderly. International Journal of Research in Dermatology. 5(1):45-51.
5. Han A, Chien AL, Kang S. (2014). Photoaging. Dermatol Clin. 32(3):291-299.
6. Leyden JJ. Clinical features of ageing skin. Br J Dermatol. 122(Suppl 35):1-3.
7. Golubjatnikov M, Walker A. (2024). Endurance Sporting Events. Emerg Med Clin North Am. 42(3):581-596.
8. Boston Athletic Association. (n.d.). Field of qualifiers notified of acceptance into the 129th Boston Marathon presented by Bank of America. Boston Athletic Association. Available at: https://www.baa.org/field-qualifiers-notified-acceptance-129th-boston-marathon-presented-bank-america#:~:text=An%20updated%20total%20of%2036%2C393,set%20at%2030%2C000%20official%20entrants
9. McCormick A, Meijen C, Marcora S. (2015). Psychological Determinants of Whole-Body Endurance Performance. Sports Med. 45(7):997-1015.
10. Scheer V, Tiller NB, Doutreleau S, Khodaee M, Knechtle B, Pasternak A, et al. (2022). Potential Long-Term Health Problems Associated with Ultra-Endurance Running: A Narrative Review. Sports Med. 52(4):725-740.
11. Bossé Y, Côté A. (2020). Asthma: An Untoward Consequence of Endurance Sports? Am J Respir Cell Mol Biol. 63(1):7-8.
12. Scheer V, Krabak BJ. (2021). Musculoskeletal Injuries in Ultra-Endurance Running: A Scoping Review. Front Physiol. 12:664071.
13. Martínez-Sanz JM, Fernández Nuñez A, Sospedra I, Martínez-Rodríguez A, Domínguez R, González-Jurado JA, et al. (2020). Nutrition-Related Adverse Outcomes in Endurance Sports Competitions: A Review of Incidence and Practical Recommendations. Int J Environ Res Public Health. 17(11):4082.
14. Nogueira A, Molinero O, Salguero A, Márquez S. (2018). Exercise Addiction in Practitioners of Endurance Sports: A Literature Review. Front Psychol. 9:1484.
15. Salminen A, Kaarniranta K, Kauppinen A. (2022). Photoaging: UV radiation-induced inflammation and immunosuppression accelerate the aging process in the skin. Inflamm Res. 71(7-8):817-831.

16. Salminen A, Kaarniranta K, Kauppinen A. (2022). Photoaging: UV radiation-induced inflammation and immunosuppression accelerate the aging process in the skin. Inflamm Res. 71(7-8):817-831.

17. Tang X, Yang T, Yu D, Xiong H, Zhang S. (2024). Current insights and future perspectives of ultraviolet radiation (UV) exposure: Friends and foes to the skin and beyond the skin. Environ Int. 185:108535.

18. Gromkowska-Kępka KJ, Puścion-Jakubik A, Markiewicz-Żukowska R, Socha K. (2021). The impact of ultraviolet radiation on skin photoaging - review of in vitro studies. J Cosmet Dermatol. 20(11):3427-3431.

19. Wolf ST, Kenney LE, Kenney WL. (2020). Ultraviolet Radiation Exposure, Risk, and Protection in Military and Outdoor Athletes. Curr Sports Med Rep. 19(4):137-141.

20. Richtig E, Ambros-Rudolph CM, Trapp M, Lackner HK, Hofmann-Wellenhof R, Kerl H, et al. (2008). Melanoma markers in marathon runners: increase with sun exposure and physical strain. Dermatology. 217(1):38-44.

21. Mastaloudis A, Leonard SW, Traber MG. (2001). Oxidative stress in athletes during extreme endurance exercise. Free Radic Biol Med. 31(7):911-922.

22. Rinnerthaler M, Bischof J, Streubel MK, Trost A, Richter K. (2015). Oxidative stress in aging human skin. Biomolecules. 5(2):545-589.

23. Powers SK, Deminice R, Ozdemir M, Yoshihara T, Bomkamp MP, Hyatt H. (2020). Exercise-induced oxidative stress: Friend or foe? J Sport Health Sci. 9(5):415-425.

24. Armstrong LE. (2021). Rehydration during Endurance Exercise: Challenges, Research, Options, Methods. Nutrients. 13(3):887.

25. Verdier-Sévrain S, Bonté F. (2007). Skin hydration: a review on its molecular mechanisms. J Cosmet Dermatol. 6(2):75-82.

26. Kottner J, Lichterfeld A, Blume-Peytavi U. (2013). Transepidermal water loss in young and aged healthy humans: a systematic review and meta-analysis. Arch Dermatol Res. 305(4):315-323.

27. Palma L, Marques LT, Bujan J, Rodrigues LM. (2015). Dietary water affects human skin hydration and biomechanics. Clin Cosmet Investig Dermatol. 8:413-21.

28. Vrhovski B, Weiss AS. (1998). Biochemistry of tropoelastin. Eur J Biochem. 258(1):1-18.

29. Langton AK, Sherratt MJ, Griffiths CE, Watson RE. (2010). A new wrinkle on old skin: the role of elastic fibres in skin ageing. Int J Cosmet Sci. 32(5):330-339.

30. Moss K, Kreutzer A, Graybeal AJ, Zhang Y, Braun-Trocchio R, Porter RR, et al. (2023). Nutrient Adequacy in Endurance Athletes. Int J Environ Res Public Health. 20(8):5469.

31. Park K. (2015). Role of micronutrients in skin health and function. Biomol Ther (Seoul). 23(3):207-217.

32. Flockhart M, Larsen FJ. (2024). Continuous Glucose Monitoring in Endurance Athletes: Interpretation and Relevance of Measurements for Improving Performance and Health. Sports Med. 54(2):247-255.

33. Michalak M, Pierzak M, Kręcisz B, Suliga E. (2021). Bioactive Compounds for Skin Health: A Review. Nutrients. 13(1):203.

34. Ghazali NI, Mohd Rais RZ, Makpol S, Chin KY, Yap WN, Goon JA. (2022). Effects of tocotrienol on aging skin: A systematic review. Front Pharmacol. 13:1006198.

35. Ahomies H, Descamps V, Leclerc-Mercier S, Kluger N. (2024). Skin Diseases in Long-Distance Runners. JEADV Clinical Practice. DOI: 10.1002/jvc2.613.

36. Lee RT, Briggs WH, Cheng GC, Rossiter HB, Libby P, Kupper T. (1997). Mechanical deformation promotes secretion of IL-1 alpha and IL-1 receptor antagonist. J Immunol. 159(10):5084-5088.

37. Agrawal R, Hu A, Bollag WB. (2023). The Skin and Inflamm-Aging. Biology (Basel). 12(11):1396.

38. De Castro-Maqueda G, Gutierrez-Manzanedo JV, Ponce-González JG, Fernandez-Santos JR, Linares-Barrios M, De Troya-Martín M. (2020). Sun Protection Habits and Sunburn in Elite Aquatics Athletes: Surfers, Windsurfers and Olympic Sailors. J Cancer Educ. 35(2):312-320.

39. Jinna S, Adams BB. (2013). Ultraviolet radiation and the athlete: risk, sun safety, and barriers to implementation of protective strategies. Sports Med. 43(7):531-537.

40. Khodaee M, Grothe HL, Seyfert JH, VanBaak K. (2016). Athletes at High Altitude. Sports Health. 8(2):126-132.

41. Green M, Kashetsky N, Feschuk A, Maibach HI. (2022). Transepidermal water loss (TEWL): Environment and pollution-A systematic review. Skin Health Dis. 2(2):e104.

42. Moehrle M. (2008). Outdoor sports and skin cancer. Clin Dermatol. 26(1):12-15.

43. Couto M, Bernard A, Delgado L, Drobnic F, Kurowski M, Moreira A, et al. (2021). Health effects of exposure to chlorination by-products in swimming pools. Allergy. 76(11):3257-3275.

44. Parrado C, Mercado-Saenz S, Perez-Davo A, Gilaberte Y, Gonzalez S, Juarranz A. (2019). Environmental Stressors on Skin Aging. Mechanistic Insights. Front Pharmacol. 10:759.

45. He X, Wan F, Su W, Xie W. (2023). Research Progress on Skin Aging and Active Ingredients. Molecules. 28(14):5556.

46. Kliniec K, Tota M, Zalesińska A, Łyko M, Jankowska-Konsur A. (2023). Skin Cancer Risk, Sun-Protection Knowledge and Behavior in Athletes-A Narrative Review. Cancers (Basel). 15(13):3281.

47. Gonzalo-Encabo P, Maldonado G, Valadés D, Ferragut C, Pérez-López A. (2021). The Role of Exercise Training on Low-Grade Systemic Inflammation in Adults with Overweight and Obesity: A Systematic Review. Int J Environ Res Public Health. 18(24):13258.

48. Militello R, Luti S, Gamberi T, Pellegrino A, Modesti A, Modesti PA. (2024). Physical Activity and Oxidative Stress in Aging. Antioxidants (Basel). 13(5):557.

49. Nieman DC, Wentz LM. (2019). The compelling link between physical activity and the body's defense system. J Sport Health Sci. 8(3):201-217.

50. Calle MC, Fernandez ML. (2010). Effects of resistance training on the inflammatory response. Nutr Res Pract. 4(4):259-269.

51. Wegierska AE, Charitos IA, Topi S, Potenza MA, Montagnani M, Santacroce L. (2022). The Connection Between Physical Exercise and Gut Microbiota: Implications for Competitive Sports Athletes. Sports Med. 52(10):2355-2369.

52. Cerqueira É, Marinho DA, Neiva HP, Lourenço O. Inflammatory Effects of High and Moderate Intensity Exercise-A Systematic Review. Front Physiol. 2020 Jan 9;10:1550.

53. Degerstrøm J, Østerud B. (2006). Increased inflammatory response of blood cells to repeated bout of endurance exercise. Med Sci Sports Exerc. 38(7):1297-1303.

54. Kahan V, Andersen ML, Tomimori J, Tufik S. (2010). Can poor sleep affect skin integrity? Med Hypotheses. 75(6):535-537.

55. Patel H, Vanguri P, Kumar D, Levin D. (2024). The Impact of Inadequate Sleep on Overtraining Syndrome in 18-22-Year-Old Male and Female College Athletes: A Literature Review. Cureus. 16(3):e56186.

56. Guan LL, Lim HW, Mohammad TF. (2021). Sunscreens and Photoaging: A Review of Current Literature. Am J Clin Dermatol. 22(6):819-828.

57. Forsea AM. (2023). Sunscreens. In European Handbook of Dermatological Treatments. pp. 1771-1785. Cham: Springer International Publishing.

58. Glaser KS, Tomecki KJ. (2020). Sunscreens in the United States: Current Status and Future Outlook. Adv Exp Med Biol. 1268:355-379.

59. Lu JT, Ilyas E. (2022). An Overview of Ultraviolet-Protective Clothing. Cureus. 14(7):e27333.

60. Pappas A, Liakou A, Zouboulis CC. (2016). Nutrition and skin. Rev Endocr Metab Disord. 17(3):443-448.

61. Fam VW, Charoenwoodhipong P, Sivamani RK, Holt RR, Keen CL, Hackman RM. (2022). Plant-Based Foods for Skin Health: A Narrative Review. J Acad Nutr Diet. 122(3):614-629.

62. Burke KE. (2018). Mechanisms of aging and development-A new understanding of environmental damage to the skin and prevention with topical antioxidants. Mech Ageing Dev. 172:123-130.

DOI: https://doi.org/10.35702/Derm.10032

63. Duplan H, Nocera T. (2018). Hydratation cutanée et produits hydratants [Skin hydration and hydrating products]. Ann Dermatol Venereol. 145(5):376-384.

64. Bergeron MF. (2015). Hydration in the Pediatric Athlete - How to Guide Your Patients. Curr Sports Med Rep. 14(4):288-293.

65. Racinais S, Ihsan M, Taylor L, Cardinale M, Adami PE, Alonso JM, et al. (2021). Hydration and cooling in elite athletes: relationship with performance, body mass loss and body temperatures during the Doha 2019 IAAF World Athletics Championships. Br J Sports Med. 55(23):1335-1341.

66. Bellemère G, Stamatas GN, Bruère V, Bertin C, Issachar N, Oddos T. (2009). Antiaging action of retinol: from molecular to clinical. Skin Pharmacol Physiol. 22(4):200-209.

67. Zapała M, Hunek A, Kaziród K, Chmielarz K, Wiśniewska-Skomra J, Tylutka K, et al. (2023). The use of retinoids in the treatment of skin lesions and prevention of signs of skin aging - a systematic review. Journal of Education, Health and Sport. 27(1):87-107.

68. Zhong J, Zhao N, Song Q, Du Z, Shu P. (2024). Topical retinoids: Novel derivatives, nano lipid-based carriers, and combinations to improve chemical instability and skin irritation. J Cosmet Dermatol. 23(10):3102-3115.

69. Farris P. (2023). Vitamin A: It's role in cosmeceuticals for antiaging. Dermatological Reviews. 4:268-277.

70. Panda P, Muppidi S, Karuturi K, Moranganti M, Mukkamala S. (2023). Assessment of the SPF and Anti-Irritating Properties of Sunscreen designed for Retinol users. International Journal of Experimental Research and Review. 30:179-189.

71. Fei H, Dan L, Qu W, Chen D, Hong Y, Sheng J, et al. (2020). Nanoliposomes codelivering bioactive peptides produce enhanced anti-aging effect in human skin. Journal of Drug Delivery Science and Technology. 57:101693.

72. Gálvez-Martín, P., Soto-Fernandez, C., Romero-Rueda, J., Cabañas, J., Torrent, A., Castells, G., & Martínez-Puig, D. (2023). A Novel Hyaluronic Acid Matrix Ingredient with Regenerative, Anti-Aging and Antioxidant Capacity. International Journal of Molecular Sciences, 24. https://doi.org/10.3390/ijms24054774.

73. Vovesná A, Zhigunov A, Balouch M, Zbytovská J. (2021). Ceramide liposomes for skin barrier recovery: a novel formulation based on natural skin lipids. Int J Pharm. 596:120264.

74. Vávrová K, Zbytovská J, Palát K, Holas T, Klimentová J, Hrabálek A, et al. (2004). Ceramide analogue 14S24 ((S)-2-tetracosanoylamino-3-hydroxypropionic acid tetradecyl ester) is effective in skin barrier repair in vitro. Eur J Pharm Sci. 21(5):581-587.

75. Techasatian L, Kiatchoosakun P. (2022). Effects of an emollient application on newborn skin from birth for prevention of atopic dermatitis: a randomized controlled study in Thai neonates. J Eur Acad Dermatol Venereol. 36(1):76-83.

76. Moldovan M. (2021). Cosmetic Products Containing Natural Based Emollients for Restoring Impaired Skin Barrier: Formulation and In Vivo Evaluation. Farmacia. 69(1):129-134.

77. Santos C, Kuhn K, Costa M, De Lima Guedes Morais S, Rosa A. (2023). Facial Skin Management: Strategies for High-Performance Athletes. International Journal of Current Science Research and Review. 6(12):8555-8562.

78. Duroux R, Jain A, Tabert M, Attia J. (2024). An upcycled fraction of Melaleuca alternifolia essential oil regenerates the skin through the skin melatonin pathway and improves sleep quality. J Cosmet Dermatol. 23(5):1840-1849.

79. Zou W, Sastry M, Gooding JJ, Ramanathan R, Bansal V. (2020). Recent Advances and a Roadmap to Wearable UV Sensor Technologies. Advanced Materials Technologies. 5(4):1901036.

80. How to apply sunscreen. (n.d.). Available at: https://www.aad.org/public/everyday-care/sun-protection/shade-clothing-sunscreen/how-to-apply-sunscreen

81. de Fine Olivarius F, Hansen AB, Karlsmark T, Wulf HC. (1996). Water protective effect of barrier creams and moisturizing creams: a new in vivo test method. Contact Dermatitis. 35(4):219-225.

82. Boo YC. (2022). Ascorbic Acid (Vitamin C) as a Cosmeceutical to Increase Dermal Collagen for Skin Antiaging Purposes: Emerging Combination Therapies. Antioxidants (Basel). 11(9):1663.

DOI: https://doi.org/10.35702/Derm.10032

83. Gao F, Liu C, Zhang L, Liu T, Wang Z, Song Z, et al. (2023). Wearable and flexible electrochemical sensors for sweat analysis: a review. Microsyst Nanoeng. 9:1.

84. Ghaffari R, Aranyosi AJ, Lee SP, Model JB, Baker LB. (2023). The Gx Sweat Patch for personalized hydration management. Nat Rev Bioeng. 1:5-7.

85. Mahoney K, Chon K, Ghaffari R, Minnis M, Huggins R, Lee E. (2023). Epicore Discovery Patch® sweat collection system to assess sweat proteomics-based biomarker discovery in exercise-heat stress and acclimation. Physiology. 38.

86. Altini M, Kinnunen H. (2021). The Promise of Sleep: A Multi-Sensor Approach for Accurate Sleep Stage Detection Using the Oura Ring. Sensors. 21(13):4302.

87. Miller DJ, Lastella M, Scanlan AT, Bellenger C, Halson SL, Roach GD, et al. (2020). A validation study of the WHOOP strap against polysomnography to assess sleep. J Sports Sci. 38(22):2631-2636.

88. Moyen NE, Ediger TR, Taylor KM, Hancock EG, Holden LD, Tracy EE, et al. (2024). Sleeping for One Week on a Temperature-Controlled Mattress Cover Improves Sleep and Cardiovascular Recovery. Bioengineering (Basel). 11(4):352.

DOI: https://doi.org/10.35702/Derm.10032